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*to be admitted *pro hac vice*

Attorneys for Plaintiff
FINISAR CORPORATION

ORIGINAL
FILED
JUL 17 2013
RICHARD W. WIEKING
CLERK, U.S. DISTRICT COURT
NORTHERN DISTRICT OF CALIFORNIA

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UNITED STATES DISTRICT COURT
NORTHERN DISTRICT OF CALIFORNIA
SAN JOSE DIVISION

FINISAR CORPORATION, a Delaware corporation, Plaintiff, v. NISTICA, INC., a Delaware corporation, Defendant.	CV 13 3345 No. ____________ **COMPLAINT FOR PATENT INFRINGEMENT** **JURY TRIAL DEMANDED**

Plaintiff Finisar Corporation ("Finisar") files this Complaint for Patent Infringement ("Complaint") against Defendant Nistica, Inc. ("Nistica"), wherein, pursuant to 35 U.S.C. §§ 271 and 281, Finisar seeks a judgment of infringement by Nistica of U.S. Patent Nos. 6,956,687 (the "'687 Patent"), 7,123,833 (the "'833 Patent"), 7,126,740 (the "'740 Patent"), 6,430,328 (the "'328 Patent"), 7,092,599 (the "'599 Patent"), 7,397,980 (the "'980 Patent") and damages resulting therefrom pursuant to 35 U.S.C. § 284, as well as preliminary and permanent injunction of the infringing activity pursuant to 35 U.S.C. § 283, and such other relief as the Court deems just and proper, and in support thereof alleges as follows:

PARTIES

1. Finisar is a Delaware corporation with a principal place of business at 1308 Moffett Park Drive, Sunnyvale, California 94089.

2. Upon information and belief, Nistica is a Delaware corporation with its principal place of business at 745 Route 202-206, Bridgewater, New Jersey 08807.

JURISDICTION AND VENUE

3. This Court has subject matter jurisdiction over this action pursuant to 28 U.S.C. §§ 1331 and 1338(a) because the action concerns infringement of a United States patent.

4. This Court has personal jurisdiction over Nistica at least by virtue of Nistica having conducted business in this District and having committed one or more acts of infringement in this District.

5. Venue is proper under 28 U.S.C. §§ 1391 and 1400.

INTRADISTRICT ASSIGNMENT

6. Assignment of this matter to the San Jose Division is appropriate because both Finisar Corporation and Nistica, Inc. do business in this District, Finisar Corporation maintains its principal place of business in this District, and both are subject to jurisdiction in this District.

THE PATENTS-IN-SUIT

7. Finisar is the owner of the '687 Patent entitled "Optical Blocking Filter Having an Array of Micro-Mirrors," which the United States Patent & Trademark Office lawfully and duly issued on October 18, 2005. A true and correct copy of the '687 Patent is attached hereto as Exhibit A.

8. Finisar is the owner of the '833 Patent entitled "Dynamically Reconfigurable Optical Smart Node," which the United States Patent & Trademark Office lawfully and duly issued on October 17, 2006. A true and correct copy of the '833 Patent is attached hereto as Exhibit B.

9. Finisar is the owner of the '740 Patent entitled "Multifunction Optical Device Having a Spatial Light Modulator with an Array of Micro-Mirrors," which the United States Patent & Trademark Office lawfully and duly issued on October 24, 2006. A true and correct copy of the '740 Patent is attached hereto as Exhibit C.

10. Finisar is the owner of the '328 Patent entitled "Optical Switch," which the United States Patent & Trademark Office lawfully and duly issued on August 6, 2002. A true and correct copy of the '328 Patent is attached hereto as Exhibit D.

11. Finisar is the owner of the '599 Patent entitled "Wavelength Manipulation System and Method," which the United States Patent & Trademark Office lawfully and duly issued on August 15, 2006. A true and correct copy of the '599 Patent is attached hereto as Exhibit E.

12. Finisar is the owner of the '980 Patent entitled "Dual-Source Optical Wavelength Processor," which the United States Patent & Trademark Office lawfully and duly issued on July 8, 2008. A true and correct copy of the '980 Patent is attached hereto as Exhibit F.

FACTUAL BACKGROUND

13. Founded in 1987 in Santa Clara County, California, Finisar Corporation produces optical communications components and subsystems. These products enable high-speed voice, video and data communications for networking, storage, wireless, and cable TV applications. Finisar has provided critical breakthroughs in optics technologies and has supplied system manufacturers with the production volumes needed to meet the exploding demand for network bandwidth. Finisar's industry-leading optical products include transceivers/transponders, active cables, wavelength selective switches ("WSS"), reconfigurable optical add-drop multiplexer ("ROADM") linecards, optical instruments, RF-over-Fiber, amplifiers, and active and passive components.

14. WSS products need a controlled element that switches light beams of different wavelengths in different directions. Two ways to perform an optical switching function include using: (1) an array of micro electronic mechanical system ("MEMS") mirrors and (2) liquid crystal on silicon ("LCOS") technology.

15. Upon information and belief, Nistica was founded in 2005 and is now a subsidiary

of Fujikura, Ltd. Nistica designs, develops, markets, sells, and offers to sell WSS products for ROADM devices that compete with the products sold by Finisar. Nistica sells certain products, such as under the trade names FLEDGE® and FULL FLEDGE®, which are WSS devices. In addition, upon information and belief, Nistica has also offered to sell certain WSS products that include LCOS technology for optical switching.

16. Nistica's products are sold and/or offered for sale to customers who incorporate Nistica's WSS and ROADM devices into products that are then sold to end users such as wireline and wireless telecommunication service providers and cable TV operators.

FIRST CLAIM FOR RELIEF

(Infringement of the 6,956,687 Patent)

17. Finisar incorporates by reference paragraphs 1 through 16 of the Complaint as if set forth here in full.

18. Upon information and belief, Nistica has been and is currently directly infringing one or more claims of the '687 Patent by making, using, offering to sell, and/or selling within the United States, and/or importing into the United States, without authority, WSS devices, including, but not limited to, Nistica's FLEDGE® and FULL FLEDGE® series of products that include an array of MEMS mirrors for optical switching (the "'687 Infringing Products").

19. Upon information and belief, upon knowledge of the '687 Patent, Nistica is contributing to the infringement of, and/or inducing infringement of the '687 Patent by, among other things, knowingly and with intent, actively encouraging its customers and suppliers to make, use, sell and/or offer for sale Nistica's '687 Infringing Products in a manner that constitutes infringement of one or more claims of the '687 Patent. There are no substantial uses of the '687 Infringing Products made, used, sold, or offered for sale by Nistica that do not infringe one or more claims of the '687 Patent.

20. As a result of Nistica's unlawful infringement of the '687 Patent, Finisar has suffered and will continue to suffer damage. Finisar is entitled to recover from Nistica the damages adequate to compensate for such infringement, which have yet to be determined.

21. Upon information and belief, any manufacturing, sales, offers for sale, uses, or

importation by Nistica of the '687 Infringing Products reflect a deliberate and conscious decision to infringe the '687 Patent or, at the very least, a reckless disregard of Finisar's patent rights. Nistica's infringement after that date has been willful and Finisar is entitled to treble damages and attorneys' fees and costs incurred in this action, along with prejudgment interest under 35 U.S.C. §§ 284, 285.

22. Nistica will continue to infringe the '687 Patent unless and until it is preliminarily and permanently enjoined by this Court.

23. Nistica's acts of infringement have caused and will continue to cause irreparable harm to Finisar unless and until Nistica is enjoined by this Court.

SECOND CLAIM FOR RELIEF

(Infringement of the 7,123,833 Patent)

24. Finisar incorporates by reference paragraphs 1 through 23 of the Complaint as if set forth here in full.

25. Upon information and belief, Nistica has been and is currently directly infringing one or more claims of the '833 Patent by making, using, offering to sell, and/or selling within the United States, and/or importing into the United States, without authority WSS devices, including, but not limited to, Nistica's FLEDGE® and FULL FLEDGE® series of products that include an array of MEMS mirrors, and/or devices that include LCOS technology, for optical switching (the "'833 Infringing Products").

26. Upon information and belief, upon knowledge of the '833 Patent, Nistica is contributing to the infringement of, and/or inducing infringement of the '833 Patent by, among other things, knowingly and with intent, actively encouraging its customers and suppliers to make, use, sell and/or offer for sale Nistica's '833 Infringing Products in a manner that constitutes infringement of one or more claims of the '833 Patent. There are no substantial uses of the '833 Infringing Products made, used, sold, or offered for sale by Nistica that do not infringe one or more claims of the '833 Patent.

27. As a result of Nistica's unlawful infringement of the '833 Patent, Finisar has suffered and will continue to suffer damage. Finisar is entitled to recover from Nistica the

damages adequate to compensate for such infringement, which have yet to be determined.

28. Upon information and belief, any manufacturing, sales, offers for sale, uses, or importation by Nistica of the '833 Infringing Products reflect a deliberate and conscious decision to infringe the '833 Patent or, at the very least, a reckless disregard of Finisar's patent rights. Nistica's infringement after that date has been willful and Finisar is entitled to treble damages and attorneys' fees and costs incurred in this action, along with prejudgment interest under 35 U.S.C. §§ 284, 285.

29. Nistica will continue to infringe the '833 Patent unless and until it is preliminarily and permanently enjoined by this Court.

30. Nistica's acts of infringement have caused and will continue to cause irreparable harm to Finisar unless and until Nistica is enjoined by this Court.

THIRD CLAIM FOR RELIEF

(Infringement of the 7,126,740 Patent)

31. Finisar incorporates by reference paragraphs 1 through 30 of the Complaint as if set forth here in full.

32. Upon information and belief, Nistica has been and is currently directly infringing one or more claims of the '740 Patent by making, using, offering to sell, and/or selling within the United States, and/or importing into the United States, without authority, WSS devices, including, but not limited to, Nistica's FLEDGE® and FULL FLEDGE® series of products that include an array of MEMS mirrors for optical switching (the "'740 Infringing Products").

33. Upon information and belief, upon knowledge of the '740 Patent, Nistica is contributing to the infringement of, and/or inducing infringement of the '740 Patent by, among other things, knowingly and with intent, actively encouraging its customers and suppliers to make, use, sell and/or offer for sale Nistica's '740 Infringing Products in a manner that constitutes infringement of one or more claims of the '740 Patent. There are no substantial uses of the '740 Infringing Products made, used, sold, or offered for sale by Nistica that do not infringe one or more claims of the '740 Patent.

34. As a result of Nistica's unlawful infringement of the '740 Patent, Finisar has

suffered and will continue to suffer damage. Finisar is entitled to recover from Nistica the damages adequate to compensate for such infringement, which have yet to be determined.

35. Upon information and belief, any manufacturing, sales, offers for sale, uses, or importation by Nistica of the '740 Infringing Products reflect a deliberate and conscious decision to infringe the '740 Patent or, at the very least, a reckless disregard of Finisar's patent rights. Nistica's infringement after that date has been willful and Finisar is entitled to treble damages and attorneys' fees and costs incurred in this action, along with prejudgment interest under 35 U.S.C. §§ 284, 285.

36. Nistica will continue to infringe the '740 Patent unless and until it is preliminarily and permanently enjoined by this Court.

37. Nistica's acts of infringement have caused and will continue to cause irreparable harm to Finisar unless and until Nistica is enjoined by this Court.

FOURTH CLAIM FOR RELIEF

(Infringement of the 6,430,328 Patent)

38. Finisar incorporates by reference paragraphs 1 through 37 of the Complaint as if set forth here in full.

39. Upon information and belief, Nistica has been and is currently directly infringing one or more claims of the '328 Patent by making, using, offering to sell, and/or selling within the United States, and/or importing into the United States, without authority, WSS devices, including, but not limited to, devices that include LCOS technology for optical switching (the "'328 Infringing Products").

40. Upon information and belief, upon knowledge of the '328 Patent, Nistica is contributing to the infringement of, and/or inducing infringement of the '328 Patent by, among other things, knowingly and with intent, actively encouraging its customers and suppliers to make, use, sell and/or offer for sale Nistica's '328 Infringing Products in a manner that constitutes infringement of one or more claims of the '328 Patent. There are no substantial uses of the '328 Infringing Products made, used, sold, or offered for sale by Nistica that do not infringe one or more claims of the '328 Patent.

41. As a result of Nistica's unlawful infringement of the '328 Patent, Finisar has suffered and will continue to suffer damage. Finisar is entitled to recover from Nistica the damages adequate to compensate for such infringement, which have yet to be determined.

42. Upon information and belief, any manufacturing, sales, offers for sale, uses, or importation by Nistica of the '328 Infringing Products reflect a deliberate and conscious decision to infringe the '328 Patent or, at the very least, a reckless disregard of Finisar's patent rights. Nistica's infringement after that date has been willful and Finisar is entitled to treble damages and attorneys' fees and costs incurred in this action, along with prejudgment interest under 35 U.S.C. §§ 284, 285.

43. Nistica will continue to infringe the '328 Patent unless and until it is preliminarily and permanently enjoined by this Court.

44. Nistica's acts of infringement have caused and will continue to cause irreparable harm to Finisar unless and until Nistica is enjoined by this Court.

FIFTH CLAIM FOR RELIEF

(Infringement of the 7,092,599 Patent)

45. Finisar incorporates by reference paragraphs 1 through 44 of the Complaint as if set forth here in full.

46. Upon information and belief, Nistica has been and is currently directly infringing one or more claims of the '599 Patent by making, using, offering to sell, and/or selling within the United States, and/or importing into the United States, without authority, WSS devices, including, but not limited to, Nistica's FLEDGE® and FULL FLEDGE® series of products that include an array of MEMS mirrors, and/or devices that include LCOS technology, for optical switching (the "'328 Infringing Products").

47. Upon information and belief, upon knowledge of the '599 Patent, Nistica is contributing to the infringement of, and/or inducing infringement of the '599 Patent by, among other things, knowingly and with intent, actively encouraging its customers and suppliers to make, use, sell and/or offer for sale Nistica's '599 Infringing Products in a manner that constitutes infringement of one or more claims of the '599 Patent. There are no substantial uses

of the '599 Infringing Products made, used, sold, or offered for sale by Nistica that do not infringe one or more claims of the '599 Patent.

48. As a result of Nistica's unlawful infringement of the '599 Patent, Finisar has suffered and will continue to suffer damage. Finisar is entitled to recover from Nistica the damages adequate to compensate for such infringement, which have yet to be determined.

49. Upon information and belief, any manufacturing, sales, offers for sale, uses, or importation by Nistica of the '599 Infringing Products reflect a deliberate and conscious decision to infringe the '599 Patent or, at the very least, a reckless disregard of Finisar's patent rights. Nistica's infringement after that date has been willful and Finisar is entitled to treble damages and attorneys' fees and costs incurred in this action, along with prejudgment interest under 35 U.S.C. §§ 284, 285.

50. Nistica will continue to infringe the '599 Patent unless and until it is preliminarily and permanently enjoined by this Court.

51. Nistica's acts of infringement have caused and will continue to cause irreparable harm to Finisar unless and until Nistica is enjoined by this Court.

SIXTH CLAIM FOR RELIEF

(Infringement of the 7,397,980 Patent)

52. Finisar incorporates by reference paragraphs 1 through 51 of the Complaint as if set forth here in full.

53. Upon information and belief, Nistica has been and is currently directly infringing one or more claims of the '980 Patent by making, using, offering to sell, and/or selling within the United States, and/or importing into the United States, without authority, WSS devices, including, but not limited to, devices that include LCOS technology for optical switching (the "'980 Infringing Products").

54. Upon information and belief, upon knowledge of the '980 Patent, Nistica is contributing to the infringement of, and/or inducing infringement of the '980 Patent by, among other things, knowingly and with intent, actively encouraging its customers and suppliers to make, use, sell and/or offer for sale Nistica's '980 Infringing Products in a manner that

constitutes infringement of one or more claims of the '980 Patent. There are no substantial uses of the '980 Infringing Products made, used, sold, or offered for sale by Nistica that do not infringe one or more claims of the '980 Patent.

55. As a result of Nistica's unlawful infringement of the '980 Patent, Finisar has suffered and will continue to suffer damage. Finisar is entitled to recover from Nistica the damages adequate to compensate for such infringement, which have yet to be determined.

56. Upon information and belief, any manufacturing, sales, offers for sale, uses, or importation by Nistica of the '980 Infringing Products reflect a deliberate and conscious decision to infringe the '980 Patent or, at the very least, a reckless disregard of Finisar's patent rights. Nistica's infringement after that date has been willful and Finisar is entitled to treble damages and attorneys' fees and costs incurred in this action, along with prejudgment interest under 35 U.S.C. §§ 284, 285.

57. Nistica will continue to infringe the '980 Patent unless and until it is preliminarily and permanently enjoined by this Court.

58. Nistica's acts of infringement have caused and will continue to cause irreparable harm to Finisar unless and until Nistica is enjoined by this Court.

PRAYER FOR RELIEF

WHEREFORE, Finisar prays for a Judgment in favor of Finisar and against Nistica as follows:

(a) That Nistica has directly infringed the '687, '833, '740, '328, '599 and '980 Patents;

(b) That Nistica has indirectly infringed the '687, '833, '740, '328, '599 and '980 Patents;

(c) That this case is "exceptional" within the meaning of 35 U.S.C. § 285 against Nistica;

(d) An order preliminarily and permanently enjoining Nistica and its affiliates, subsidiaries, officers, directors, employees, agents, representatives, licensees, successors, assigns, and all those acting for them and on their behalf, or acting in concert with them directly or indirectly, from further acts of infringement of the '687, '833, '740, '328, '599 and '980 Patents;

(e) A full accounting for and an award of damages to Finisar for Nistica's infringement of the '687, '833, '740, '328, '599 and '980 Patents; including enhanced damages pursuant to 35 U.S.C. § 284, together with pre- and post-judgment interest;

(f) An award of Finisar's reasonable attorneys' fees, expenses, and costs; and

(g) A grant of such other and further equitable or legal relief as this Court deems proper.

Dated: July 17, 2013

WEIL, GOTSHAL & MANGES LLP

By: ______________________
CHRISTOPHER J. COX

Attorneys for Plaintiff
FINISAR CORPORATION

Of Counsel:
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TIGRAN VARDANIAN (to be admitted *pro hac vice*)
GREGORY S. MASKEL (to be admitted *pro hac vice*)
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DEMAND FOR JURY TRIAL

Plaintiff hereby demands a jury trial on all issues so triable under the laws as provide by Rule 38(b) of the Federal Rules of Civil Procedure.

Dated: July 17, 2013

WEIL, GOTSHAL & MANGES LLP

By: ______________________
CHRISTOPHER J. COX

Attorneys for Plaintiff
FINISAR CORPORATION

Of Counsel:
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EXHIBIT A

US006956687B2

(12) **United States Patent**
Moon et al.

(10) **Patent No.: US 6,956,687 B2**
(45) **Date of Patent: Oct. 18, 2005**

(54) **OPTICAL BLOCKING FILTER HAVING AN ARRAY OF MICRO-MIRRORS**

(75) Inventors: **John A. Moon**, Wallingford, CT (US); **Alan D. Kersey**, Glastonbury, CT (US); **James S. Sirkis**, Wallingford, CT (US); **James R. Dunphy**, Glastonbury, CT (US); **Joseph Pinto**, Wallingford, CT (US); **Paul Szczepanek**, Middletown, CT (US); **Michael A. Davis**, Glastonbury, CT (US); **Martin A. Putnam**, Cheshire, CT (US)

(73) Assignee: **CiDRA Corporation**, Wallingford, CT (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **10/327,695**

(22) Filed: **Dec. 19, 2002**

(65) **Prior Publication Data**

US 2003/0184843 A1 Oct. 2, 2003

Related U.S. Application Data

(63) Continuation-in-part of application No. 10/120,617, filed on Apr. 11, 2002, now abandoned, which is a continuation-in-part of application No. 10/115,647, filed on Apr. 3, 2002.

(60) Provisional application No. 60/365,741, filed on Mar. 18, 2002, provisional application No. 60/365,461, filed on Mar. 18, 2002, provisional application No. 60/332,319, filed on Nov. 16, 2001, provisional application No. 60/332,318, filed on Nov. 16, 2001, provisional application No. 60/311,002, filed on Aug. 8, 2001, provisional application No. 60/283, 197, filed on Apr. 11, 2001, and provisional application No. 60/281,079, filed on Apr. 3, 2001.

(51) **Int. Cl.**[7] **G02B 26/00**; G02B 26/08

(52) **U.S. Cl.** **359/223**; 359/224; 359/290; 359/291; 385/16; 385/39; 398/45; 398/83; 398/85

(58) **Field of Search** 359/571–573, 359/900, 290–292, 395, 297, 298, 301–302, 315, 318, 320, 223, 850, 872, 224, 308, 618, 629, 634, 639; 398/45, 49, 51, 54, 83, 85, 87–88, 79, 81; 385/33, 31, 39, 1–3, 15–18, 11, 24

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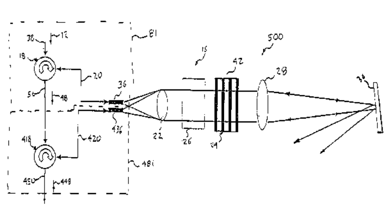
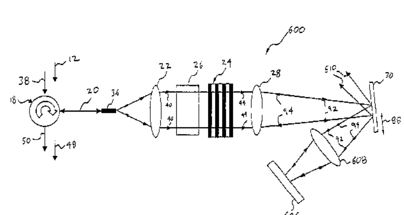
Primary Examiner—Hung Xuan Dang
Assistant Examiner—Joseph Martinez

(57) **ABSTRACT**

A reconfigurable optical blocking filter deletes a desired optical channel(s) from an optical WDM input signal, and includes a spatial light modulator having a micro-mirror device with a two-dimensional array of micro-mirrors that tilt between first and second positions in a “digital” fashion in response to a control signal provided by a controller in accordance with a switching algorithm and an input command. A collimators, diffraction grating, and Fourier lens, collectively collimate, separate and focus the optical input channels onto the array of micro-mirrors. The optical channel is focused on the micro-mirrors onto a plurality of micro-mirrors of the micro-mirror device, which effectively pixelates the optical channels. To delete an input channel of the optical input signal, micro-mirrors associated with each desired input channel are tilted to reflect the desired input channel away from the return path.

51 Claims, 30 Drawing Sheets





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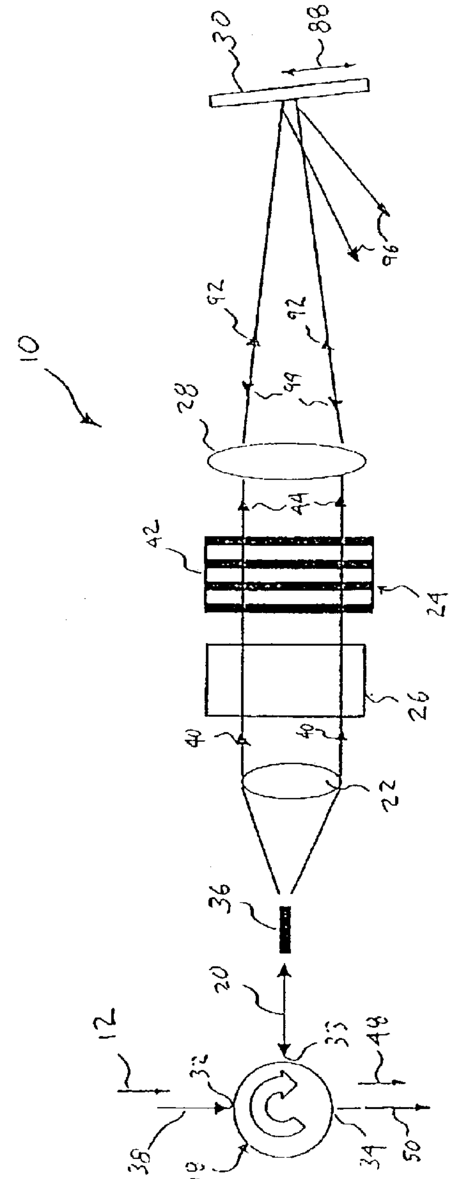

Fig. 1

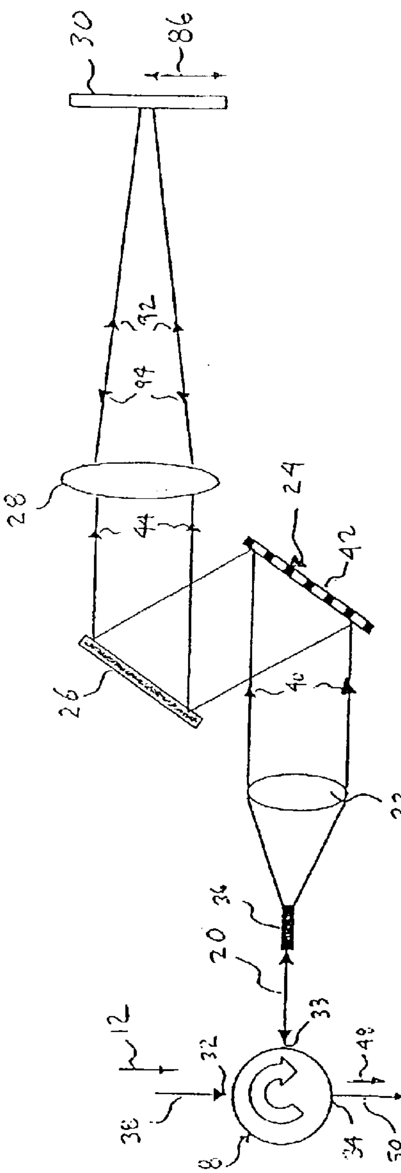

Fig. 2

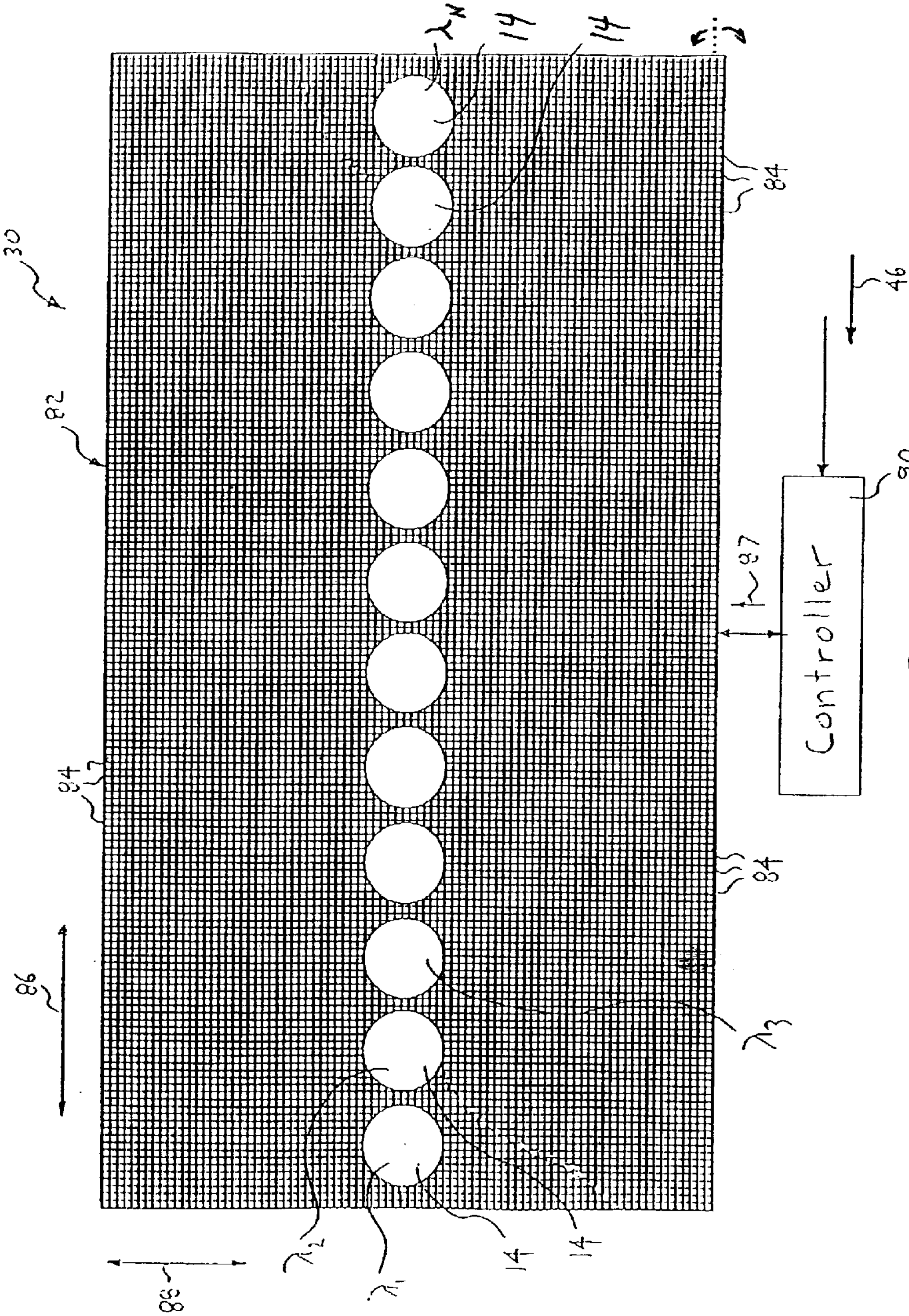

Fig. 3

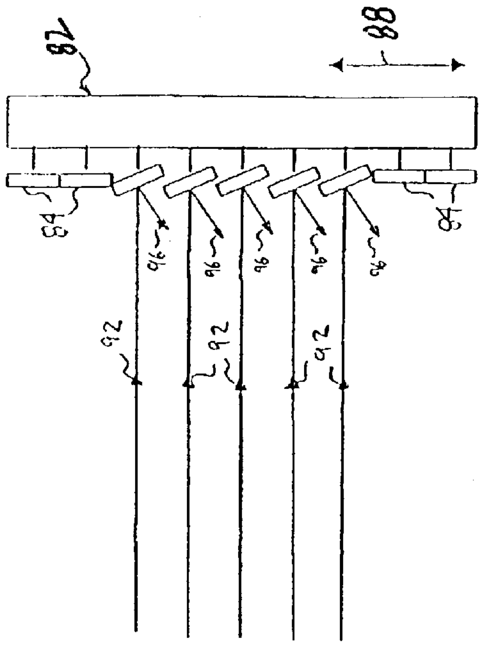

Fig. 4b

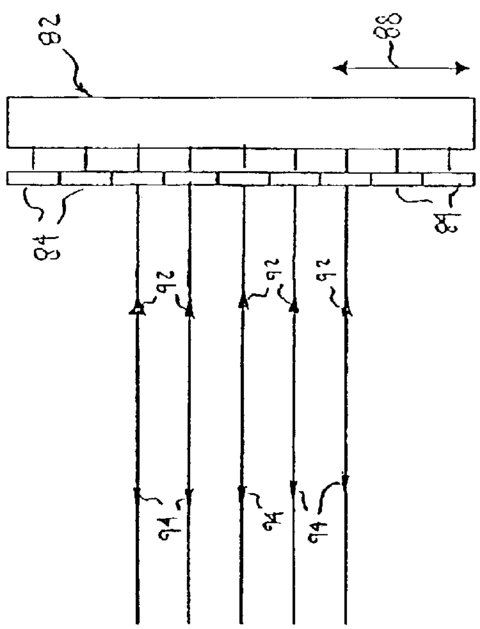

Fig. 4a

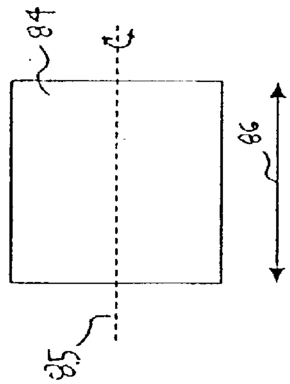

Fig. 5

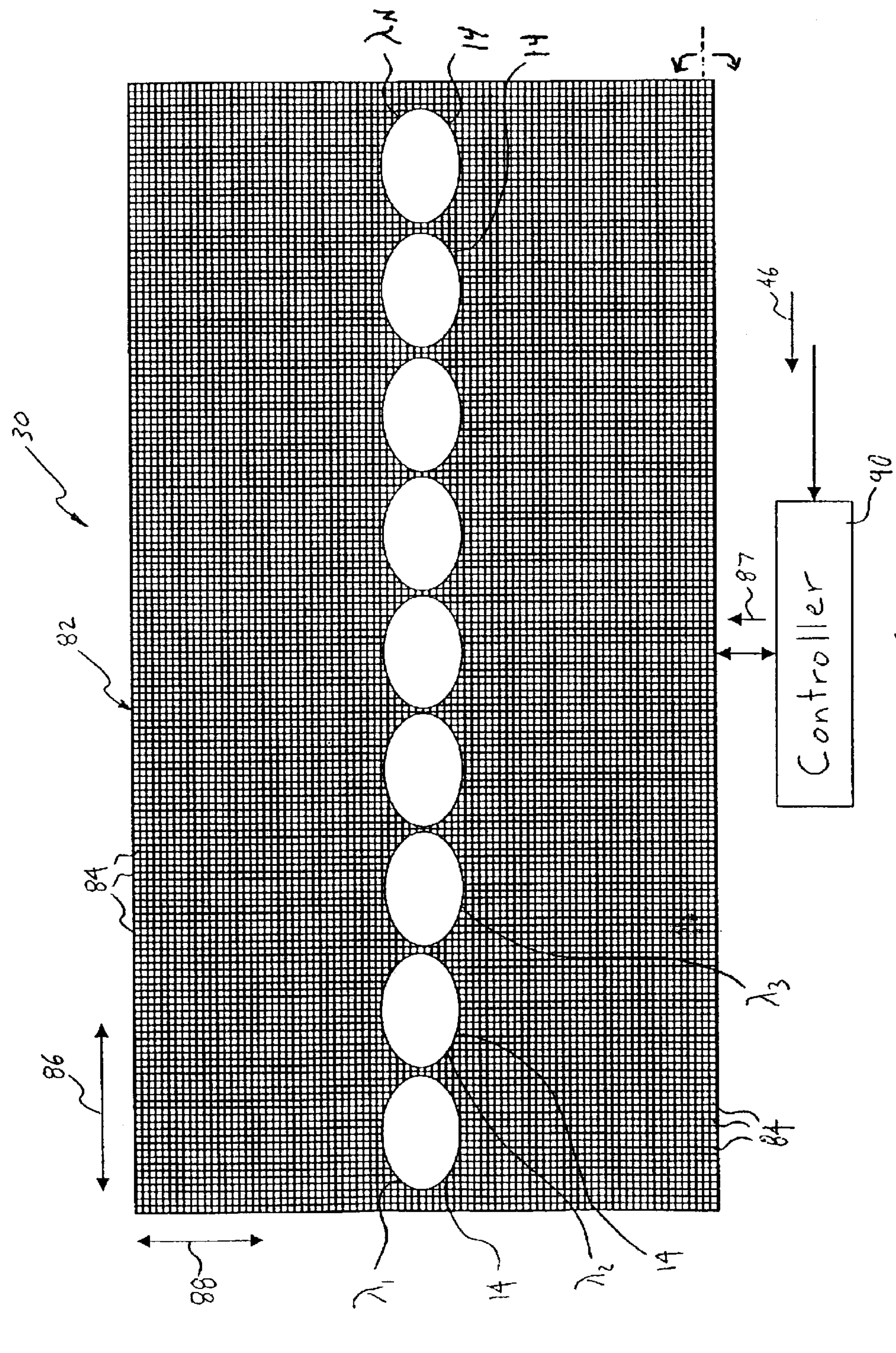
30
82
84
86
88
λ_1
14
λ_2
14
λ_3
84
87
Controller
90
46
λ_N
14
14

Fig. 6

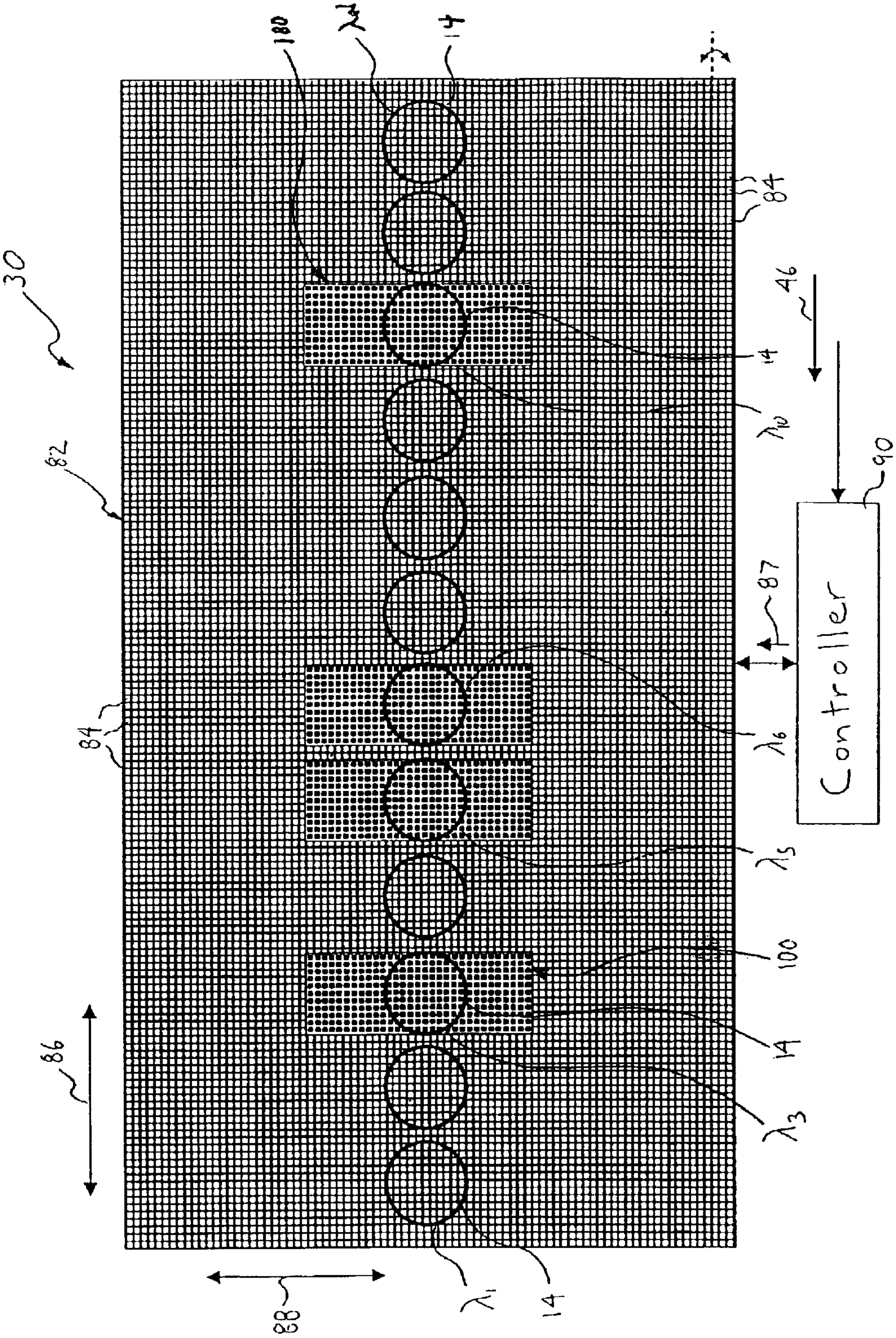
30
82
84
84
86
88
180
14
14
14
14
46
87
90
100
Controller
λ_1
λ_3
λ_5
λ_6
λ_{10}

Fig. 7

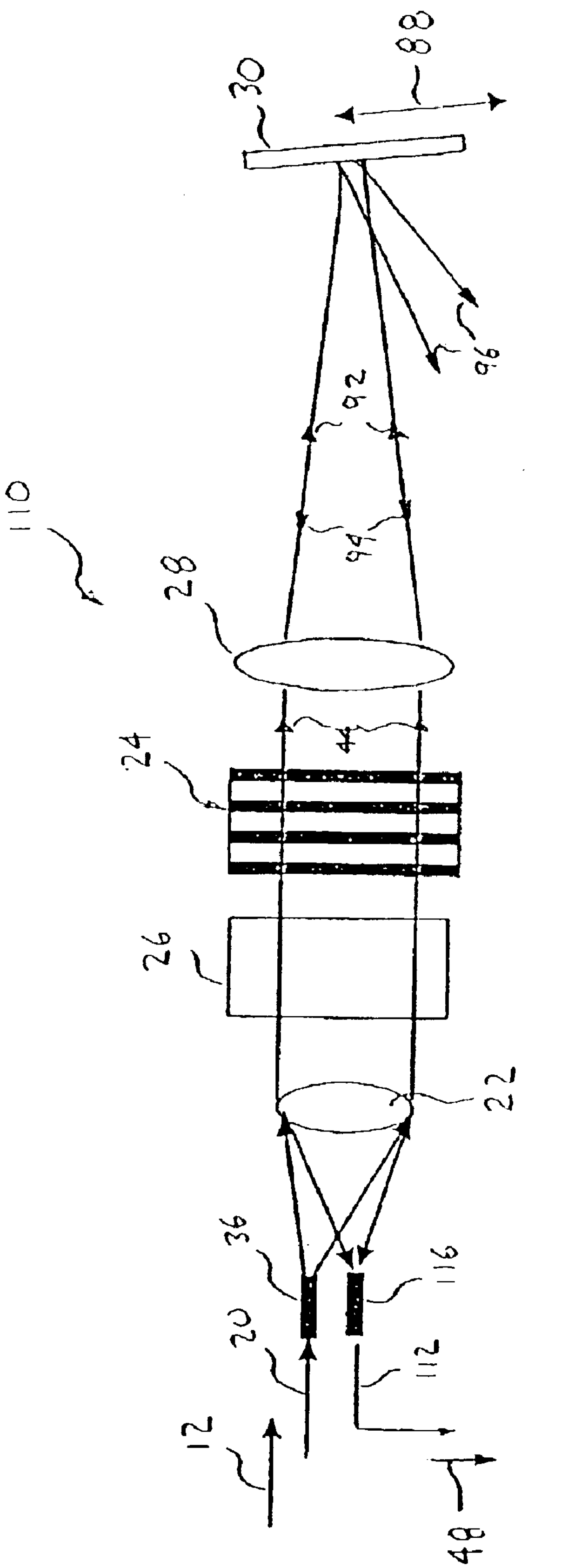

Fig. 8

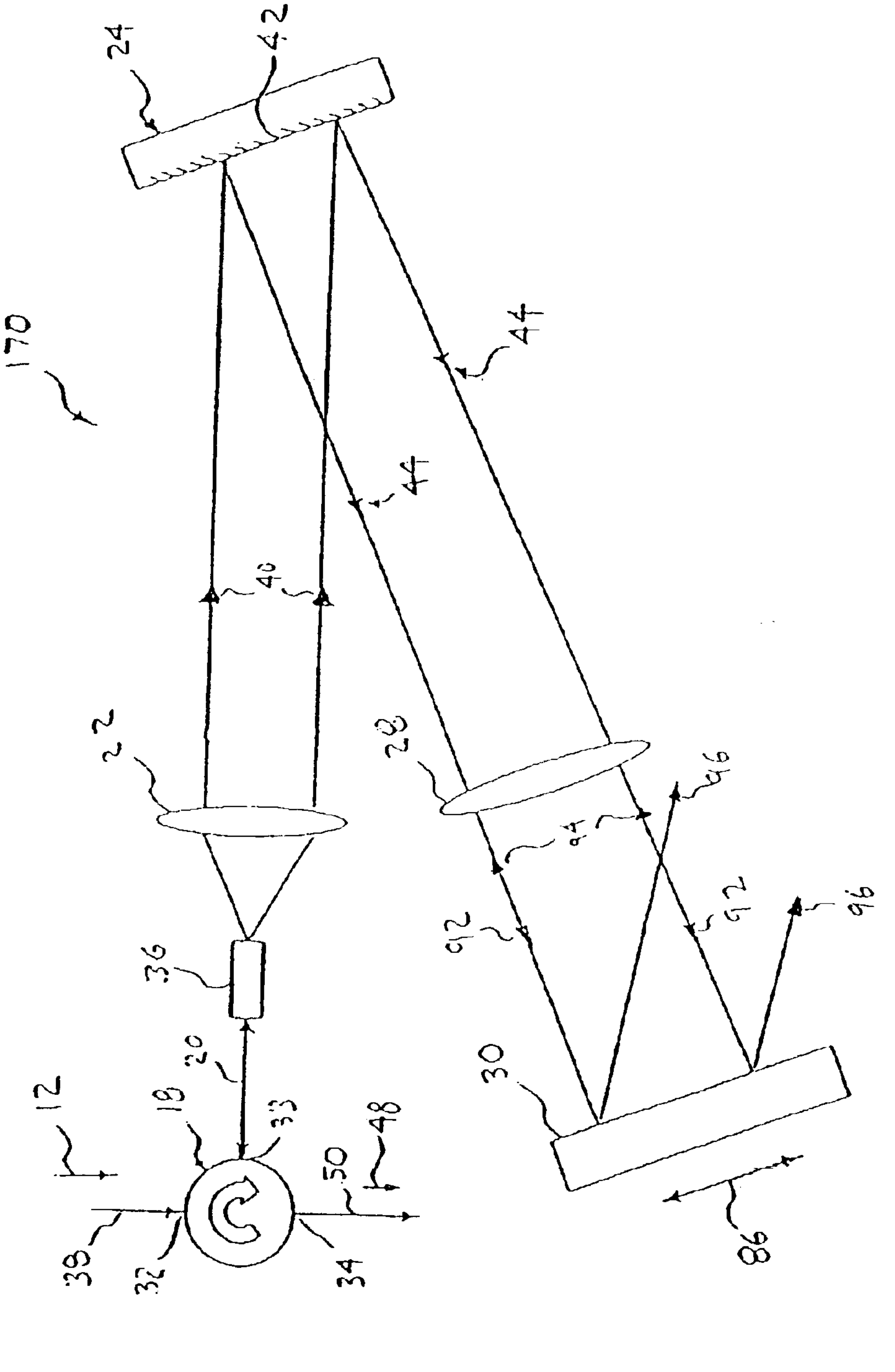
24
42
170
44
44
40
22
28
94
96
92
92
96
36
20
19
33
12
48
50
38
32
34
30
86

Fig. 9

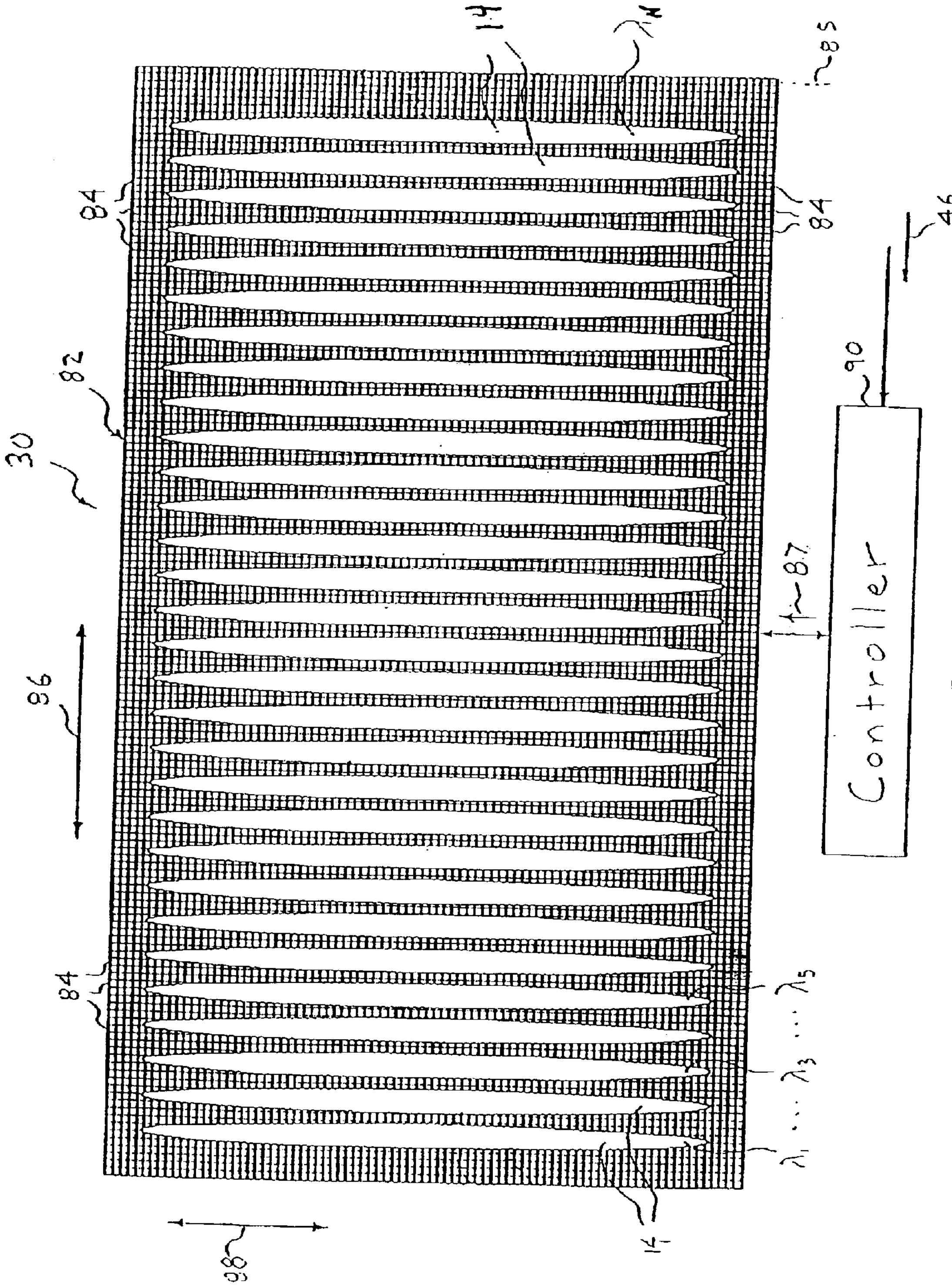
Controller
30
82
84
84
84
85
87
90
46
96
98
14
14
λ_1 ... λ_3 ... λ_5
λ_N

Fig. 10

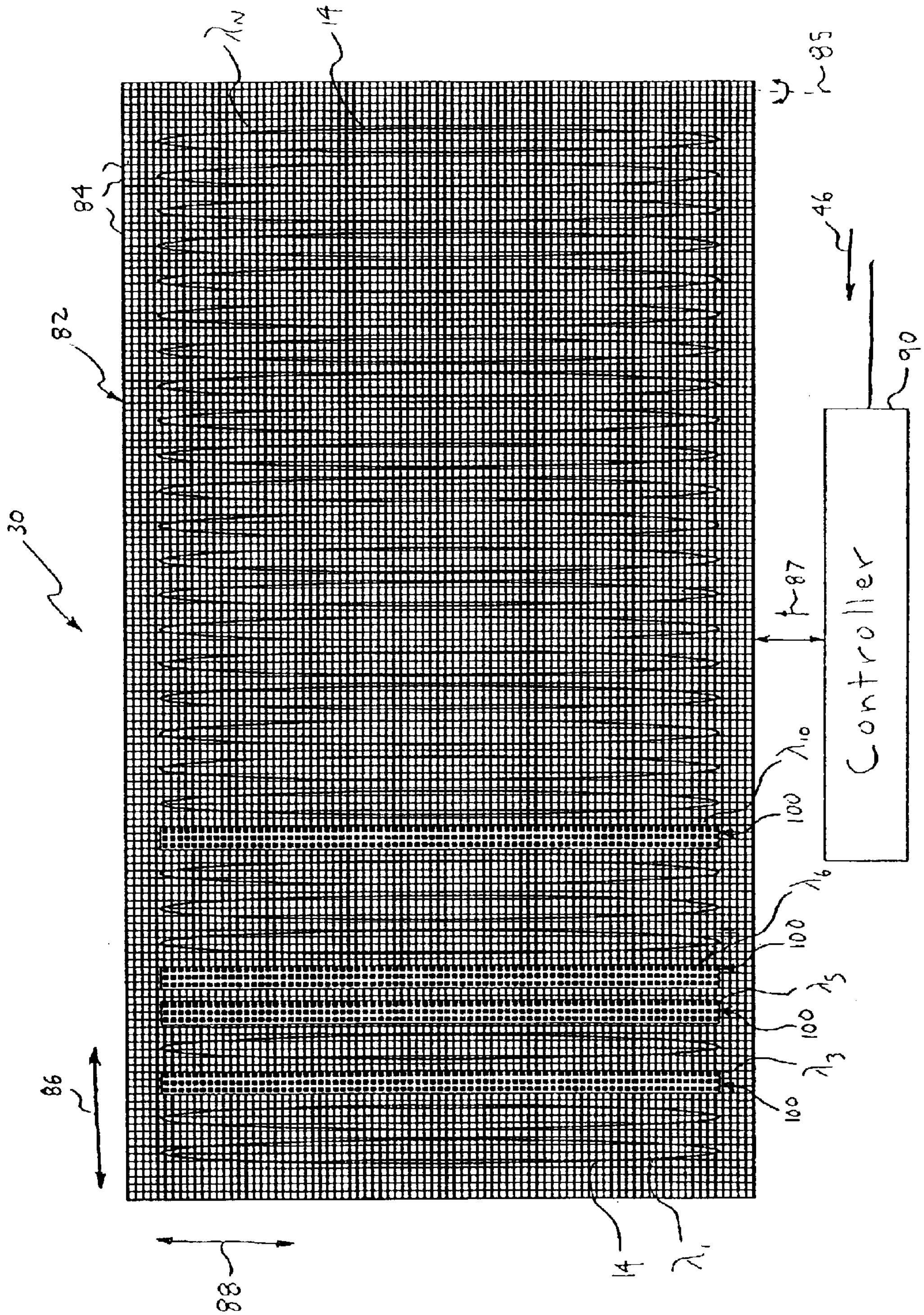
30
82
84
86
88
14
λ_N
85
46
90
87
Controller
100
λ_{10}
λ_6
λ_5
λ_3
λ_1

Fig 11

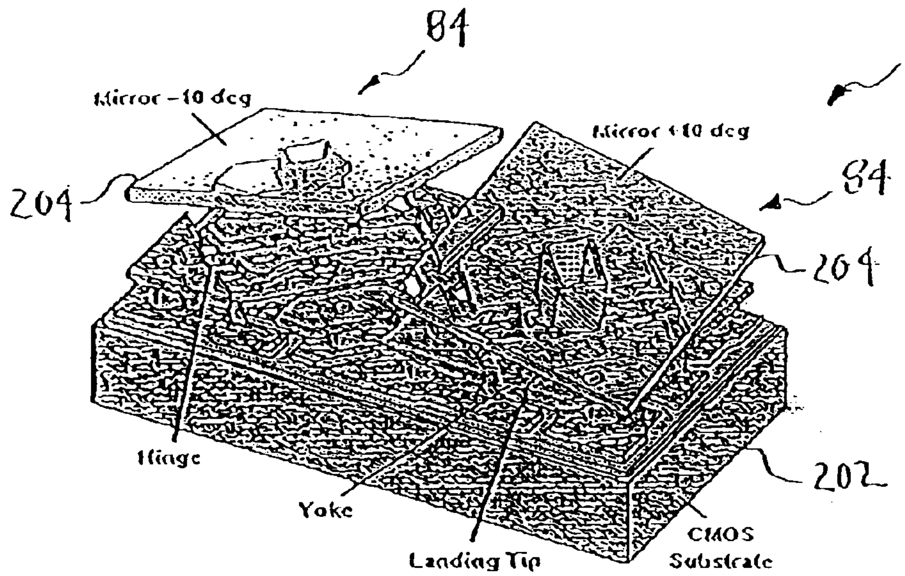

Fig. 12 (Prior Art)

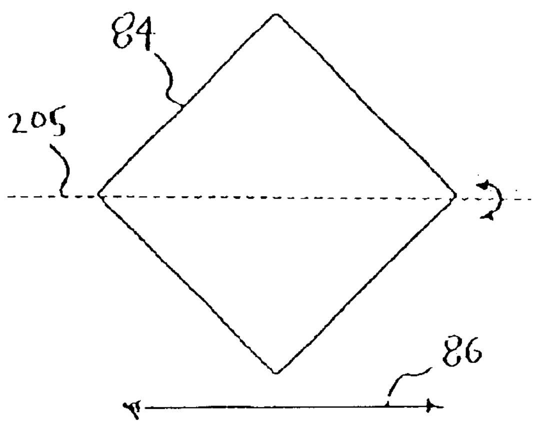

Fig 13

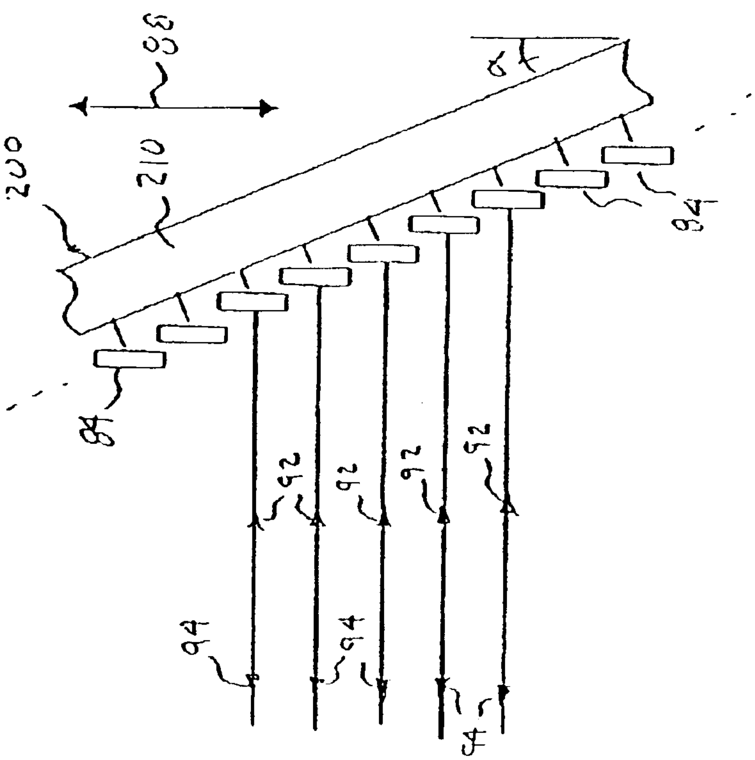

Fig. 14a

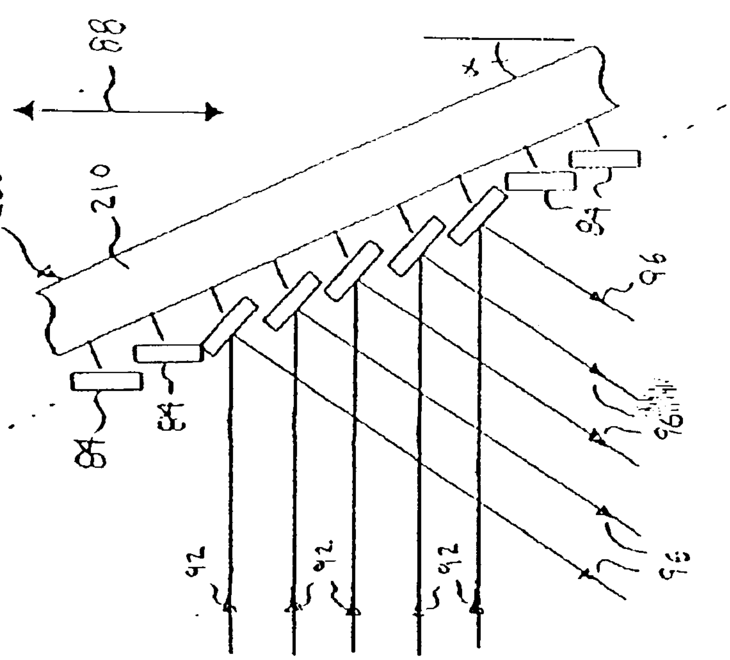

Fig. 14b

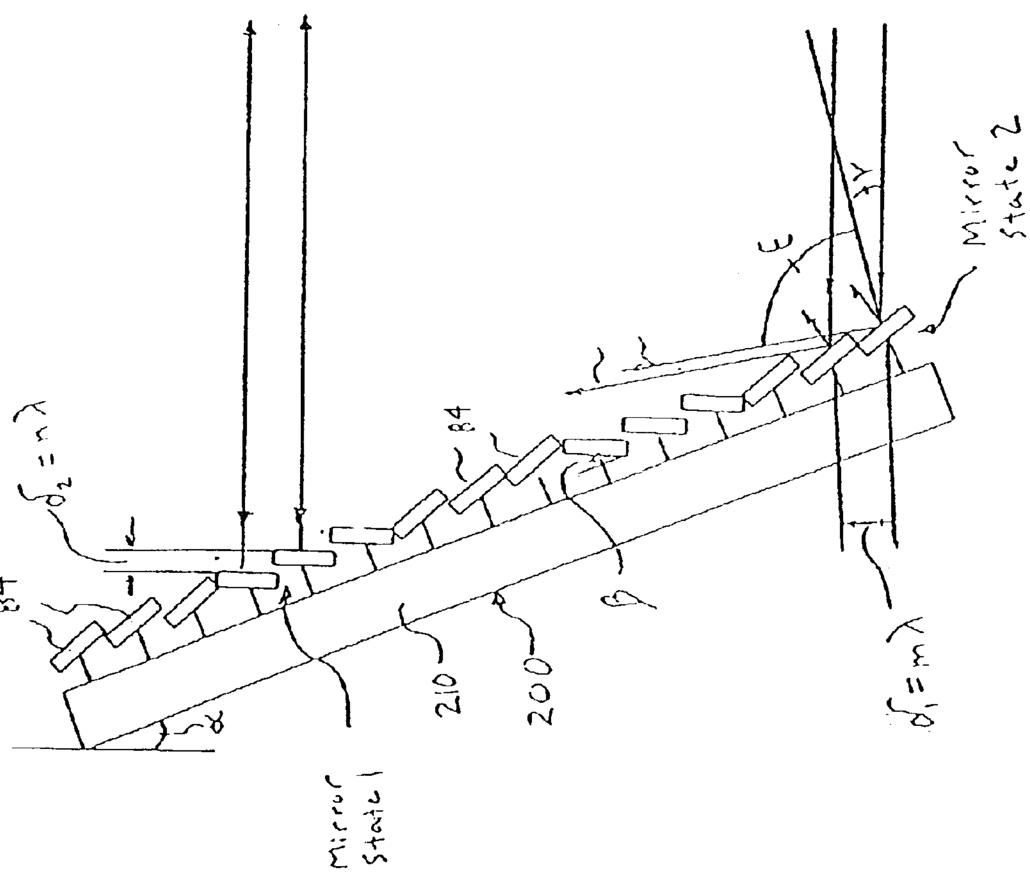

Fig. 15

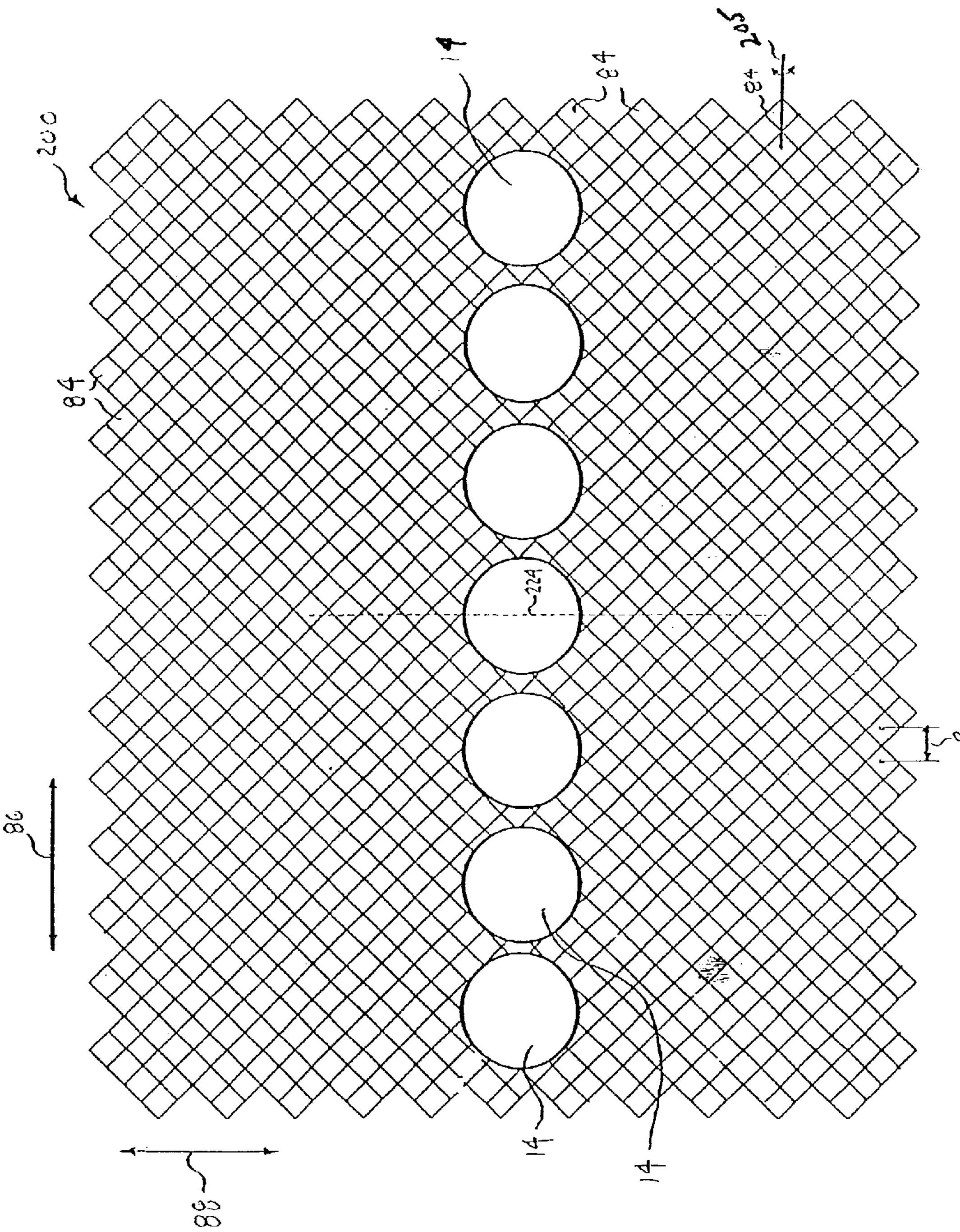

Fig. 16

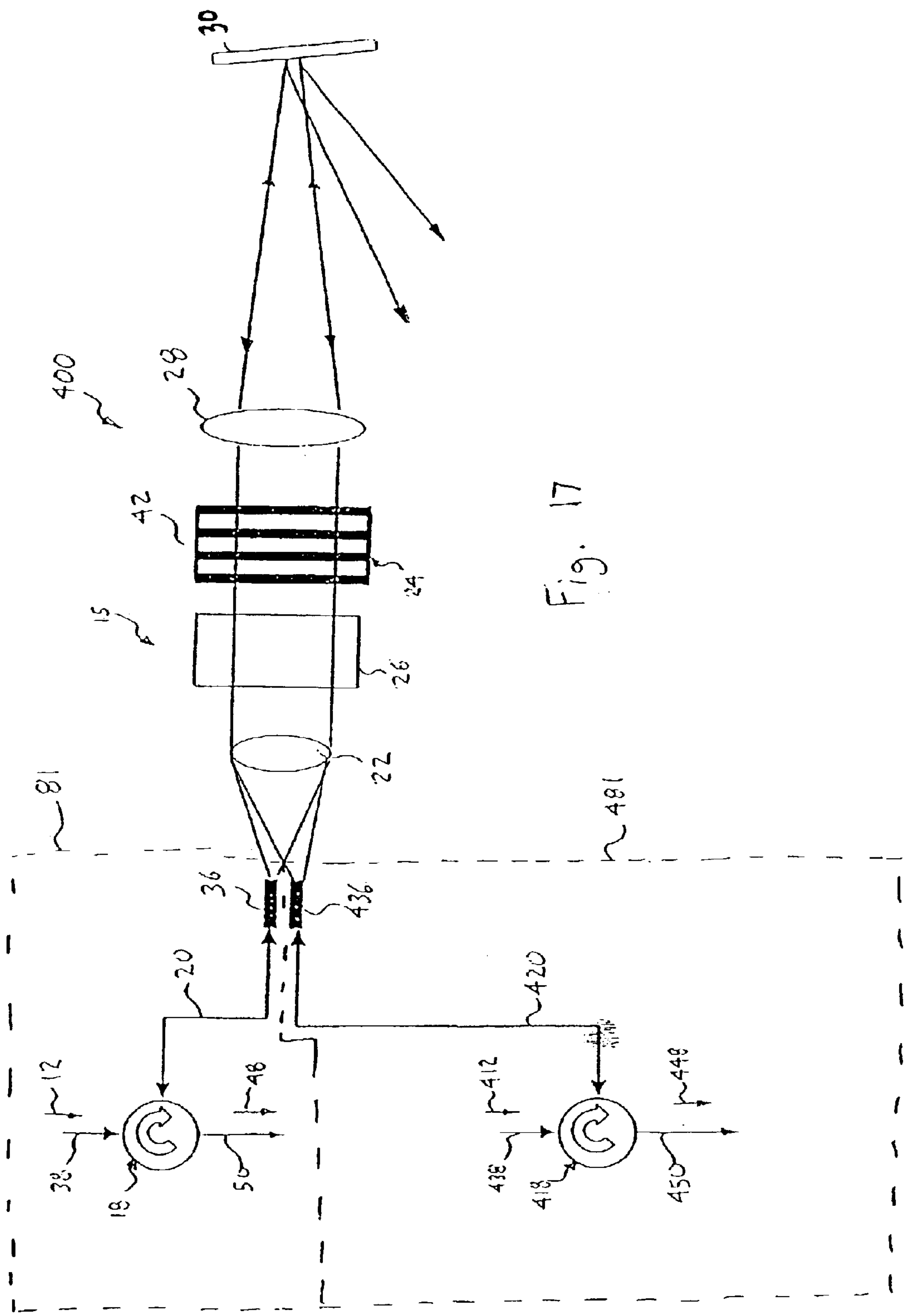
30
400
28
42
24
15
26
22
81
481
36
436
20
420
12
48
412
448
38
18
50
438
418
450

Fig. 17

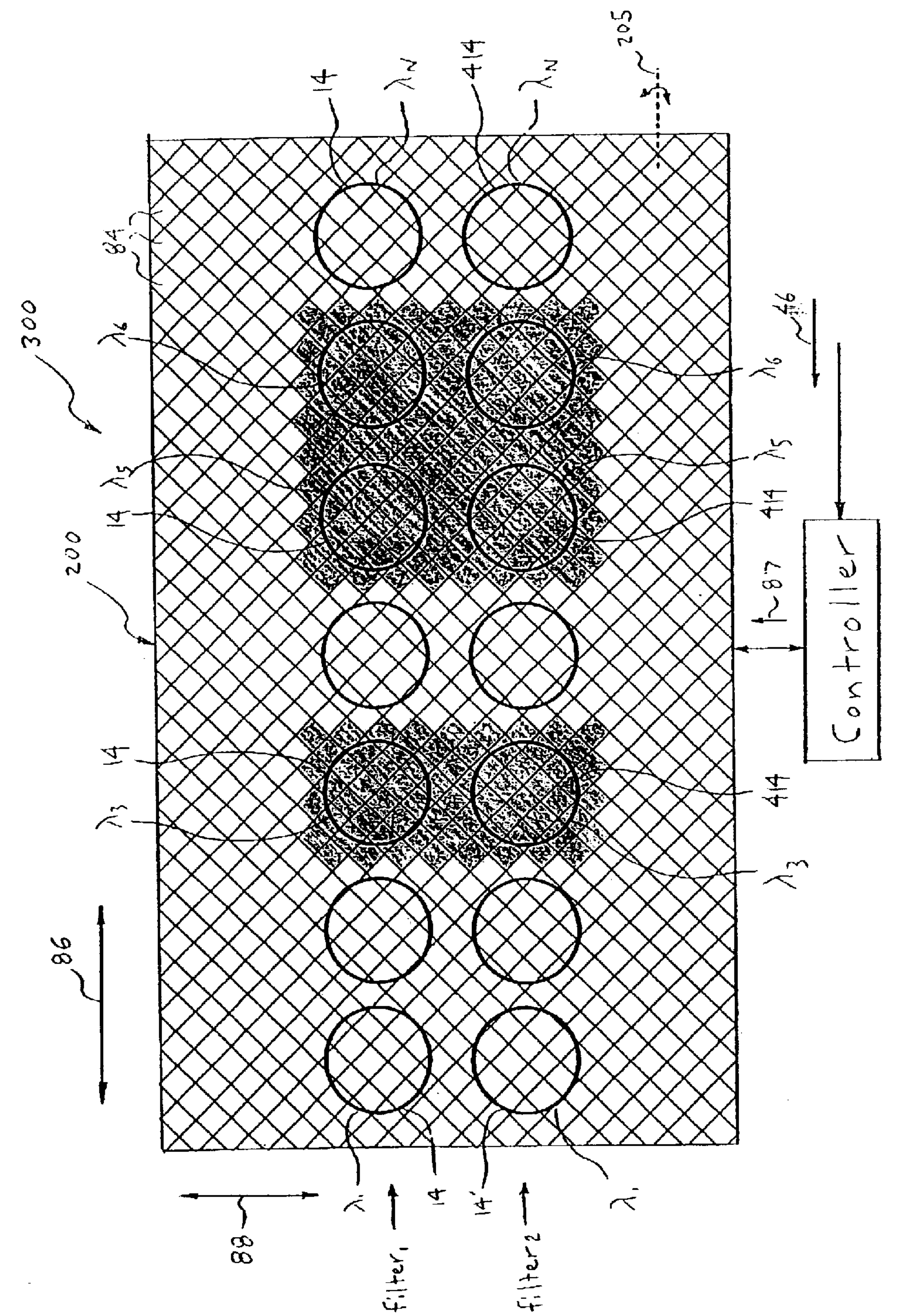
300
200
84
14
λ_N
414
205
46
λ_6
λ_5
87
Controller
λ_3
86
88
λ_1
14'
filter1
filter2

Fig. 18

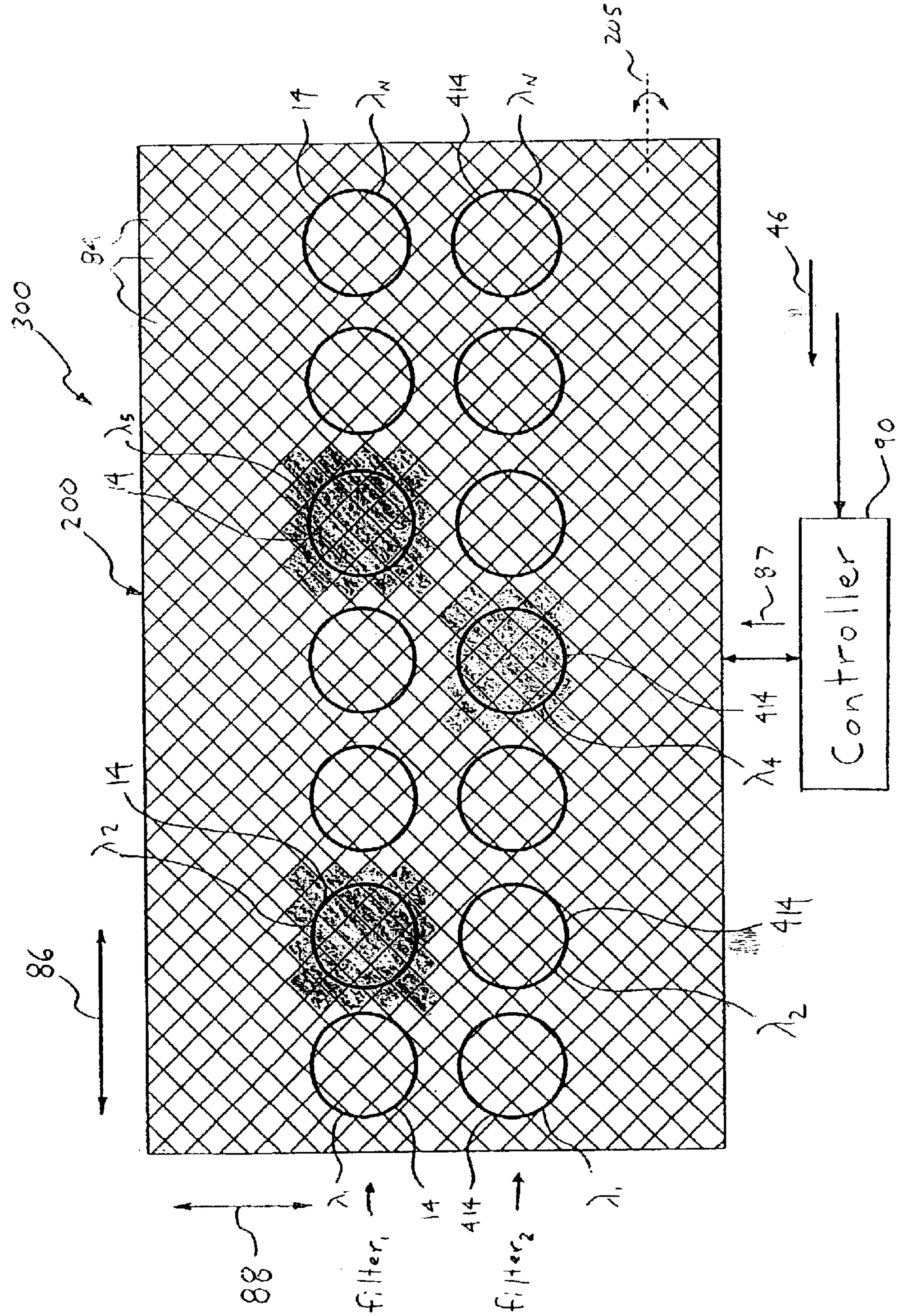

Fig. 19

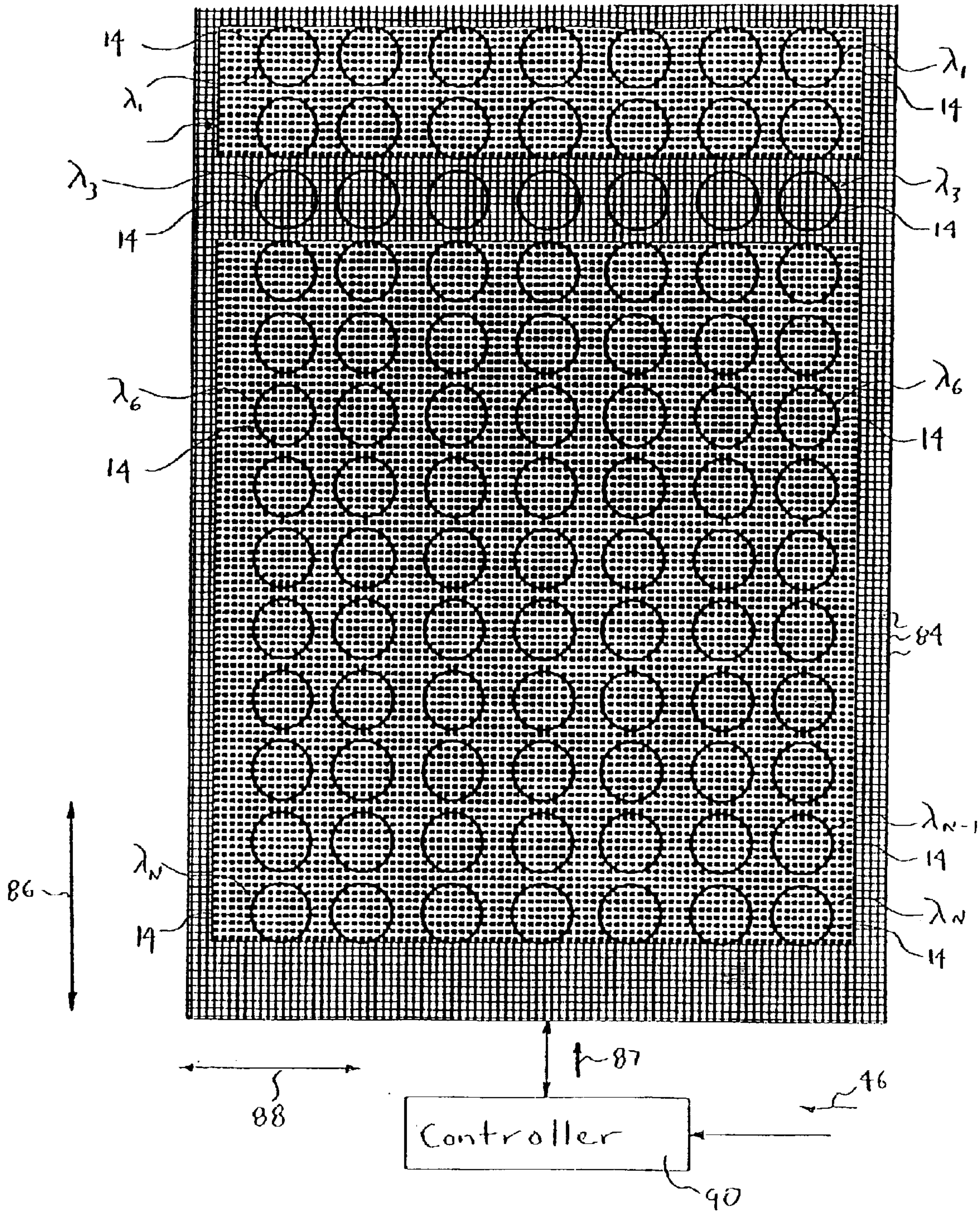
14
λ1
λ3
14
λ6
14
λ1
14
λ3
14
λ6
14
84
86
λN
14
λN-1
14
λN
14
87
88
46
Controller
90

Fig. 20

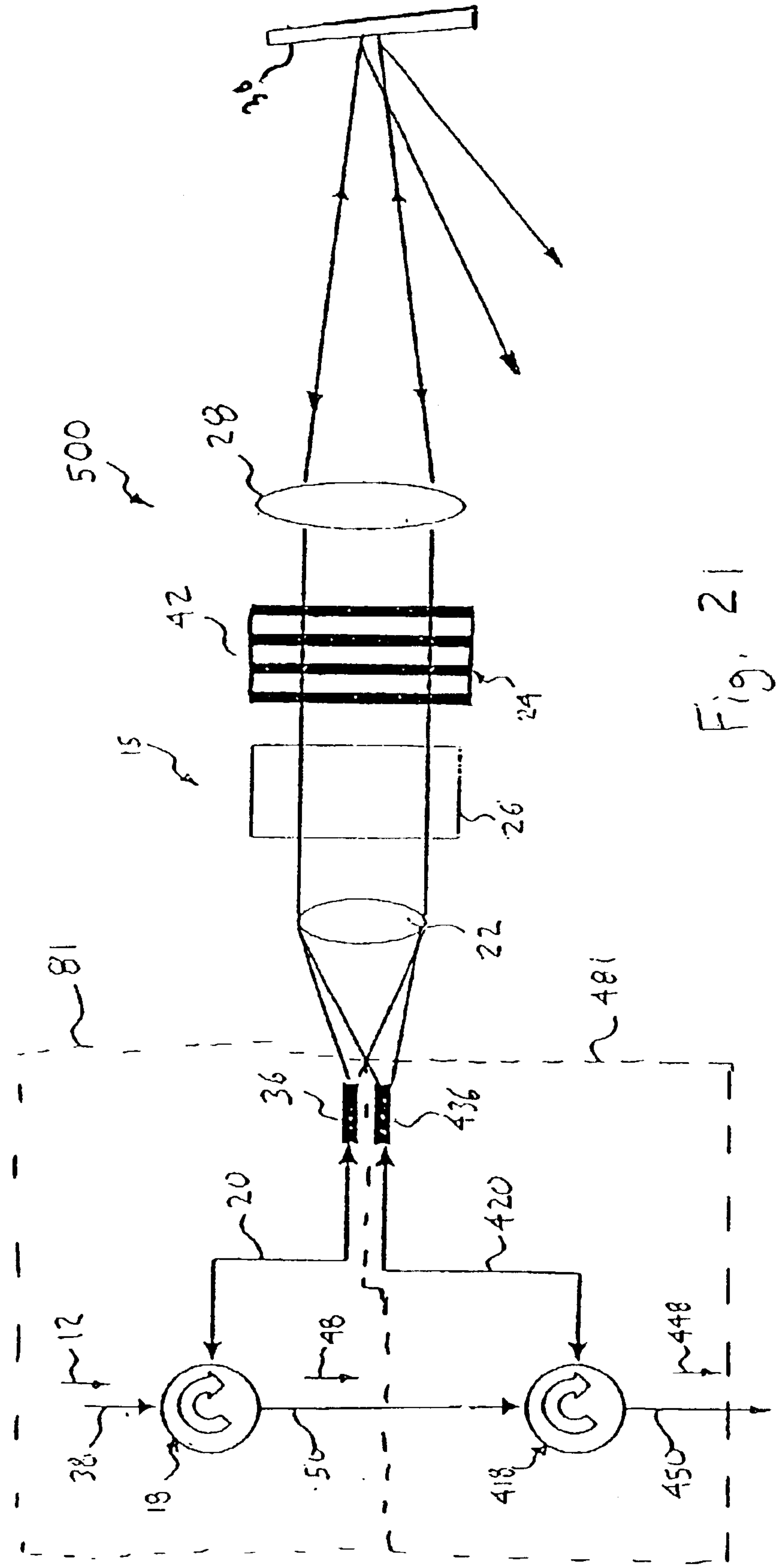

Fig. 21

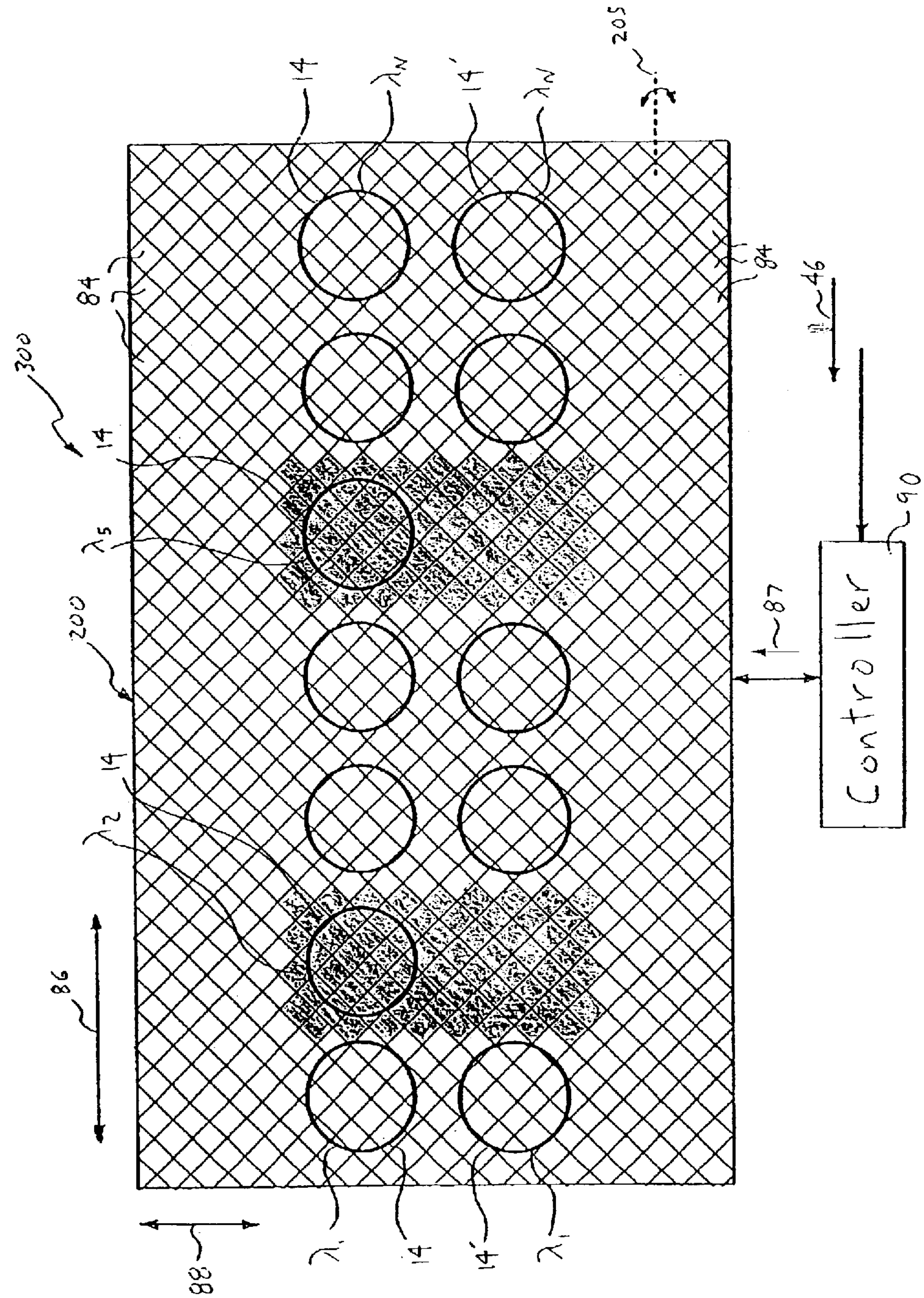
300
200
205
84
14
14'
λ_N
λ_5
λ_2
λ_1
86
87
88
46
90
Controller

Fig. 22

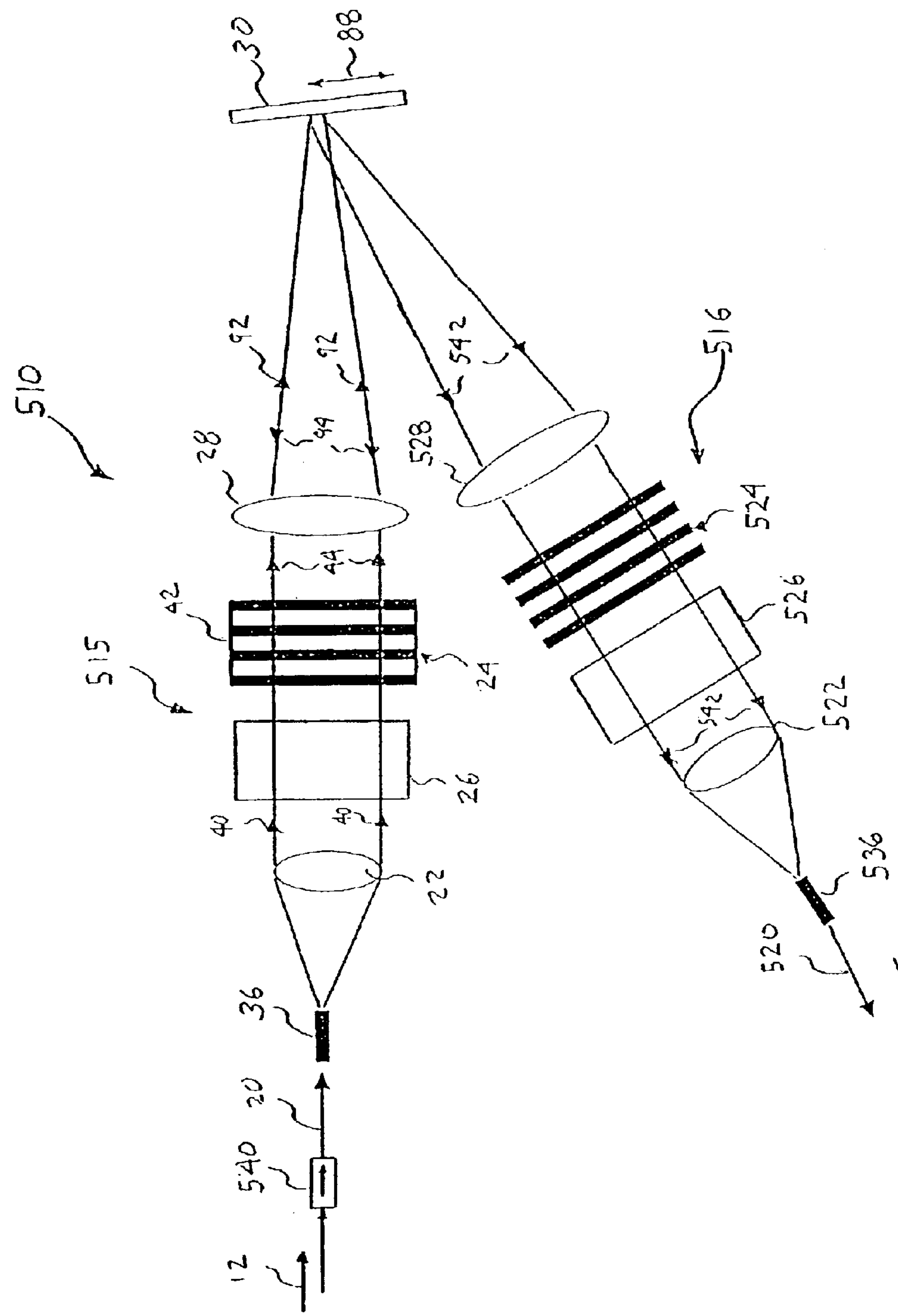
510
515
516
30
88
92
92
542
94
94
28
528
44
44
42
24
524
526
26
522
542
40
40
22
536
36
20
540
12
520
544

Fig. 23

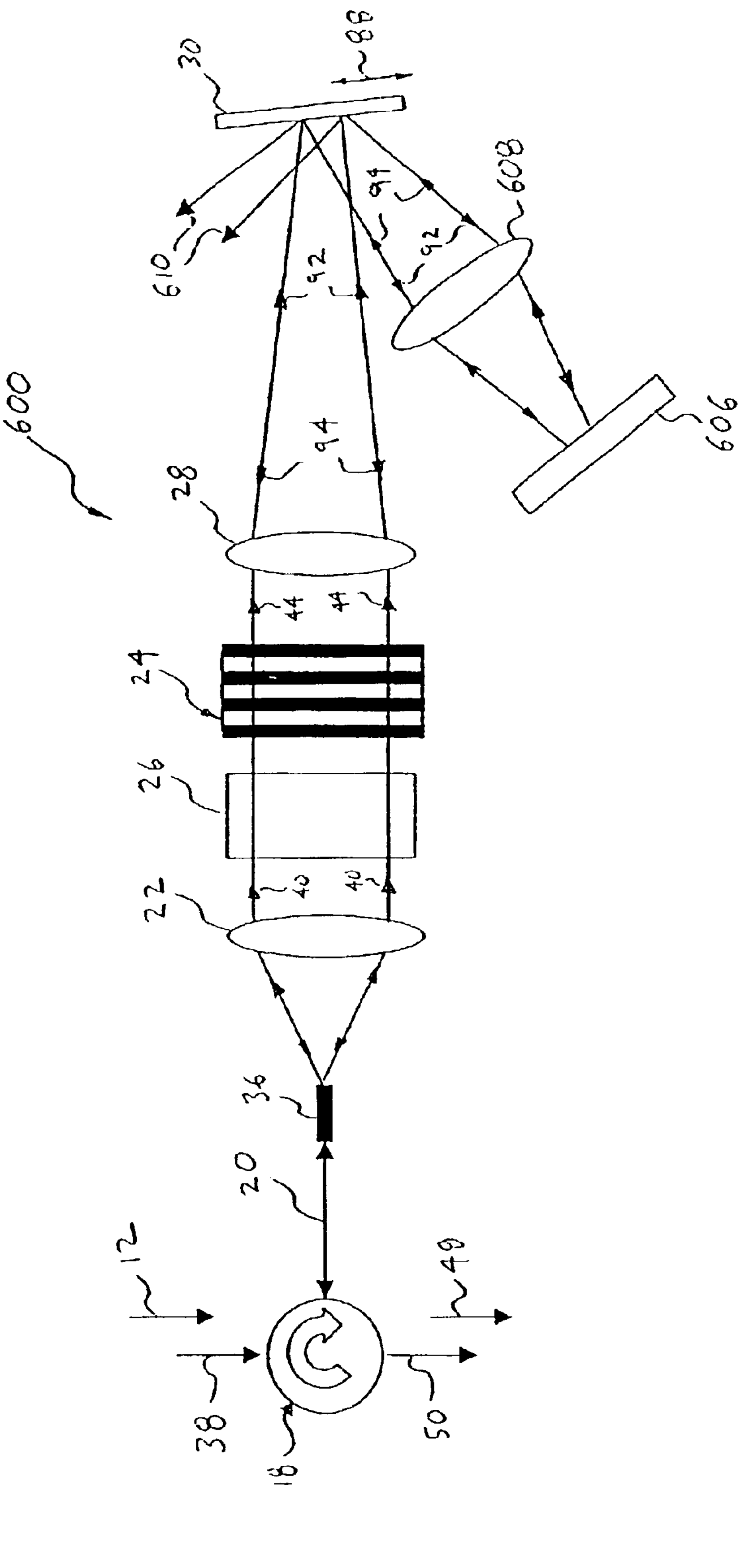

Fig. 24

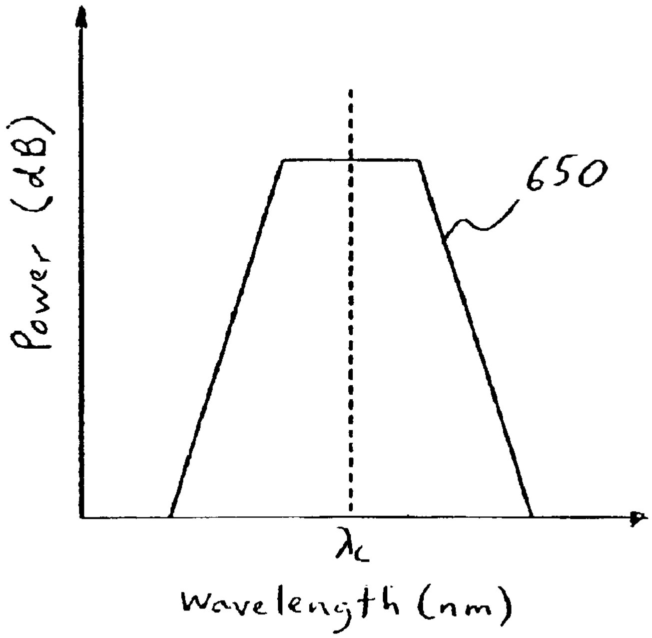

Fig. 25

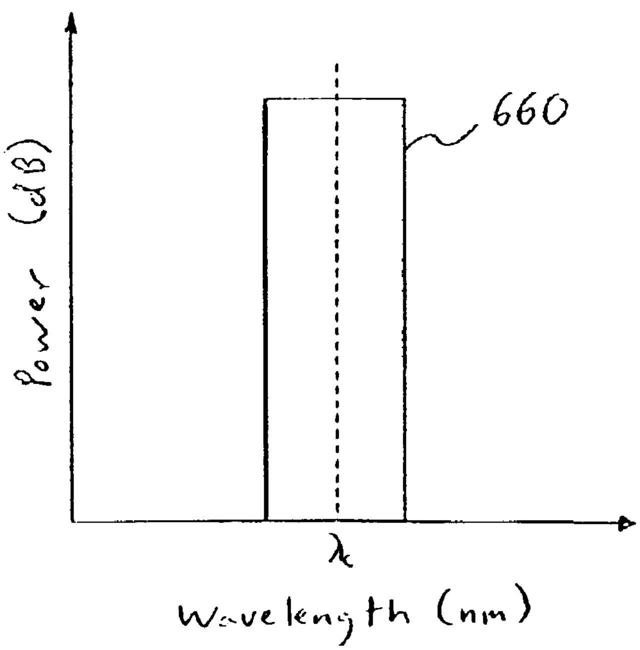

Fig. 26

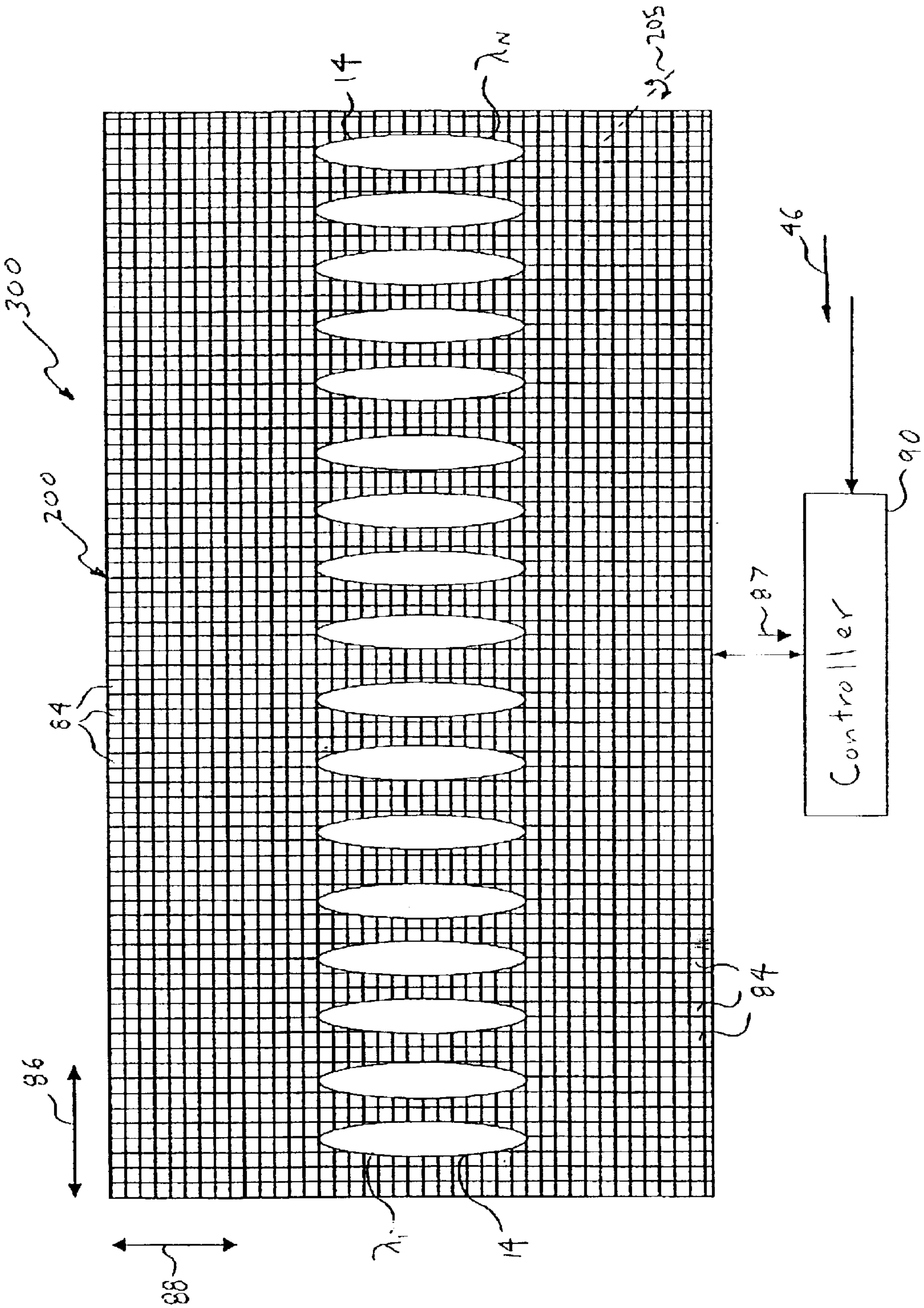
300
200
84
14
λ_N
205
46
90
87
Controller
84
86
88
λ_1
14

Fig. 27

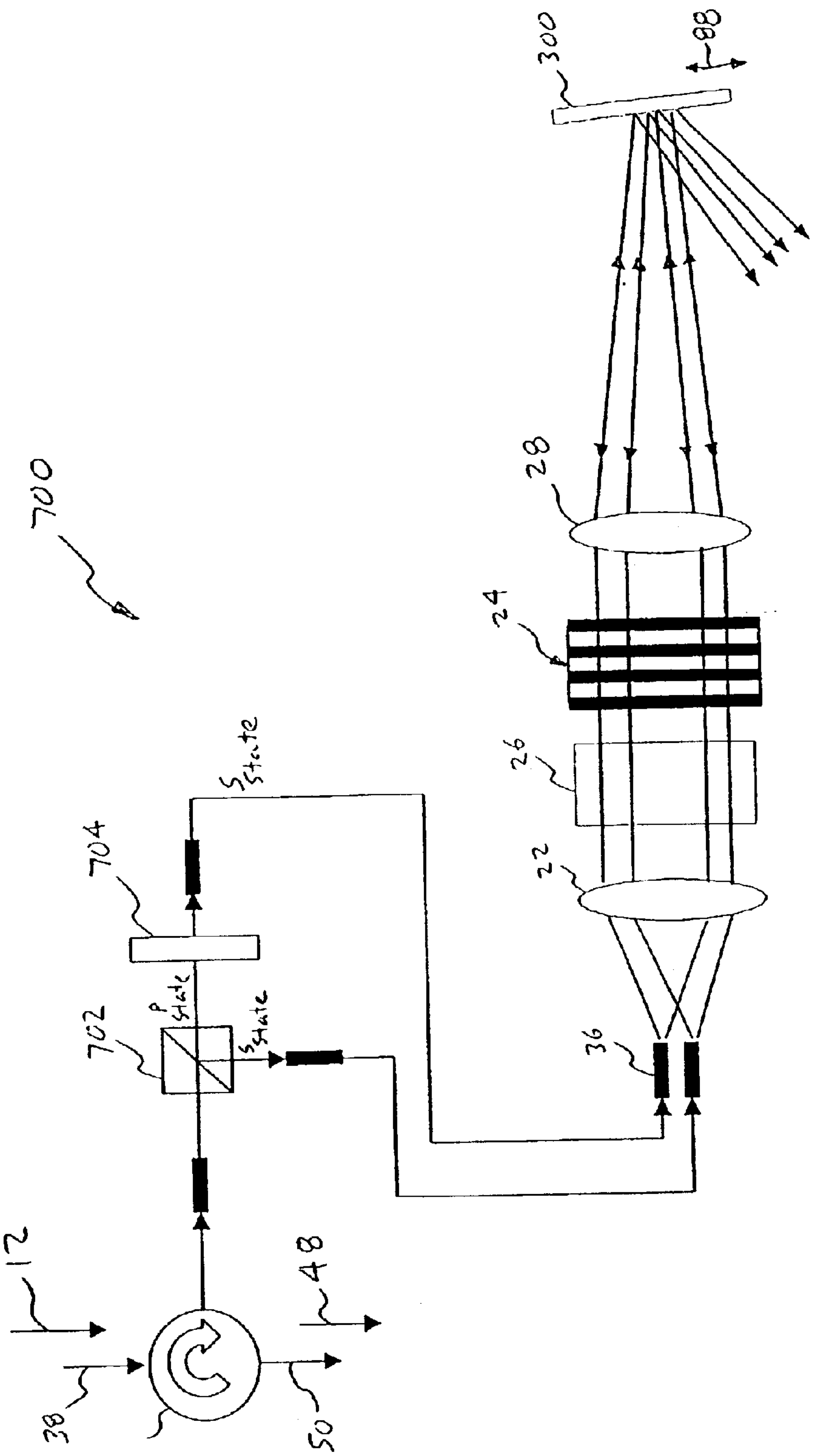
700
300
88
28
24
26
22
36
704
702
P State
S State
S State
12
48
38
50

Fig. 28

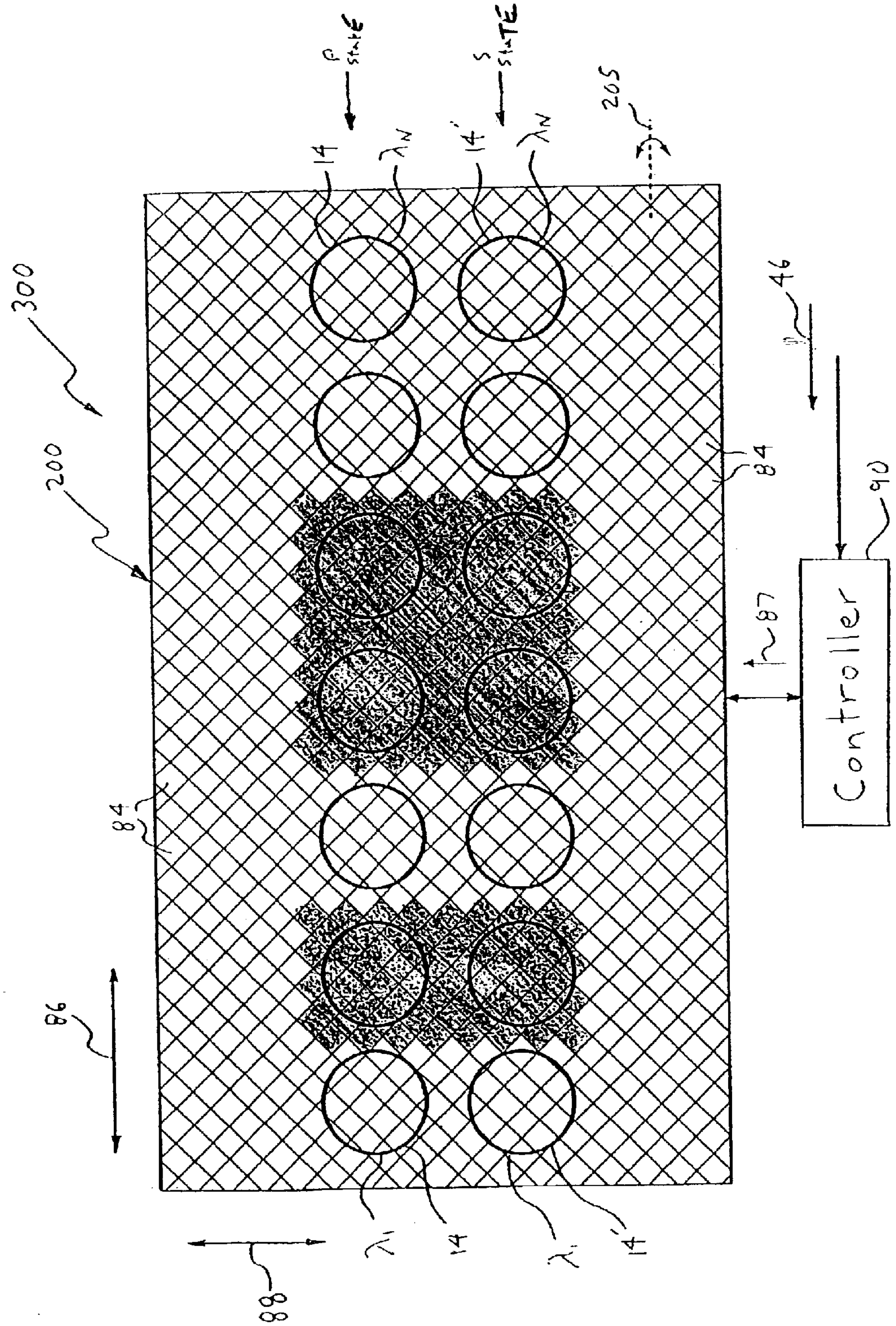

Fig. 29

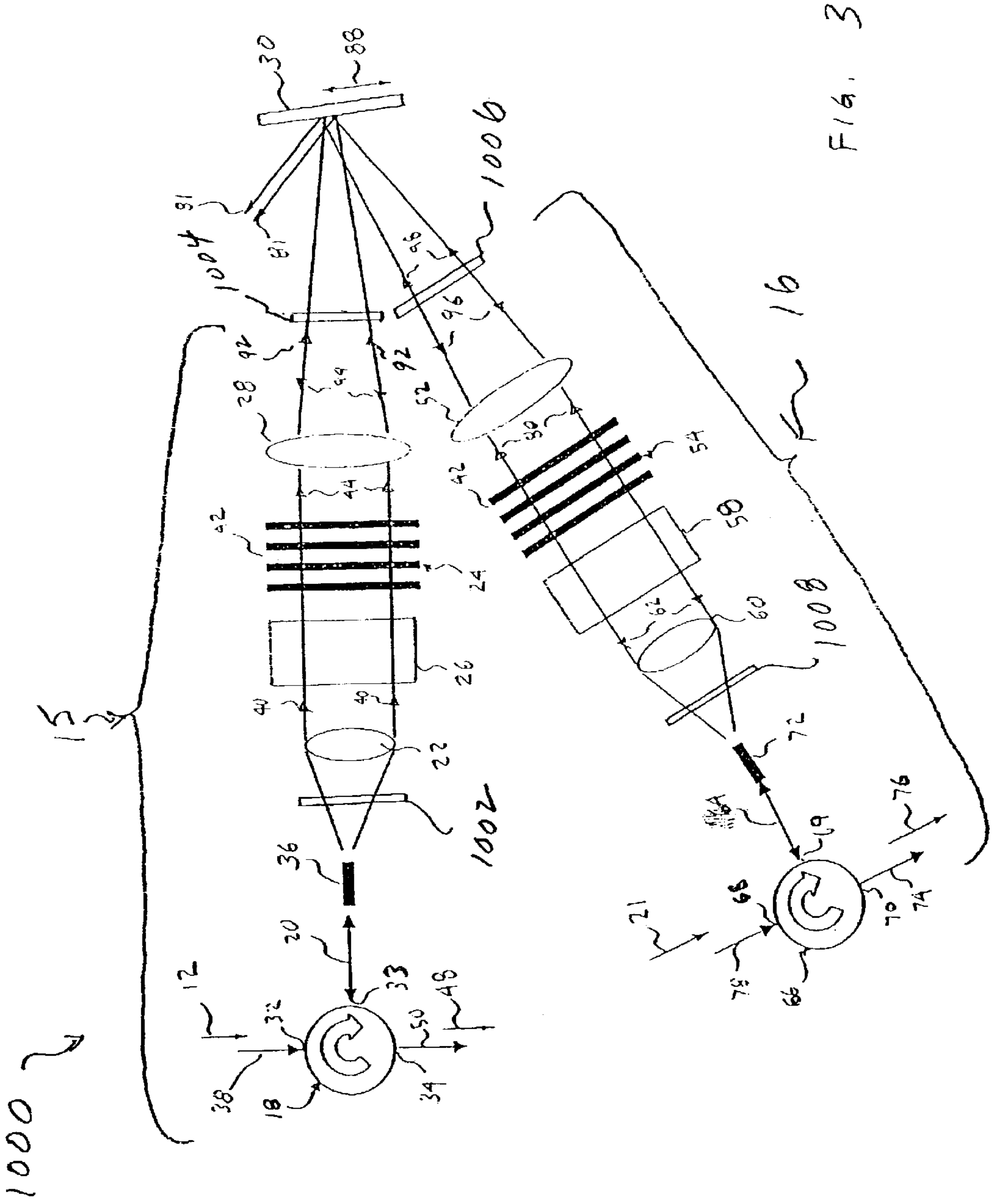

FIG. 3D

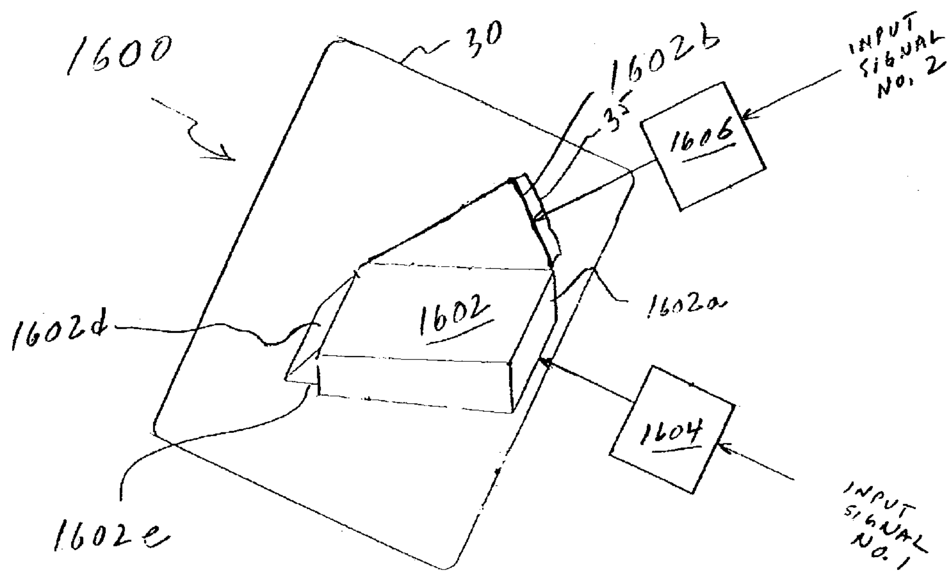
1600
30
1602b
35
1606
INPUT SIGNAL NO. 2
1602
1602a
1602d
1604
1602e
INPUT SIGNAL NO. 1

FIGURE 31

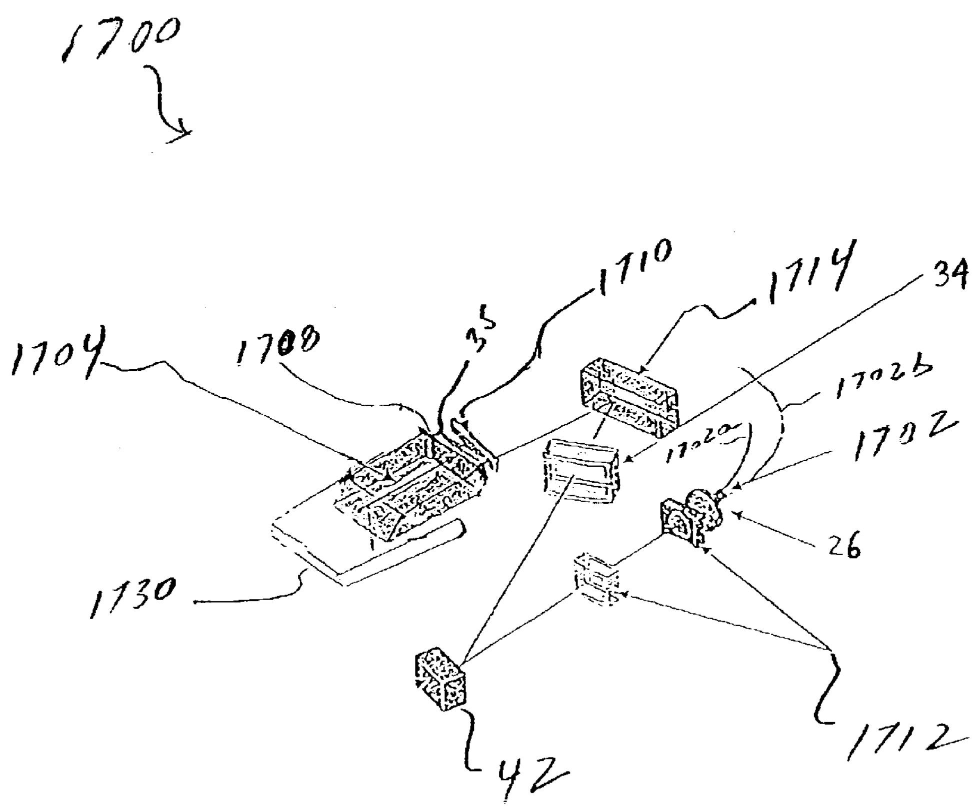
1700
1704
1708
35
1710
1714
34
1702b
1702a
1702
26
1130
1712
42

FIG. 32

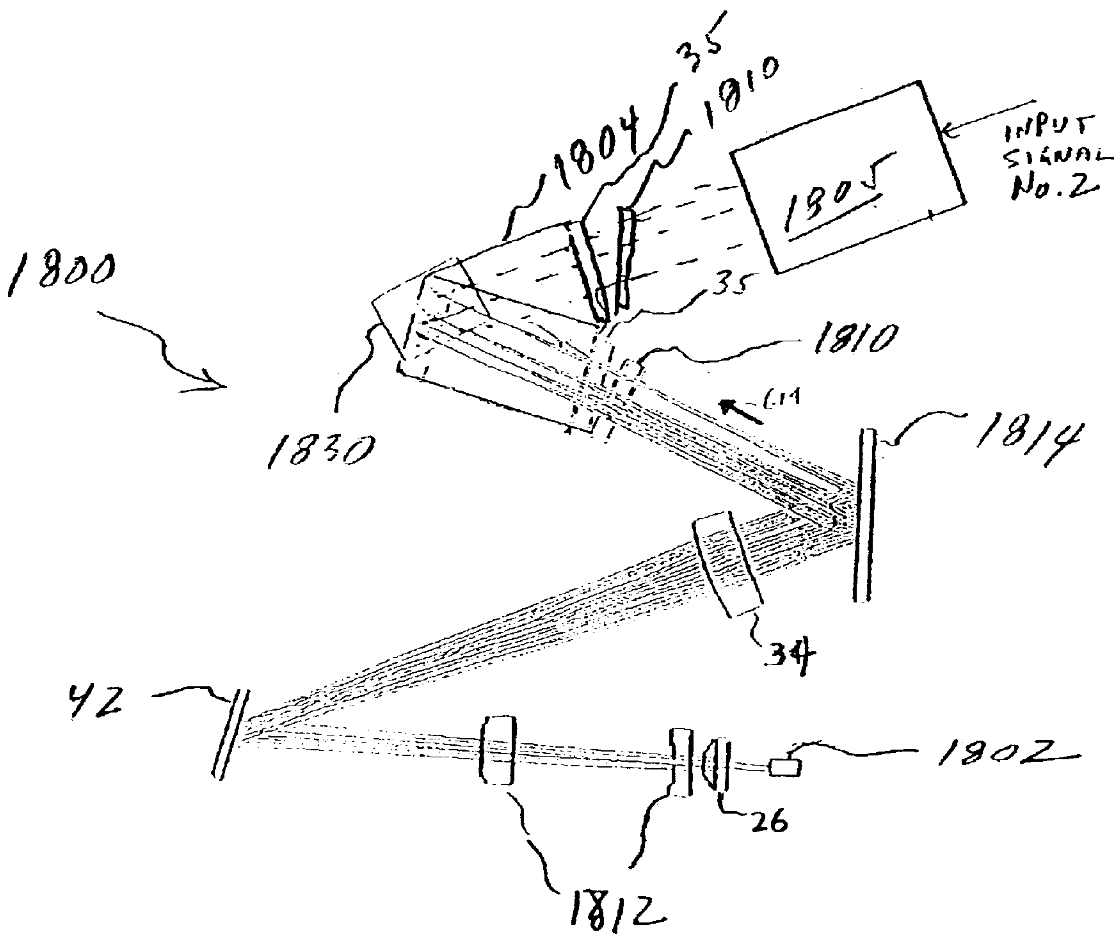
1800
1804
35
1810
1805
INPUT SIGNAL No. 2
35
1810
1830
1814
34
42
1802
26
1812

FIGURE 33

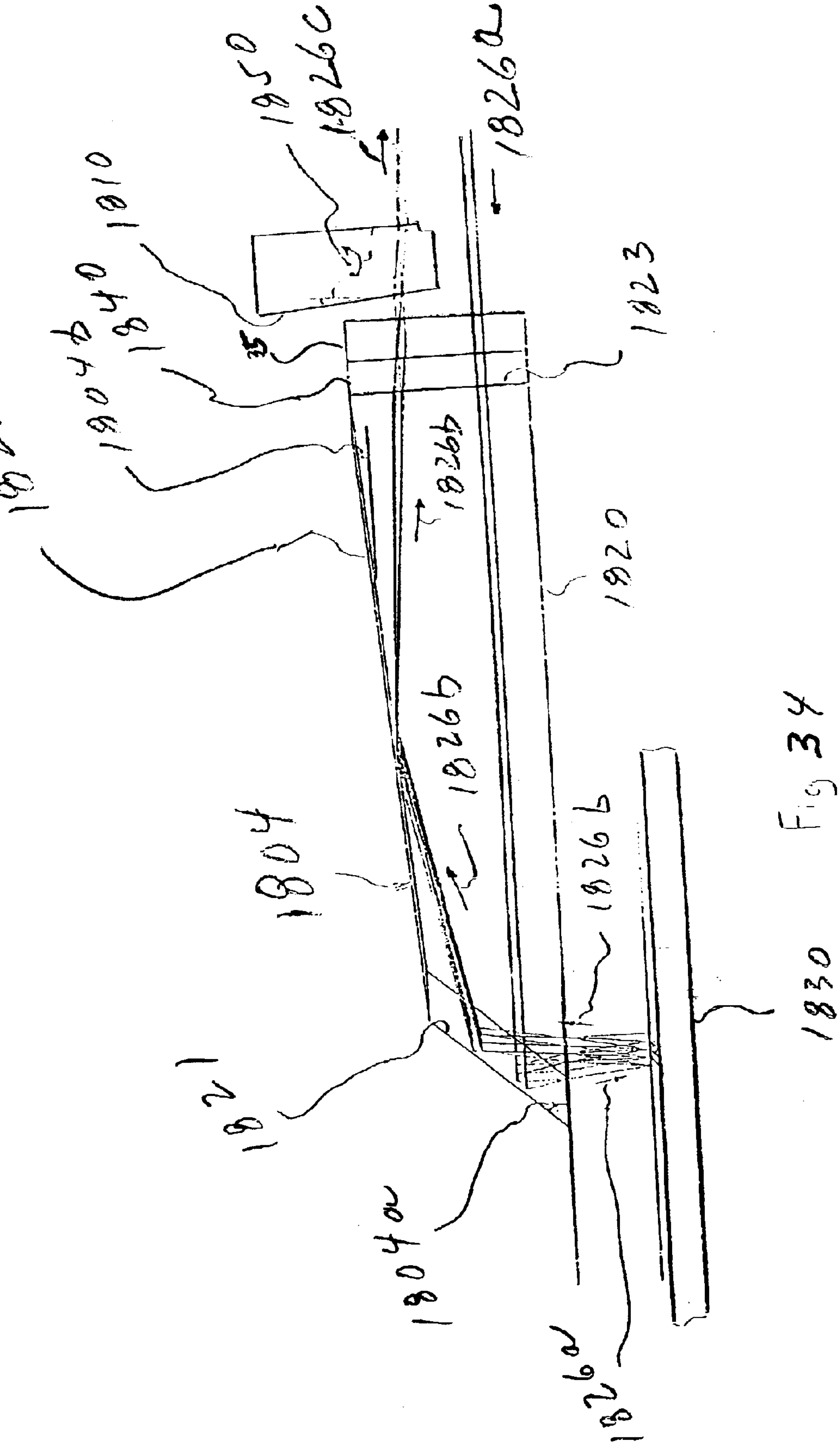
1822
1900
1840
1810
1950
1826c
1826a
1823
1826b
1920
1804
1826b
1830
1821
1804a
1826a

Fig 34

OPTICAL BLOCKING FILTER HAVING AN ARRAY OF MICRO-MIRRORS

CROSS REFERENCE TO RELATED APPLICATIONS

This patent claims the benefit to U.S. Provisional Patent Application Ser. No. 60/332,318, filed Nov. 16, 2001, and is a continuation-in-part of U.S. patent application Ser. No. 10/115,647, filed Apr. 3, 2002, which claims the benefit of U.S. Provisional Patent Application Ser. No. 60/281,079, filed Apr. 3, 2001; U.S. Provisional Patent Application Ser. No. 60/311,002, filed Aug. 8, 2001; U.S. Provisional Patent Application Ser. No. 60/332,319, filed Nov. 16, 2001; U.S. Provisional Patent Application Ser. No. 60/365,741, filed Mar. 18, 2002; and U.S. Provisional Patent Application Ser. No. 60/365,461, filed Mar. 18, 2002; and is a continuation-in-part of U.S. patent application Ser. No. 10/120,617, filed Apr. 11, 2002, now abandoned, which claims the benefit of U.S. Provisional Patent Application Ser. No. 60/283,197, all of which are incorporated herein by reference in their entirety.

BACKGROUND OF THE INVENTION

1. Technical Field

The present invention relates to a tunable optical filter, and more particularly to a dynamic optical filter, such as a reconfigurable blocking filter having a multi-dimensional array of micromirrors to selectively delete individual channels within a wavelength division multiplexed (WDM) optical signal.

2. Description of Related Art

MEMS micro-mirrors have been widely explored and used for optical switching and attenuation applications. The most commonly used application is for optical cross-connect switching. In most cases, individual micro-mirror elements are used to 'steer' a beam (i.e., an optical channel) to a switched port or to deflect the beam to provide attenuation on a channel-by-channel basis. Each system is designed for a particular 'wavelength plan' —e.g. "X" number of channels at a spacing "Y", and therefore each system is not 'scalable' to other wavelength plans.

Further, dynamic gain equalization (or "flattening") is a critical technology for deployment of next-generation optical network systems. Dynamic gain equalizing filters (DGEF's) function by adding varying amounts of attenuation at different spectral locations in the signal spectrum of optical fiber communication systems. For instance, a DGEF may be designed to operate in the "C-band" (~1530–1565 nm) of the communication spectrum that is capable of selectively attenuating spectrally concatenated "bands" of some preselected spectral width (e.g., 3 nm). The total number of bands within the DGEF is determined by the width of an individual band.

In the networking systems, it is often necessary to route different channels (i.e., wavelengths) between one fiber and another using a reconfigurable optical add/drop multiplexer (ROADM) and/or an optical cross-connect device. Many technologies can be used to accomplish this purpose, such as Bragg gratings or other wavelength selective filters.

One disadvantage of Bragg grating technology is that it requires many discrete gratings and/or switches, which makes a 40 or 80 channel device quite expensive. A better alternative would be to use techniques well known in spectroscopy to spatially separate different wavelengths or channels using bulk diffraction grating technology. For example, each channel of an ROADM is provided to a different location on a generic micro-electro-mechanical system (MEMS) device. The MEMs device is composed of a series of tilting mirrors, where each discrete channel hits near the center of a respective mirror and does not hit the edges. In other words, one optical channel reflects off a single respective mirror.

One issue with the above optical MEMs device is that it is not "channel plan independent". In other words, each MEMs device is limited to the channel spacing (or channel plan) originally provide. Another concern is that if the absolute value of a channel wavelength changes, a respective optical signal may begin to hit an edge of a corresponding mirror leading to large diffraction losses. Further, since each channel is aligned to an individual mirror, the device must be carefully adjusted during manufacturing and kept in alignment when operated through its full temperature range in the field.

It would be advantageous to provide an optical blocking filter that mitigates the above problems by using an array of micro-mirrors.

SUMMARY OF THE INVENTION

An object of the present invention is to provide a pixilated optical blocking filter having a spatial light modulator that includes a micro-mirror device having an array of micro-mirrors, wherein a plurality of micro-mirrors, actuated in concert, eliminates a selected channel, a specified selection of channels, or selected bands of channels by deflecting the light beam constituting the optical channels away from the return path. The present invention effectively meets the requirements of a blocking filter by eliminating all (attenuation greater than −45 Db) the power of the selected channel or channels while transmitting the remaining channels virtually unaffected (minimum insertion loss and flat, within a fraction of a Db, pass bands). The pixilated filter configuration advantageously permits the optical filter to be reconfigurable by changing a filtering algorithm that drives the micromirrors to effect both the channel position, channel bandwidth, and band pass profile without changing any hardware or configuration.

In accordance with an embodiment of the present invention, a blocking filter includes a first collimator that collimates an optical input signal. The optical input signal comprises a plurality of optical input channels, each of which are centered at a central wavelength. A first light dispersion element substantially separates the optical input channels of the collimated optical input signal. A spatial light modulator reflects each separated optical input channel along a respective first optical path or second optical path in response to a control signal. The spatial light modulator includes a micro-mirror device that has an array of micro-mirrors selectively disposable between a first and a second position in response to the control signal. Each separated optical input channel is incident on a respective group of micro-mirrors. Each respective separated optical input channel reflects along the respective first optical path when the micro-mirrors are disposed in the first position, or along the respective second optical path when the micro-mirrors are disposed in the second position. A controller generates the control signal in accordance with a switching algorithm.

BRIEF DESCRIPTION OF THE DRAWINGS

The drawing includes the following Figures:

FIG. 1 is a top plan view of an optical blocking filter including a spatial light modulator in accordance with the present invention;

FIG. **2** is a side elevational view of the optical blocking filter of FIG. **1**;

FIG. **3** is a front view of a spatial light modulator of the optical blocking filter of FIG. **1** having a micro-mirror device, wherein the optical channels of a WDM input signal are distinctly projected onto the micro-mirror device, in accordance with the present invention;

FIG. **4***a* is a pictorial cross-sectional view of the micro-mirror device of FIG. **3** showing a partial row of micro-mirrors, when the micro-mirrors are disposed in a first position perpendicular to the light beam of the input signal in accordance with the present invention;

FIG. **4***b* is a pictorial cross-sectional view of the micro-mirror device of FIG. **3** showing a partial row of micro-mirrors, when the micro-mirrors are disposed in a second position non-orthogonal to the light beam of the input signal in accordance with the present invention;

FIG. **5** is a front view of a micro-mirror of the micro-mirror device of FIG. **3** in accordance with the present invention;

FIG. **6** is a front view of a spatial light modulator of the optical blocking filter of FIG. **1** having a micro-mirror device, wherein the optical channels of a WDM input signal are distinctly projected onto the micro-mirror device, in accordance with the present invention;

FIG. **7** is a front view of a spatial light modulator of the optical blocking filter of FIG. **3**, wherein groups of micro-mirrors are tilted to select/filter an optical channel from the WDM input signal, in accordance with the present invention;

FIG. **8** is a top plan view of another embodiment of an optical blocking filter including a spatial light modulator, in accordance with the present invention;

FIG. **9** is a top plan view of another embodiment of an optical blocking filter including a spatial light modulator, in accordance with the present invention.

FIG. **10** is a front view of a spatial light modulator of the optical blocking filter of FIG. **9** having a micro-mirror device, wherein the optical channels of a WDM input signal are distinctly projected onto the micro-mirror device, in accordance with the present invention;

FIG. **11** is a front view of a spatial light modulator of the optical blocking filter of FIG. **9**, wherein groups of micro-mirrors are tilted to select/filter an optical channel from the WDM input signal, in accordance with the present invention;

FIG. **12** is a perspective view of a portion of a known micro-mirror device;

FIG. **13** is a plan view of a micro-mirror of the micro-mirror device of FIG. **12**;

FIG. **14***a* is a pictorial cross-sectional view of the micro-mirror device of FIG. **12** showing a partial row of micro-mirrors, when the micro-mirror surfaces are disposed in a first position orthogonal to the light beam of the input signal in accordance with the present invention;

FIG. **14***b* is a pictorial cross-sectional view of the micro-mirror device of FIG. **12** showing a partial row of micro-mirrors, when the micro-mirror surfaces are disposed in a second position perpendicular to the light beam of the input signal in accordance with the present invention;

FIG. **15** is a pictorial cross-sectional view of the micro-mirror device of FIG. **12** disposed at a predetermined angle in accordance with the present invention;

FIG. **16** is an expanded front view of the micromirror device of the spatial light modulator of FIG. **15**, wherein the optical channels of a WDM input signal are distinctly projected onto the micro-mirror device, in accordance with the present invention;

FIG. **17** is a top plan view of another embodiment of an optical blocking filter including a plurality of blocking filters using a single spatial light modulator, in accordance with the present invention;

FIG. **18** is a front view of the spatial light modulator of the optical blocking filter of FIG. **17**, wherein the optical channels of a plurality of WDM input signals are distinctly projected onto the micro-mirror device, in accordance with the present invention;

FIG. **19** is a front view of the spatial light modulator of the optical blocking filter of FIG. **17**, wherein the optical channels of a plurality of WDM input signals are distinctly projected onto the micro-mirror device, in accordance with the present invention;

FIG. **20** is a front view of a spatial light modulator of the optical blocking filter of FIG. **17**, wherein groups of micro-mirrors are tilted to select respective input channels from the plurality of WDM input signals, in accordance with the present invention;

FIG. **21** is a top plan view of a dual pass optical blocking filter including a spatial light modulator, in accordance with the present invention;

FIG. **22** is a front view of the spatial light modulator of the optical blocking filter of FIG. **21**, wherein the optical channels of a plurality of WDM input signals are distinctly projected onto the micro-mirror device, in accordance with the present invention;

FIG. **23** is a top plan view of another embodiment of a blocking filter including a spatial light modulator, in accordance with the present invention;

FIG. **24** is a top plan view of another embodiment of an optical blocking filter including a spatial light modulator, in accordance with the present invention;

FIG. **25** is a plot of the filter function of the micromirror device of FIG. **16** disposed in a diagonal orientation;

FIG. **26** is a plot of the filter function of the micromirror device of FIG. **16** disposed in a orthogonal orientation;

FIG. **27** is a front view of the spatial light modulator of the optical blocking filter, wherein the optical channels of a plurality of WDM input signals are distinctly projected onto the micro-mirror device, in accordance with the present invention;

FIG. **28** is a block diagram of another embodiment of a blocking filter including a spatial light modulator, in accordance with the present invention; and

FIG. **29** is a front view of the spatial light modulator of the optical blocking filter of FIG. **28**, wherein the optical channels of a plurality of WDM input signals are distinctly projected onto the micro-mirror device, in accordance with the present invention;

FIG. **30** shows an alternative embodiment of an optical channel monitor one or more optic devices for minimizing polarization dispersion loss (PDL);

FIG. **31** shows an embodiment of a channel monitor having a chisel prism in accordance with the present invention;

FIG. **32** shows an alternative embodiment of a channel monitor having a chisel prism in accordance with the present invention;

FIG. **33** shows an alternative embodiment of a channel monitor having a chisel prism in accordance with the present invention; and

FIG. **34** is side elevational view of a portion of the optical channel filter of FIG. **33**.

DETAILED DESCRIPTION OF THE INVENTION

Referring to FIGS. **1–3**, an optical blocking filter, generally shown as **10**, deletes at least one desired optical channel **14** of light (i.e., a wavelength band) from an optical WDM input signal **12**. Each of the optical channels **14** (see FIG. **3**) of the input signal **12** is centered at a respective channel wavelength ($\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_N$)

FIG. **1** is a top plan view of the blocking filter **10**. To better understand the blocking filter **10** of FIG. **1**, a side elevational view of the blocking filter is illustrated in FIG. **2**. As shown in FIG. **2**, the optics of the blocking filter **10** is disposed in two tiers or horizontal planes. Specifically, the blocking filter includes a three-port circulator **18**, an optical fiber or pigtail **20**, a collimator **22**, a light dispersive element **24**, a mirror **26**, and a bulk lens **28** for directing light to and from a spatial light modulator **30**. As shown, the pigtail **20**, the collimator **22** and the light dispersive element **24** are disposed in a first tier or horizontal plane. The mirror **26**, bulk lens **28** and the spatial light modulator **30** are disposed in the second tier or second horizontal plane which is substantially parallel to the first horizontal plane.

Referring to FIGS. **1** and **2**, the three-port circulator **18** directs light from a first port **32** to a second port **33** and from the second port to a third port **34**. The optical fiber or pigtail **20** is optically connected to the second port of the circulator **18**. A capillary tube **36**, which may be formed of glass, is attached to one end of the pigtail **20** such as by epoxying or collapsing the tube onto the pigtail. The circulator **18** at the first port **32** receives the WDM input signal **12** tapped from an optical network (not shown) via optical fiber **38**, and directs the input light to the pigtail **20**. The input signal **12** exits the pigtail (into free space) and passes through the collimator **22**, which collimates the input signal. The collimator **22** may be an aspherical lens, an achromatic lens, a doublet, a GRIN lens, a laser diode doublet or similar collimating lens. The collimated input signal **40** is incident on the light dispersion element **24** (e.g., a diffraction grating or a prism), which separates spatially the optical channels of the collimated input signal **40** by diffracting or dispersing the light from (or through) the light dispersion element.

In one embodiment, the diffraction grating **24** comprises a blank of polished fused silica or glass with a reflective coating (such as evaporated gold or aluminum), wherein a plurality of grooves **42** (or lines) are etched, ruled or otherwise formed in the coating. The diffractive grating **24** has a predetermined number of lines, such as 600 lines/mm, 850 lines/mm and 1200 lines/mm. The resolution of the blocking filter improves as the number of lines/mm in the grating increases. The grating **24** may be similar to those manufactured by Thermo RGL, part number 3325FS-660 and by Optometrics, part number 3-9601. Alternatively, the diffraction grating may be formed using holographic techniques, as is well known in the art. Further, the light dispersion element may include a prism or optical splitter to disperse the light as the light passes therethrough, or a prism having a reflective surface or coating on its backside to reflect the dispersed light.

As best shown in FIG. **2**, the diffraction grating **24** directs the separated light **44** to the mirror **26** disposed in the second tier. The mirror **26** reflects the separated light **44** to the bulk lens **28** (e.g., a Fourier lens), which focuses the separated light onto the spatial light modulator **30**, as shown in FIG. **3**. In response to a switching algorithm and input command **46**, the spatial light modulator **30** reflects at least one optical input channel (i.e., the deleted input channel(s)) away from the bulk lens **28** as indicated by arrows **96**, and reflects the remaining optical signals (i.e., the through channels) back through the same optical path to the pigtail **20** as indicated by arrows **94**, as best shown in FIG. **1**. The through channels propagate from the second port **33** to the third port **34** of the optical circulator **18** to provide an output signal **48** from optical fiber **50**.

As shown in FIG. **3**, the spatial light modulator **30** comprises a micro-mirror device **82** having a two-dimensional array of micro-mirrors **84**, which cover a surface of the micro-mirror device. The micro-mirrors **84** are generally square and typically 14–20 μm wide with 1 μm spaces between them. FIG. **4*a*** illustrates a partial row of micro-mirrors **84** of the micro-mirror device **82**, when the micro-mirrors are disposed in a first position to reflect the light back along the return path **94** and provide the through channel(s) **14** to the optical fiber **50**. FIG. **4*b*** illustrates a partial row of micro-mirrors **84** when the micro-mirrors are disposed in a second position, and therefore delete the corresponding input channels **14** along optical path **96**, as will be described in greater detail hereinafter. The micro-mirrors may operate in a "digital" fashion. In other words, as the micro-mirrors either lie flat in a first position, as shown in FIG. **4*a***, or be tilted, flipped or rotated to a second position, as shown in FIG. **4*b***.

As described herein before, the positions of the mirrors, either flat or tilted, are described relative to the optical path **92** wherein "flat" refers to the mirror surface positioned orthogonal to the optical path, either coplanar in the first position or parallel as will be more fully described hereinafter. The micro-mirrors flip about an axis **85** parallel to the spectral axis **86**, as shown in FIGS. **3** and **5**. One will appreciate, however, that the micromirrors may flip about any axis, such as parallel to the spatial axis **88** or at a 45 degrees angle to the spatial axis.

Referring to FIG. **3**, the micro-mirrors **84** are individually flipped between the first position and the second position in response to a control signal **87** provided by a controller **90** in accordance with a switching algorithm and an input command **46** from the processing unit **54**. The switching algorithm may provide a bit (or pixel) map indicative of the state (flat or tilted) of each of the micro-mirrors **84** of the array to return and/or drop the desired optical channel(s) **14** to provide the output signal **48** at optical fiber **50** (see FIG. **1**), and thus requiring a bit map for each configuration of channels to be dropped. Alternatively, each group of mirrors **84**, which reflect a respective optical channel **14**, may be individually controlled by flipping the group of micro-mirrors to direct the channel along a desired optical path (i.e., through or delete).

As shown in FIGS. **1** and **4*a***, the micro-mirror device **82** is oriented to reflect the focused light **92** of the input signal **12** back through the bulk lens **28** to the pigtail **20**, as indicated by arrows **94**, to provide the output signal **48**, when the micro-mirrors **84** are disposed in the first position. As shown in FIGS. **1** and **4*b***, the focused light **92** reflects away from the bulk lens **28**, as indicated by arrows **96**. This "digital" mode of operation of the micro-mirrors advantageously eliminates the need for any type of feedback control for each of the micro-mirrors. The micro-mirrors are either "on" or "off" (i.e., first position or second position), respectively, and therefore, can be controlled by simple binary digital logic circuits.

FIG. **3** further illustrates the outline of the optical channels **14** of the optical input signal **12**, which are dispersed off the diffraction grating **24** and focused by the bulk lens **28**, onto the array of micro-mirrors **84** of the micro-mirror device **82**. Each optical channel **14** is distinctly separated from other channels across the spectrum and has a generally circular cross-section, such that the input channels do not substantially overlap spatially when focused onto the spatial light modulator **30**. The optical channels have a circular cross-section to project as much of the beam as possible over a multitude of micro-mirrors **84**, while keeping the optical channels separated by a predetermined spacing. One will appreciate though that the diffraction grating **24** and bulk lens **28** may be designed to reflect and focus any input channel or group of input channels with any desired cross-sectional geometry, such as elliptical, rectangular, square, polygonal, etc in any desired orientation on the micro-mirror device. For example, FIG. **6** illustrates the outline of the optical channels **14** dispersed onto the micromirror device **82**, wherein the channels have an elliptical cross-section. Regardless of the cross-sectional geometry selected, the cross-sectional area of the channels **14** should illuminate a plurality of micro-mirrors **84**, which effectively pixelates the optical channels. In an exemplary embodiment, the cross sectional area of the input channels **14** is generally circular in shape, whereby the width of the optical channel beam spans over approximately 11 micro-mirrors.

One will appreciate that while the spacing between the channels are predetermined, the spacing between may be non-uniform. For example, one grouping of channels may be spaced to correspond to a 100 Ghz spacing, and another group of channels may be spaced to correspond to a 50 Ghz spacing.

Advantageously, the present invention provides a blocking filter that is channel plan independent. In other words, the blocking filter may be used for optical system having different channel spacings (e.g., 25 Ghz, 50 Ghz and 100 Ghz) by simply modifying or switching the software without having to modify the hardware. Further, the blocking filters of the present invention enable their filter functions to be dynamically changed, for example by modifying the tilting patterns of the micromirror device to achieve the desired filter function. These modifications include varying the width, height and shape of the micromirror patterns. The present invention further contemplates blocking or deleting blocks of adjacent optical channels.

FIG. **7** is illustrative of the position of the micro-mirrors **84** of the micro-mirror device **82** for deleting the optical channels **14** at λ_3, λ_5, λ_6 and λ_{10}, for example. The outline of each channel **14** is shown to provide a reference to visually locate the group of tilted mirrors **100**. As shown, the group of mirrors **100** of the optical channels at λ_3, λ_5, λ_6 and λ_{10} are tilted away from the return path **94** to the second position, as indicated by the blackening of the micro-mirrors **84**, and therefore deleted from the input channel **12**. The group of tilted mirrors **100** provides a generally rectangular shape, but one will appreciate that any pattern or shape may be tilted to delete the desired input channels. In an exemplary embodiment, the groups of micro-mirrors **100** reflect substantially all the light of the input channels **14**, at λ_3, λ_5, λ_6 and λ_{10} away from the bulk lens **28** indicated by arrows **96** (see FIG. **1**). The micro-mirrors **84** of the through input channels **14** at λ_1, λ_2, λ_4, λ_7–λ_9 and λ_{11}–λ_N are flat (i.e., first position), as indicated by the white micro-mirrors, to reflect the light **92** back along the return path **94** to the first pigtail **20**, as described hereinbefore.

In another exemplary embodiment, a blocking filter **110** is provided in FIG. **8** that is substantially similar to the blocking filter **10** of FIG. **1**, and therefore, common components have the same reference numeral. The blocking filter **110** replaces the circulator **18** of FIG. **1** with a second pigtail **112**. The second pigtail **112** has a glass capillary tube **116** attached to one end of the second pigtail. The second pigtail **112** receives the through input channels reflected from the micro-mirror device back along an optical return path. Specifically, the second pigtail **112** receives the through input channels **14** reflected back along the return optical path **94** from the spatial light modulator **30**.

To accomplish these expected return paths, the spatial light modulator **30** cannot be an image plane of the first pigtail **20** along the spatial axis **88**. These conditions can be established by ensuring that the lens system **22** and **28** be astigmatic. In particular, the lens **28** may be a cylindricalized lens with its cylindrical axis parallel to the spatial axis **88**. By tilting the spatial light modulator **30**, the return path can be displaced to focus at the second pigtail **112**.

In another embodiment similar to the blocking filters **10**, **110** of FIGS. **1**, **2** and **8**, the mirror **26** of each blocking filter **10**, **110** may be eliminated with the bulk lens **28** and the spatial light modulator **30** repositioned to directly receive the light dispersed by the diffraction grating **24**.

FIG. **9** illustrates another embodiment of a blocking filter **170** in accordance with the present invention, which is similar to the blocking filter **10** of FIG. **1**, and therefore similar components have the same reference numerals. The blocking filter **170** is substantially the same as the blocking filter **10** depicted in FIG. **1**, except the optical components of the blocking filter **170** are disposed in one horizontal plane, rather than two tiers or planes, as shown in FIG. **2**. Rather than using a mirror **26** (in FIGS. **1** and **2**) to direct the dispersed light **44** to the bulk lens **28** and the spatial light modulator **30**, the diffraction grating **24** is tilted to directly disperse the light onto the bulk lens **28** which focuses the light onto the spatial light modulator.

Functionally, the blocking filter **170** of FIG. **9** and blocking filter **10** of FIG. **1** are substantially the same. For illustrative purposes however, the collimator **22** and the bulk lens **28** of the blocking filter **170** may be astigmatic to provide dispersed optical channels **14** incident on the micro-mirror device **82** having a substantially elliptical cross-section, as shown in FIG. **10**. Further, the diffraction grating is rotated approximately 90 degrees such that the spectral axis **86** of the optical channels is parallel to the horizontal plane, and the micro-mirror device **82** is similarly rotated approximately 90 degrees such that the spectral axis **86** of the optical channels **14** is perpendicular to the tilt axis **85** of the micro-mirrors **84**.

FIG. **11** is illustrative of the position of the micro-mirrors **84** of the micro-mirror device **82** for deleting the optical input channel **14** at λ_3, λ_5, λ_6 and λ_{10}, for example. The outline of each channel **14** is shown to provide a reference to visually locate the group of tilted mirrors **100**. As shown, groups of mirrors **100** associated with the input channels at λ_3, λ_5, λ_6 and λ_{10}, are tilted away from the return path to the second position, as indicated by the blackening of the micro-mirrors **84**. The groups of tilted micro-mirrors **100** provide a generally rectangular shape having sufficient dimensions to delete the respective channels. The micro-mirrors **84** of the selected channel **14** at λ_1, λ_2, λ_6, λ_7–λ_9, and λ_{11}–λ_N are flat (i.e., first position), as indicated by the white micro-mirrors, to reflect the light back along the return path **94** to the pigtail **22**, as described hereinbefore.

The micro-mirror device **82** of FIGS. **1–3** is similar to the Digital Micromirror Device™ (DMD™) manufactured by Texas Instruments and described in the white paper entitled

"Digital Light Processing™ for High-Brightness, High-Resolution Applications", white paper entitled "Lifetime Estimates and Unique Failure Mechanisms of the Digital Micromirror Device (DMD)", and news release dated September 1994 entitled "Digital Micromirror Display Delivering On Promises of 'Brighter' Future for Imaging Applications", which are incorporated herein by reference.

FIG. **12** illustrates a pair of micro-mirrors **84** of a micro-mirror device **200** manufactured by Texas Instruments, namely a digital micro-mirror device (DMD™). The micro-mirror device **200** is monolithically fabricated by CMOS-like processes over a CMOS memory **202**. Each micro-mirror **84** includes an aluminum mirror **204**, 16 μm square, that can reflect light in one of two directions, depending on the state of the underlying memory cell **202**. Rotation, flipping or tilting of the mirror **204** is accomplished through electrostatic attraction produced by voltage differences between the mirror and the underlying memory cell. With the memory cell **202** in the on (1) state, the mirror **204** rotates or tilts approximately +10 degrees. With the memory cell in the off (0) state, the mirror tilts approximately −10 degrees. As shown in FIG. **14**, the micro-mirrors **84** flip about an axis **205**.

FIGS. **14***a* and **14***b* illustrate the orientation of a micro-mirror device **200** similar to that shown in FIG. **12**, wherein neither the first or second position (i.e., on or off state) of the micro-mirrors **84** is parallel to the base or substrate **210** of the micro-mirror device **200**, as shown in FIGS. **4***a* and **4***b*. Consequently as shown in FIG. **14***a*, the base **210** of the micro-mirror device **200** is mounted at a non-orthogonal angle a relative to the collimated light **83** to position the micro-mirrors **84**, which are disposed at the first position, perpendicular to the collimated light **44**, so that the light reflected off the micro-mirrors in the first position reflect substantially back through the return path, as indicated by arrows **94**, to provide the output signal **48** at optical fiber **50**. Consequently, the tilt angle of the mirror between the horizontal position and the first position (e.g., 10 degrees) is approximately equal to the angle α of the micro-mirror device. FIG. **14***b* is illustrative of the micro-mirror device **200** when the micro-mirrors **84** are disposed in the second position to drop an input channel **14** to the output signal **48** at optical fiber **50**.

In using the micro-mirror array device **200**, it is important that the reflection from each micro-mirror **84** adds coherently in the far field, so the angle a to which the micro-mirror device **200** is tilted has a very strong influence on the overall efficiency of the device. FIG. **15** illustrates the phase condition of the micro-mirrors in both states (i.e., State **1**, State **2**) for efficient reflection in either condition.

In an exemplary embodiment of the micro-mirror device **200** in FIG. **15**, the effective pixel pitch ρ is about 19.4 μm (see FIG. **16**), so for a mirror tilt angle β of 9.2 degrees, the array is effectively blazed for Littrow operation in the n=+2 order for the position indicated as Mirror State 1 in FIG. **16** (i.e., first position). For Mirror State 2, the incident angle γ on the micro-mirror device **200** is now 9.2 degrees and the exit angle ϵ from the array is 27.6 degrees. Using these numbers, the micro-mirror device is nearly blazed for fourth-order for mirrors in Mirror State 2.

As described hereinbefore, the micro-mirrors **84** of the micro-mirror device **200** flip about a diagonal axis **205** as shown in FIGS. **13** and **16**. In an exemplary embodiment of the present invention shown in FIG. **16**, the optical input channels **14** are focused on the micro-mirror device **200** such that the spectral axis **86** of the optical channels **14** is parallel to the tilt axis **205** of the micro-mirrors. This configuration is achieved by rotating the micro-mirror device 45 degrees compared to the configuration shown in FIG. **3**. Alternatively, the optical channels **14** may be focused such that the spectral axis **86** of the channels are perpendicular to tilt axis **205** of the micro-mirrors similar to that shown in FIGS. **9** and **10**. Further, one will appreciate that the orientation of the tilt axis **205** and the spectral axis **86** may be at any angle.

While the embodiments of the present invention described hereinabove illustrate a single blocking filter using a set of optical components, it would be advantageous to provide an embodiment including a plurality of blocking filters that uses a substantial number of common optical components, including the spatial light modulator.

FIG. **17** illustrates such an embodiment of a blocking filter **400**, which is substantially the same as the blocking filter **10** in FIG. **1** having a spatial light modulator **300** including a micro-mirror device **22** of FIG. **16**. Common components between the embodiments have the same reference numerals. The blocking filter **400** provides a pair of blocking filters (i.e., filter, $filter_2$), each of which use substantially all the same optical components, namely the collimating lens **22**, the mirror **26**, the diffraction grating **24**, the bulk lens **28** and the spatial light modulator **300**. The first blocking filter (blocking $filter_1$) is substantially the same as the blocking filter **10** of FIG. **10**. The second blocking filter ($filter_2$) is provided by adding a complementary set of input optical components **481**. The input optical components **81** of the first blocking filter ($filter_1$) and the input optical components **481** of the second blocking filter ($filter_2$) have the same last two numerals, and therefore the input optical components **481** of second blocking filter are the same as those of the similar components **81** of the first blocking filter.

To provide a plurality of blocking filters ($filter_1$, $filter_2$) using similar components, each blocking filter uses a different portion of the micro-mirror device **200**, as shown in FIG. **18**, which is accomplished by displacing spatially the ends **36**,**436** of the pigtails **20**,**420** of the blocking filters. As shown, the input channels of each blocking filter are spaced in the spatial axis **88** a predetermined distance on the micro-mirror device **200**, as shown in FIG. **18**. Similar to that described hereinabove, the groups of micro-mirrors **370**, **372** of shaded micro-mirrors **84** delete the optical channels at λ_3, λ_5 and λ_6 of both blocking filters (blocking $filter_1$, blocking $filter_2$), and reflect the through input channels at λ_1, λ_2, λ_4, and λ_7–λ_N back to each respective input pigtail **20**, **420**. One will recognize that while the same optical channels are reflected back to the first pigtail (at λ_1, λ_2, λ_4, and λ_7–λ_N, for example) in the embodiment shown in FIG. **18**, the micro-mirrors **84** may be tilted to individually reflect back different optical input channels **14**,**414**, as shown in FIG. **19**.

FIG. **20** illustrates the micro-mirror device **480** of another embodiment of the present invention similar to that shown in FIGS. **17** and **18**, wherein the embodiment has N number of blocking filters ($filter_1$–$filter_N$). The embodiment includes N number of complementary input optical components **81**,**481** (see FIG. **17**) that provide respective input signals to the set of common optical components **20**, **22**, **24**, **26**, **28**, **480**. The embodiment functions substantially the same as the blocking filter **400** of FIG. **17**, as described hereinbefore.

A further embodiment of the present invention includes a dual pass or double bounce blocking filter **500**, as shown in FIGS. **21** and **22**. The dual pass blocking filter **500** is substantially similar to the dual blocking filter **400** shown in FIG. **17**, and therefore common components have the same reference numeral. Functionally, the dual pass blocking filter **500** reflects the through optical input channel off the spatial light modulator **300** and through the optics **22, 24, 26, 28** twice. The multiplicative properties of the double pass technique provide a very narrow filter function having steep sides and greater isolation between filter functions.

The ability to control the tilt patterns of the micro-mirror device enables the shape (e.g., narrowness) and center wavelength to be statically or dynamically modified, which is similar to that disclosed in U.S. patent application Ser. Nos. 09/648,525 and 09/751,589, which are incorporated herein by reference.

Referring to FIGS. **21** and **22** in the operation of the blocking filter **500**, the input signal **12** is first dispersed by the diffraction grating **24** onto the micro-mirror device **200**. Each input channel **14** is spread along the spectral axis **86** as shown in FIG. **22**. Similar to that described hereinabove, the groups of micro-mirrors **370, 372** of shaded micro-mirrors **84** delete the optical input channels at λ_2 and λ_5 of the input signal **12**, and reflect the through input channels at λ_1, λ_3, λ_4, and λ_6–λ_N back to the first pigtail **20**. The through input channels at λ_1, λ_3, λ_4, and λ_6–λ_N then propagate to second pigtail **420** through the first and second circulators **20,420** respectively. The end **436** of the second pigtail **420** is displaced spatially such that the through input channels **14'** at λ_1, λ_3, λ_4, and λ_6–λ_N are dispersed onto the micro-mirror device **200** and spaced in the spatial axis **88** a predetermined distance from the input channels **14** at λ_1, λ_3, λ_4, and λ_6–λ_N, as shown in FIG. **22**. The micro-mirrors **84** are titled to reflect the selected input channel **14'** back to second pigtail **420**, while the micro-mirrors adjacent the input channels at λ_2 and λ_5 are tilted to delete any remaining light. The through input channels **14'** then propagate through the second circulator **418** to the output fiber **450**.

While the micro-mirror patterns that reflect the desired input channel **14** and the selected input channel **14'** are shown to be the same, one will recognize that the patterns may be different such that the each pattern reflects a different portion of the desired input channel **14** and the selected input channel **14'**, which results in a different overall blocking filter function.

The blocking filters **10, 110** may be configured for any wavelength plan by simply modifying the software. For example, an blocking filter for deleting a 50 Ghz WDM optical signal may be modified to delete a 100 Ghz or 25 Ghz WDM optical signal by simply modifying or downloading a different switching algorithm, without modifying the hardware. In other words, the blocking filter may be modified by simply changing statically or dynamically the switching algorithm (e.g., modifying the bit map) to accommodate any designs, upgrades, modifications or adjustments of the optical network (such as variances in the spacing of the channels, the shapes of the light beams, and/or the center wavelength of the light beams), or compensate for changes (e.g., thermal or mechanical drift) of the blocking filter. For example, the software can be modified or written to provide a first pattern of micro-mirrors **84** having a predetermined width that pass a selected 50 Ghz optical channel(s) **14** back to the output fiber, and/or provide a second pattern of micro-mirrors **84** having a predetermined width that reflects a selected 100 Ghz optical channel(s) back to the output fiber, wherein the width of the first pattern is greater than the width of the second pattern.

Another embodiment of a blocking filter **510** is shown in FIG. **23**, which is similar to the blocking filter **10** of FIG. **1**. The blocking filter **510** includes a pair of similar optical portions **515,516** for providing respective optical input channels **14** to and receiving the input channels from the spatial light modulator **30**. The optical components **520, 522, 524, 526, 528, 536** of the optical portion **516** are substantially similar to the complementary optical components **20, 22, 24, 26, 28, 36** of the first optical portion **515**.

In the operation of the blocking filter **510**, the micro-mirrors **84** of the spatial light modulator are tilted to reflect all the deleted input channels **14** of the input signal **12** back along the return path **94**, which are blocked by the optical isolator **540**. The through optical channels are reflected along the output optical path **542** to provide the output signal **544** at pigtail **520**.

Referring to FIG. **24**, another exemplary embodiment of a blocking filter **600** is shown that is similar to the blocking filter **510** of FIG. **23**, and therefore, similar components have the same reference numerals. The optical components are disposed in two tiers or horizontal planes similar to the embodiments discussed hereinbefore. Specifically, the three-port circulator **18**, the pigtail **20**, the collimator **22** and the diffraction grating **24** are disposed in a first tier or horizontal plane. The mirror **26**, the bulk lens **28** and the spatial light modulator **30** are disposed in the second tier or horizontal plane. Further, the mirror **606** and the lens **608** are disposed in the second tier.

The circulator **18** directs the input signal **12** from the optical fiber **38** to the pigtail **20**. The input signal **12** exits the first pigtail (into free space) and passes through the collimator **22**, which collimates the input signal. The collimated input signal **40** is incident on the diffraction grating **24**, which separates spatially the optical input channels **14** of the collimated input signal **40** by diffracting or dispersing the light from the diffraction grating. The diffraction grating **24** directs the separated light **44** to the mirror **26** disposed in the second tier. The mirror **26** reflects the separated light **44** to the bulk lens **28** (e.g., a Fourier lens), which focuses the separated light onto the micro-mirror device **82** of the spatial light modulator **30**, as shown in FIG. **2**. In response to a switching algorithm and input command **46**, the spatial light modulator **300** selectively reflects the through channel(s) **14** of the input signal through the lens **608** to the mirror **606**, and back through common optical components to pigtail **20**. The deleted channels are reflected away from the return optical path **94**, as indicated by arrows **610**.

In the operation of the blocking filter **600**, the micro-mirrors **84** of the spatial light modulator **30** are tilted to a first position to delete a desired optical channel(s) from the WDM input signal **12** by directing the deleted channels away from the return path **94** and the first optical path **92**, as indicated by arrow **610**. The micro-mirrors **84** of the spatial light modulator **30** are tilted to a second position to reflect the through optical channels **14** of the input signal **12** through the lens **608** to the mirror **606** which then reflects the through channel(s) back along the return path **94** to provide the output signal **48** at optical fiber **50**. While the blocked or deleted channels are directed along the optical path **610**, some scattered light of the blocked optical channels propagate along the first optical path **92**. This edge scattering from the micro-mirrors limits the extinction of the blocked channel that can be achieved.

By properly choosing the angle of incidence of the signal light onto the spatial light modulator, the coherent scattering from the blocked channel mirrors can be directed away from the return path **94** and provide the highest blocked channel extinction.

Under conditions of power loss the mirrors of the spatial light modulator revert to a neutral position, splitting the angle between the first position and the second position and lying parallel to the spatial light modulator substrate. Choosing this position orthogonal to the input light beam provides a fail safe device that in the advent of power loss reverts to a condition in which all input channels are propagated through the device.

FIG. **25** illustrates the resulting transfer function or filter function **650**, centered at λ_c, of the micromirrors **85** of the micromirror device **200**, which is similar to that shown in FIGS. **16** and **19**. As shown, the micromirror device **200** is rotated 45 degrees. Consequently the sides of the transfer function are sloping as a result of the serrated edges of the micromirrors in this diagonal orientation. The total device transfer function is the convolution of the mirror transfer function and the optics point spread function.

FIG. **26** illustrates the resulting transfer function of filter function **660**, centered at λ_c, of the micromirrors **85** of the micromirror device **200**, which is similar to that shown in FIGS. **16** and **19**, except the micromirror is not rotated 45 degrees. As shown in FIG. **27**, the micromirror device **200** is oriented in an orthogonal orientation such that the micromirror edges align with the spectral and spatial axes of the optical system. Further, the micromirrors **84** tilted about the diagonal axis **205**. Consequently, the sides of the transfer function **660** are substantially more parallel than the transfer function **650** of FIG. **25** to provide a much sharper transfer function due to the parallel edge of the micromirrors.

One will appreciate that each portion or pixel of light reflects the optical channel by a percentage defined by the number of micro-mirrors **84** illuminated by the optical input channel. For example, assuming each optical channel **14** illuminates 300 micro-mirrors, each micro-mirror is representative of approximately 0.3% of light (or approximately 0.02 Db) of the optical signal when the micro-mirror is tilted away. The above example assumes that the intensity of the light of each optical channel is uniform over the entire cross-section of the beam of light. One will appreciate that the intensity from one end to the other end of the beam of the optical channel may be Gaussian in shape, and therefore, the intensity of the pixels of light at the ends of the beams of the optical channels **14** is less than the center portion of the beams, which advantageously increases the resolution of the power of the selected input channel **14**, the greater the resolution of the power of the redirected portion of that optical channel.

One skilled in the art will appreciate that a diffraction grating has a predetermined polarization dependence loss (PDL) associated therewith. The PDL of a diffraction grating **24** is dependent on the geometry of the etched grooves **42** of the grating. Consequently, means to mitigate PDL may be desired. One method of mitigating the PDL for any of the embodiments described hereinbefore is to provide a $\lambda/4$ plate (not shown) between the spatial light modulator **30** and the diffraction grating **24** (before or after the bulk lens **28**). The fast axis of the $\lambda/4$ plate is aligned to be approximately 45 degrees to the direction or axis of the lines **42** of the diffraction grating **24**. The mirror is angled to reflect the separated channels back through the $\lambda/4$ plate to the diffraction grating. In transiting the phase plate twice, a phase difference π is accumulated between the components at 45 degrees to the grating and the orthogonal component. Since π is equivalent to a multiplication by a negative sign, this produces a reflection of a vector about the 45 degree axis. Effectively, the $\lambda/4$ plate averages the polarization of the light aligned and orthogol to the grating to reduce or eliminate the PDL. One will appreciate that the $\lambda/4$ plate may not be necessary if the diffraction grating has low polarization dependencies, or other PDL compensating techniques are used.

FIG. **28** illustrates another embodiment of an optical blocking filter **700** that compensates for the grating differential loss associated with different polarization states. In this embodiment, the signal component of the input signal is initially separated into each polarization state (i.e., P state and S state) one of a number of polarization separators **702**, such as a Wollistan prism, a polarization beam splitter and a fiber coupler. The component having the poorest grating reflection coefficient, normally the P polarization state, is rotated using a $\lambda/2$ wave plate **704** into the most favorable grating polarization state. The polarization components are then provided to a pair of pigtail **20**, **720**, which are spatially separated to provide the light beams separate in the spatial plane. Each component (or polarization state) including the frequency components is dispersed and imaged onto the micromirror device **730**, as shown in FIG. **29**, which are retro-reflected by the micromirror device. The retro-reflection of the components along return optical path removes any polarization rotation imparted in the first pass. The retro-reflected polarization states are then recombined with each other by the polarization separator **702** and wave plate **704** to provide the output signal **48** at optical fiber **50**. The first grating PDL mitigation technique effectively averages to grating loss in the two polarization states. The current technique provides a grating loss of the least lossy component. Particularly, for strongly dispersive gratings **24**, this embodiment can provide significantly lower device insertion loss.

As shown in FIG. **29**, the pattern of micromirrors **84** tilted to block or deleted an optical channel or block of channels extends over both components of the optical channel.

While the micro-mirrors **84** may switch discretely from the first position to the second position, as described hereinabove, the micro-mirrors may move continuously (in an "analog" mode) or in discrete steps between the first position and second position. In the "analog" mode of operation the micro-mirrors can be can be tilted in a continuous range of angles. The ability to control the angle of each individual mirror has the added benefit of much more attenuation resolution than in the digital control case. In the "digital" mode, the number of micro-mirrors **84** illuminated by each channel determines the attenuation step resolution. In the "analog" mode, each mirror can be tilted slightly allowing fully continuous attenuation of the return beam. Alternatively, some combination of micro-mirrors may be switched at a predetermined or selected pulse width modulation to attenuate the optical channel or band.

One will appreciate that each embodiment described hereinbefore and those contemplated by the present invention may function as a tunable single pass or double pass filter, bandpass filter and/or optical drop device by eliminating the optical detector (i.e., photodiode **51**).

The present invention also contemplates including the function of selectively attenuating the through channels of the optical blocking filter of any described hereinbefore. In the combined embodiment, the desired optical channels may be attenuated by tilting a selected number of micromirrors associated with a through channel **14** to direct a portion of the channel away from the return path, similar to that described in U.S. patent applications Ser. No. 60/281,079, entitled "Reconfigurable Pixelated Optical Filter" and U.S. patent application Ser. No. 60/311,002, entitled "Dynamic Optical Filter Having an Array of Micromirrors", which are incorporated herein by reference in their entirety. In a specific embodiment, the dual function blocking filter may function as a dynamic gain flattening filter, wherein the through channels are attenuated to have equal power levels in response to optical feedback provided by an optical detector.

FIG. **30** shows an embodiment of an optical blocking filter generally indicated as **1000** having optical portions **15**, **16** with one or more optical PDL devices **1002**, **1004**, **1006**, **1008** for minimizing polarization dependence loss (PDL). The one or more optical PDL devices **1002**, **1008** are arranged between the capillary tube **36** and the grating **24**, while the one or more optical PDL devices **1004**, **1006** are arranged between the grating **24** and the spatial light modulator **30**.

The optical PDL device **1002** may include a polarization splitter for splitting each channel into its pair of polarized light beams and a rotator for rotating one of the polarized light beams of each optical channel. The optical PDL device **1008** may include a rotator for rotating one of the previously rotated and polarized light beams of each optical channel and a polarization splitter for combining the pair of polarized light beams of each channel.

The one or more optical devices **1002**, **1004**, **1006**, **1008** may be incorporated in any of the embodiments shown and described above, including but not limited to the embodiments shown in FIGS. **1**, **8**, **9**, **17**, **21**, **23**, **24**, and **28**. In effect, as a person skilled in the art will appreciate, a diffraction grating such as the optical elements **42**, **54** has a predetermined polarization dependence loss (PDL) associated therewith. The PDL of the diffraction grating **24** is dependent on the geometry of the etched grooves **42** of the grating. Consequently, means to mitigate PDL may be desired. The λ/4 plate between the spatial light modulator **30** and the diffraction grating(s) **24**, **54** (before or after the bulk lens **28**, **52**) mitigates the PDL for any of the embodiments described hereinbefore. The fast axis of the λ/4 plate is aligned to be approximately 45 degrees to the direction or axis of the lines **42** of the diffraction grating **24**. The mirror is angled to reflect the separated channels back through the λ/4 plate to the diffraction grating. In the first pass through the λ/4 plate, the λ/4 plate circularly polarizes the separated light. When the light passes through the λ/4 plate again, the light is linearly polarized to effectively reflect the polarization about an axis 45 degrees to the grating. Effectively, the λ/4 plate averages the polarization of the light to reduce or eliminate the PDL. One will appreciate that the λ/4 plate may not be necessary if the diffraction grating has low polarization dependencies, or other PDL compensating techniques are used that are known now or developed in the future.

As shown and described herein, the polarized light beams may have a generally circular cross-section and are imaged at separate and distinct locations on the spatial light modulator **30**, such that the polarized light beams of the optical channels do not substantially overlap spatially when focused onto the spatial light modulator, as shown, for example, in FIGS. **3**, **6**, **7**, **10**, **11**, **16**, **18**, **19**, **20**, **22**, **27** and **29**.

FIG. **32** shows the DMD portion of an optical blocking filter generally indicated as **1600** similar to that shown above, except that the DMD device of the spatial light modulator is laid down and arranged in a horizontal position in relation to the optical components discussed above in order to reduce the profile of the overall packaging. (In the embodiments discussed above, the DMD chip in the spatial light modulator is arranged vertical in relation to the optical components.) In FIG. **31**, the micromirror device is rotated and lies in the plane of the optical path oriented such that the tilt axis **85** is perpendicular to the spectral axis **86**, similar to that discussed above. The blocking filter **1600** has a chisel prism **1602** arranged in relation to the spatial light modulator **30**, a set of optical components **1604**, a retromirror **1605** and a complimentary set of optical components **1606**. The chisel prism **1602** rotates the optical input and output signals onto the spatial light modulator **30**. The underlying configuration of the blocking filter **1600** may be implemented in any of the embodiments show and described above in which the pivot or tilt axis of the mirrors of the micromirror device **30** is perpendicular to the spectral axis of the channels projected on the micromirror device **30**. A single set of optical components **1604** may be used in suitable embodiments similar to that shown in FIGS. **1**, **8**, **9**, **24** and **28**, while the complimentary set of optical components **1606** may also be used in suitable embodiments similar to that shown in FIGS. **17**, **21** and **23**.

The set of optical components **1604** and the complimentary set of optical components **1606** are similar to the optical portions **15**, **16** shown and described herein. For example, see FIG. 1A. The spatial light modulator **30** is shown and described herein as the well known micromirror device. The chisel prism **1602** has multiple faces, including a front face **1602***a*, a beveled front face **1602***b*, a rear face **1602***d* and a bottom face generally indicated by **1602***e*. Light from the set of optical components **1604** and the complimentary set of optical components **1606** passes through one or more faces of the chisel prism **1602**, reflects off the spatial light modulator back to the chisel prism **1602**, reflects off one or more internal surfaces of the chisel prism **1602** and passes back through the chisel prism **1602**, passes back to the set of optical components **1604** or the complimentary set of optical components **1606**.

The chisel prism design described herein addresses a problem in the optical art when using micro-mirror devices. The problem is the ability to send a collimated beam out to a reflective object and return it in manner that is insensitive to the exact angular placement of the reflective object. Because a light beam is typically collimated and spread out over a relatively large number of micro-mirrors, any overall tilt of the array causes the returned beam to "miss" the optical component, such as a pigtail, intended to receive the same.

The present invention provides a way to reduce the tilt sensitivity by using a classical optical design that certain combinations of reflective surfaces stabilize the reflected beam angle with respect to angular placement of the reflector. Examples of the classical optical design include a corner-cube (which stabilize both pitch and yaw angular errors) or a dihedral prism (which stabilize only one angular axis.).

One advantage of the configuration of the present invention is that it removes the tilt sensitivity of the optical system (which may comprise many elements besides a simple collimating lens such as element **26** shown and described above) leading up to the retro-reflective spatial light modulator **30**. This configuration allows large beam sizes on the spatial light modulator without the severe angular alignment sensitivities that would normally be seen.

Patent application Ser. No. 10/115,647, which is hereby incorporated by reference, shows and describes the basic principal of these highly stable reflective elements in which all the surfaces of the objects being stable relative to one another, while the overall assembly of the surfaces may be tilted without causing a deviation in reflected angle of the beam that is large compared to the divergence angle of the input beam.

FIG. **32** illustrates a schematic diagram of an optical blocking filter generally indicated as **1700** having a chisel prism **1704** that provides improved sensitivity to tilt, alignment, shock, temperature variations and packaging profile, which incorporates such a tilt insensitive reflective assembly. The scope of the invention is intended to include using the chisum prism technology described herein in any one or more of the embodiments described herein having a single optical input signal. Similar to that discussed above in relation to FIG. **31**, the chisel prism configuration may be suitable adapted to for use in any one or more of the embodiments described herein having two optical input signals.

Similar to the embodiments described hereinbefore, and by way of example, the blocking filter **1700** includes a first set of optical components having a dual fiber pigtail **1702** (circulator free operation), the collimating lens **26**, a bulk diffraction grating **42**, a Fourier lens **34**, a ¼λ plate **35**, a reflector **26** and a spatial light modulator **1730** (similar to that shown above). The dual fiber pigtail **1702** includes a transmit fiber **1702***a* and a receive fiber **1702***b*. The first set of optical components typically provide a first optical input signal having one or more optical bands or channels on the receive fiber **1702***b*, as well as providing an optical output signal on the transmit fiber **1702***b*.

Similar to the embodiment described above, the chisel prism **1704** has multiple internally reflective surfaces, including a top surface, and a back surface, as well as transmissive surfaces including a front surface and a bottom surface. The micro-mirror device **1730** is placed normal to the bottom surface of the chisel prism **1704**, as shown. In operation, the chisel prism **1704** reflects the first optical input signal from the first set of optical components to the spatial light modulator **1730**, and reflects the optical output signal back to the first set of optical components.

The chisel prism **1704** decreases the sensitivity of the optical filter to angular tilts of the optics. The insensitivity to tilt provides a more rugged and robust device to shock vibration and temperature changes. Further, the chisel prism **1704** provides greater tolerance in the alignment and assembly of the optical filter **1700**, as well as reduces the packaging profile of the filter. To compensate for phase delay associated with each of the total internal reflection of the reflective surfaces of the prism (which will be described in greater detail hereinafter), a λ/9 wave plate **1708** is optically disposed between the prism **1704** and λ/4 wave plate **35**. An optical wedge or lens **1710** is optically disposed between the λ/4 wave plate **35** and the diffraction grating **42** for directing the output beam from the micro-mirror device **1730** to the receive pigtail **1702***a* of the dual fiber pigtail **1702***b*. The optical wedge or lens **1710** compensates for pigtail and prism tolerances. The scope of the invention is intended to cover embodiments in which the optical wedge **1710** is arranged parallel or oblique to the front surface of the wedge **1704**. Moreover, as shown, these components are only arranged in relation to one front surface; however, as a person skilled in the art would appreciate, these optical components would typically be arranged in relation to any one or more front surfaces shown in FIG. **36**, as well as the front surfaces in the other chisel prism embodiments shown ad described herein.

The optical device **1700** further includes a telescope **1712** having a pair of cylindrical lens that are spaced a desired focal length. The telescope **1712** functions as a spatial beam expander that expands the input beam (approximately two times) in the spectral plane to spread the collimated beam onto a greater number of lines of the diffraction grating. The telescope **1712** may be calibrated to provide the desired degree of beam expansion. The telescope advantageously provides the proper optical resolution, permits the package thickness to be relatively small, and adds design flexibility.

A folding mirror **1714** is disposed optically between the Fourier lens **34** and the λ/4 wave plate **35** to reduce the packaging size of the optical filter **1700**.

FIG. **33** shows another embodiment of a tilt-insensitive reflective assembly **1800** having a specially shaped prism **1804** arranged in relation to the micro-mirror device **1830**, a set of optical components as shown and a compliment set of optical components generally indicated as **1805** consistent with that discussed above.

Unlike an ordinary 45 degree total internal reflection (TIR) prism, in this embodiment the back surface of the chisel prism **1804** is cut at approximately a 48 degree angle relative to the bottom surface of the chisel prism **1804**. The top surface of the chisel prism **1804** is cut at a 4 degree angle relative to the bottom surface to cause the light to reflect off the top surface via total internal reflection. The front surface of the chisel prism **1804** is cut at a 90 degree angle relative to the bottom surface. The chisel prism **1804** therefore provides a total of 4 surface reflections in the optical assembly (two TIRs off the back surface, one TIR off the micromirror device **1830**, and one TIR off the top surface.)

In order to remove the manufacturing tolerances of the prism angles, a second smaller compensating prism or wedge **1810** (or wedge), having a front surface cut at a shallow angle (e.g., as 10 degrees) with respect to a back surface, may also be used. Slight tilting or pivoting about a pivot point of the compensation wedge **1810** causes the light beam to be pointed in the correct direction for focusing on the receive pigtail **1802**.

The combination of the chisel prism **1804** and the compensation wedge **1810** allows for practical fabrication of optical devices that spread a beam out over a significant area and therefore onto a plurality of micro-mirrors, while keeping the optical system robust to tilt errors introduced by vibration or thermal variations.

In FIG. **34**, the input light rays **1826***a* first pass through the λ/4 wave plate **35** and the λ/9 wave plate **1840**. The input rays **1826***a* reflect off the back surface **1821** of the prism **1804** the micro-mirror device **1830**. The rays **1826***b* then reflect off the micromirror device **1830** back to the back surface **1821** of the prism **1804** The rays **1826***b* then reflect off the top surface **1822** for a total of 4 surfaces (an even number) and passes through the front surface **1823** of the prism **1804**. The rays **1826***b* then pass back through the λ/4 wave plate **35** and the λ/9 wave plate **1840** to the wedge **1810**. The wedge **1810** redirects the output rays **1826***c* to the receive pigtail **1802**. As shown by arrows **1851**, the wedge **1810** may be pivoted about its long axis **1850** during assembly to slightly steer the output beam **1826***c* to the receive pigtail **1802** with minimal optical loss by removing manufacturing tolerances of the chisel prism.

In FIG. **33**, the prism **1804** (with wave plates **35**, **1840** mounted thereto) and the micro-mirror device **1830** are mounted or secured in fixed relations to each other. The prism **1804** and micro-mirror device **1830** are tilted a predetermined angle off the axis of the input beam **614** (e.g., approximately 9.2 degrees) to properly direct the input beam onto the micromirrors of the micromirror device, as described hereinbefore. The wedge **1810** however is perpendicular to the axis of the input beam **1826***a*. Consequently, the receive pigtail of the dual fiber pigtail **1802** is rotated a predetermined angle (approximately 3 degrees) from a vertically aligned position with the transmit pigtail. Alternatively, the wedge **1810** may be rotated by the same predetermined angle as the prism and the micromirror device (e.g., approximately 9.2 degrees) from the axis of the input beam. As a result, the receive pigtail of the dual pigtail assembly **1802** may remain vertically aligned with transmit pigtail.

THE SCOPE OF THE INVENTION

The dimensions and geometries for any of the embodiments described herein are merely for illustrative purposes and, as much, any other dimensions may be used if desired, depending on the application, size, performance, manufacturing requirements, or other factors, in view of the teachings herein.

It should be understood that, unless stated otherwise herein, any of the features, characteristics, alternatives or modifications described regarding a particular embodiment herein may also be applied, used, or incorporated with any other embodiment described herein. Also, the drawings herein are not drawn to scale.

Although the invention has been described and illustrated with respect to exemplary embodiments thereof, the foregoing and various other additions and omissions may be made therein without departing from the spirit and scope of the present invention.

What is claimed is:

1. An optical blocking filter for receiving an optical signal having one or more optical bands or channels, characterized in that

the optical blocking filter comprises a spatial light modulator having a micro-mirror device with an array of micro-mirrors for selectively deflecting the one or more optical bands or channels so that each optical band or channel is reflected off a respective plurality of micro-mirrors to eliminate a selected band or channel or a specified selection of bands or channels from the optical signal provided along an optical return path, wherein scattered light from a dropped signal is directed onto the micromirror device to reflect away from the return path.

2. An optical blocking filter according to claim **1**, wherein the optical blocking filter comprises an optical arrangement for providing the optical signal along an optical path to the array of micromirrors.

3. An optical blocking filter according to claim **2**, wherein the optical arrangement is a free optics arrangement.

4. An optical blocking filter according to claim **3**, wherein the free optics arrangement provides the optical signal to the spatial light modulator, and also provide an optical output signal having each remaining band or channel reflected off the spatial light modulator.

5. An optical blocking filter according to claim **4**, wherein the free optics arrangement includes either one or more circulators, one or more waveguides, or a combination thereof.

6. An optical blocking filter according to claim **5**, wherein the one or more circulators includes a pair of circulators.

7. An optical blocking filter according to claim **6**, wherein the one or more circulators includes a three port circulator.

8. An optical blocking filter according to claim **5**, wherein the one or more waveguides includes a pair of capillary tubes.

9. An optical blocking filter according to claim **5**, wherein the free optics arrangement comprise a further optical portion for receiving a reflected optical signal from the spatial light modulator and providing a re-reflected optical signal back to the spatial light modulator.

10. An optical blocking filter according to claim **9**, wherein the re-reflected optical signal is reflected off the spatial light modulator and eliminated.

11. An optical blocking filter according to claim **9**, wherein the further optical portion includes a bulk lens, a reflector, or a combination thereof.

12. An optical blocking filter according to claim **9**, wherein the further optical portion includes a mirror for re-reflecting the optical signal back to the spatial light modulator.

13. An optical blocking filter according to claim **4**, wherein the free optics arrangement includes a collimator, a reflective surface, a dispersion element, a bulk lens, or a combination thereof.

14. An optical blocking filter according to claim **13**, wherein the collimator includes either an aspherical lens, an achromatic lens, a doublet, a GRIN lens, a laser diode doublet, or a combination thereof.

15. An optical blocking filter according to claim **13**, wherein the reflective surface includes a mirror.

16. An optical blocking filter according to claim **15**, wherein the reflective surface is curved.

17. An optical blocking filter according to claim **13**, wherein the bulk lens includes a Fourier lens.

18. An optical blocking filter according to claim **13**, wherein the dispersion element has a low PDL.

19. An optical blocking filter according to claim **13**, wherein the dispersion element includes a diffraction grating, a tilted grating, an echelle grating, an etalon, a prism or a holographic optical device.

20. An optical blocking filter according to claim **3**, wherein the free optics arrangement includes one or more optical PDL mitigating devices for minimizing polarization dependence loss (PDL).

21. An optical blocking filter according to claim **20**, wherein one optical PDL mitigating device is arranged between a waveguide and a grating in the optical arrangement, and another optical PDL mitigating device is arranged between a grating and the spatial light modulator.

22. An optical blocking filter according to claim **20**, wherein the one or more optical PDL mitigating devices include a pair of optical PDL mitigating devices.

23. An optical blocking filter according to claim **20**, wherein the one or more optical PDL mitigating devices includes one optical PDL mitigating device having a polarization splitter for splitting each channel into a pair of polarized light beams and a rotator for rotating one of the polarized light beams of each optical channel.

24. An optical blocking filter according to claim **23**, wherein the one or more optical PDL mitigating devices includes another optical PDL mitigating device having a rotator for rotating one of the previously rotated and polarized light beams of each optical channel and a polarization splitter for combining the pair of polarized light beams of each channel.

25. An optical blocking filter according to claim **20**, wherein the one or more optical PDL mitigating devices includes a ·/4 plate.

26. An optical blocking filter according to claim **2**, wherein the optical arrangement includes a chisel prism having multiple faces for modifying the direction of the optical signal.

27. An optical blocking filter according to claim **26**, wherein the multiple faces include at least a front face, a rear face, a top face and a bottom face.

28. An optical blocking filter according to claim **26**, wherein the optical light from the free optics arrangement passes through one or more faces of the chisel prism, reflects off one or more internal surfaces of the chisel prism, reflects off the spatial light modulator, again reflects off the one or more internal surfaces of the chisel prism, and passes back to the free optics arrangement.

29. An optical blocking filter according to claim **2**, wherein the optical arrangement includes a field correction lens for respectively compensating for the one or more channels reflecting of the spatial light modulator.

30. An optical blocking filter according to claim **1**, wherein the spatial light modulator is programmable for reconfiguring the optical blocking filter to eliminate each band or channel by changing a switching algorithm that drives the array of micro-mirrors.

31. An optical blocking filter according to claim **30**, wherein the spatial light modulator is selectively reconfigurable by statically or dynamically modifying the switching algorithm to accommodate different channel spacing, the shape of the light beam, or the center wavelength of the light beam of the optical signal.

32. An optical blocking filter according to claim **30**, wherein the switching algorithm is based on the wavelength of the optical signal and the one or more optical bands or channels being eliminated.

33. An optical blocking filter according to claim **30**, wherein the spatial light modulator is configured so one group of optical channels is spaced at 100 Hz and another group of optical channels is spaced at 50 Hz.

34. An optical blocking filter according to claim **1**, wherein the array of micro-mirrors includes a multiplicity of micro-mirrors that are separately controllable for tilting on an axis depending on a control signal in accordance with a switching algorithm.

35. An optical blocking filter according to claim **1**, wherein the optical signal is a wavelength division multiplexed (WDM) optical signal having a plurality of wavelengths and a corresponding plurality of optical bands or channels.

36. An optical blocking filter according to claim **1**, wherein each micro-mirror is tiltable in either a first position or a second position along an axis either substantially parallel to the spectral axis of the optical signal, parallel to the spatial axis of the optical signal, or at an angle of 45 degrees in relation to the spatial axis.

37. An optical blocking filter according to claim **1**, wherein the one or more optical bands or channels have a desired cross-sectional geometry, including an elliptical, a rectangular, a square or a polygonal shape.

38. An optical blocking filter according to claim **1**, wherein the optical arrangement includes a first free optics arrangement that provides the optical signal to the spatial light modulator, and a second free optics arrangement that provides an eliminated optical signal from the spatial light modulator.

39. An optical blocking filter according to claim **38**, wherein the common free optics arrangement includes

a first optical circulator for providing a first optical signal to the first optical blocking filter and for providing a first optical output signal with first remaining optical bands or channels; and

a second optical circulator for providing a second optical signal to the second optical blocking filter and for providing a second optical output signal with second remaining optical bands or channels.

40. An optical blocking filter according to claim **1**, wherein the optical blocking filter includes a first optical blocking filter and a second optical blocking filter, each sharing a common free optics arrangement.

41. An optical blocking filter according to claim **1**, wherein the optical arrangement comprises:

one or more polarization separators for separating the optical signal into a P state optical signal and an S state optical signal, and for combining a P state optical return signal and an S state optical return signal into an optical output signal; and

a ½· wave plate for rotating the P state optical signal into a rotated S state optical signal, and for rotating an S state optical return signal into the P state optical return signal.

42. An optical blocking filter according to claim **41**, wherein the one or more polarization separators include a Wollistan prism, a polarization beam splitter, a fiber coupler or some combination thereof.

43. An optical blocking filter according to claim **1**, wherein the optical arrangement is arranged in relation to an optical axis and the micromirror surfaces when the array of micromirrors is the neutral position are non-orthogonal in relation to the optical axis.

44. An optical blocking filter according to claim **1**, wherein the optical arrangement is arranged on an optical axis and the micromirror surfaces when the array of micromirrors is in the neutral position are orthogonal to the optical axis so during a failure of the spatial light modulator the optical signal is reflected back along the optical return path and propagated through the optical blocking filter.

45. An optical blocking filter according to claim **1**, wherein the optical signal includes a plurality of channels, each having at least one respective spectral band or section.

46. An optical blocking filter according to claim **1**, wherein the optical signal includes at least one channel having respective spectral bands or sections arranged in non-uniform spectral arrays on the array of micro-mirror.

47. An optical blocking filter according to claim **46**, wherein the non-uniform spectral arrays include arrays having a different length, width, number or combination thereof on the array of micro-mirrors.

48. An optical blocking filter according to claim **1**, wherein the optical signal includes a plurality of channels that are non-linearly disposed on the array of micro-mirrors.

49. An optical blocking filter for receiving an optical signal having one or more optical bands or channels, characterized in that

the optical blocking filter comprises a spatial light modulator having a micro-mirror device with an array of micro-mirrors for selectively deflecting the one or more optical bands or channels to a reflecting device, which re-reflects the one or more optical bands or channels back to the spatial light modulator for re-deflecting the one or more optical bands or channels, in order to eliminate a selected band or channel or a specified selection of bands or channels from the optical signal provided along an optical return path, wherein scattered light from a dropped signal is directed onto the micro-mirror device to reflect away from the return path.

50. An optical blocking filter according to claim **49**, wherein the reflecting device is a mirror.

51. An optical blocking filter according to claim **49**, wherein each optical band or channel is reflected off a respective plurality of micro-mirrors.

* * * * *

EXHIBIT B

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(54) **DYNAMICALLY RECONFIGURABLE OPTICAL SMART NODE**

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H04B 10/08 (2006.01)

(52) **U.S. Cl.** **398/33**

(58) **Field of Classification Search** 398/33, 398/81–83, 177
See application file for complete search history.

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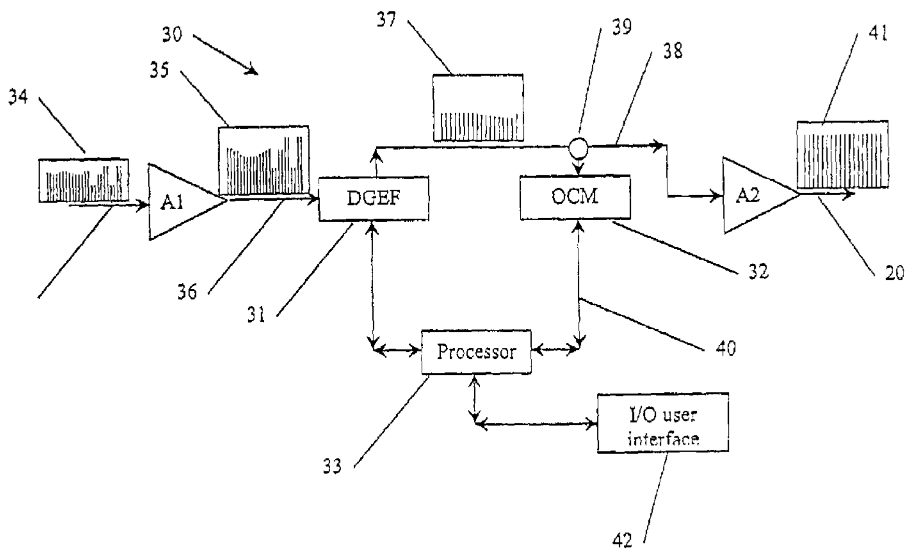
(57) **ABSTRACT**

A smart node is provided for use in an optical communications network wherein the smart node comprising dynamically reconfigurable optical signal manipulation devices in combination with sensing devices and processors to provide real time closed and open loop control of various channels of the network.

42 Claims, 10 Drawing Sheets



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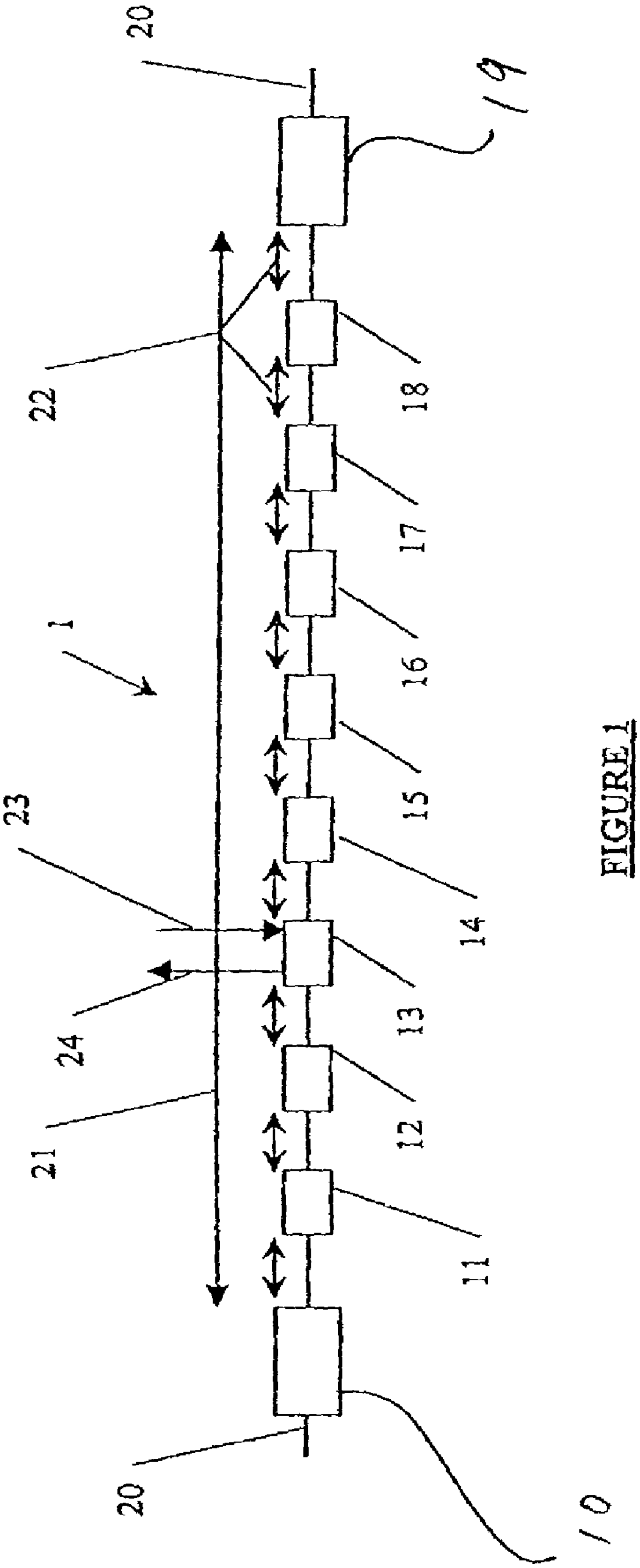
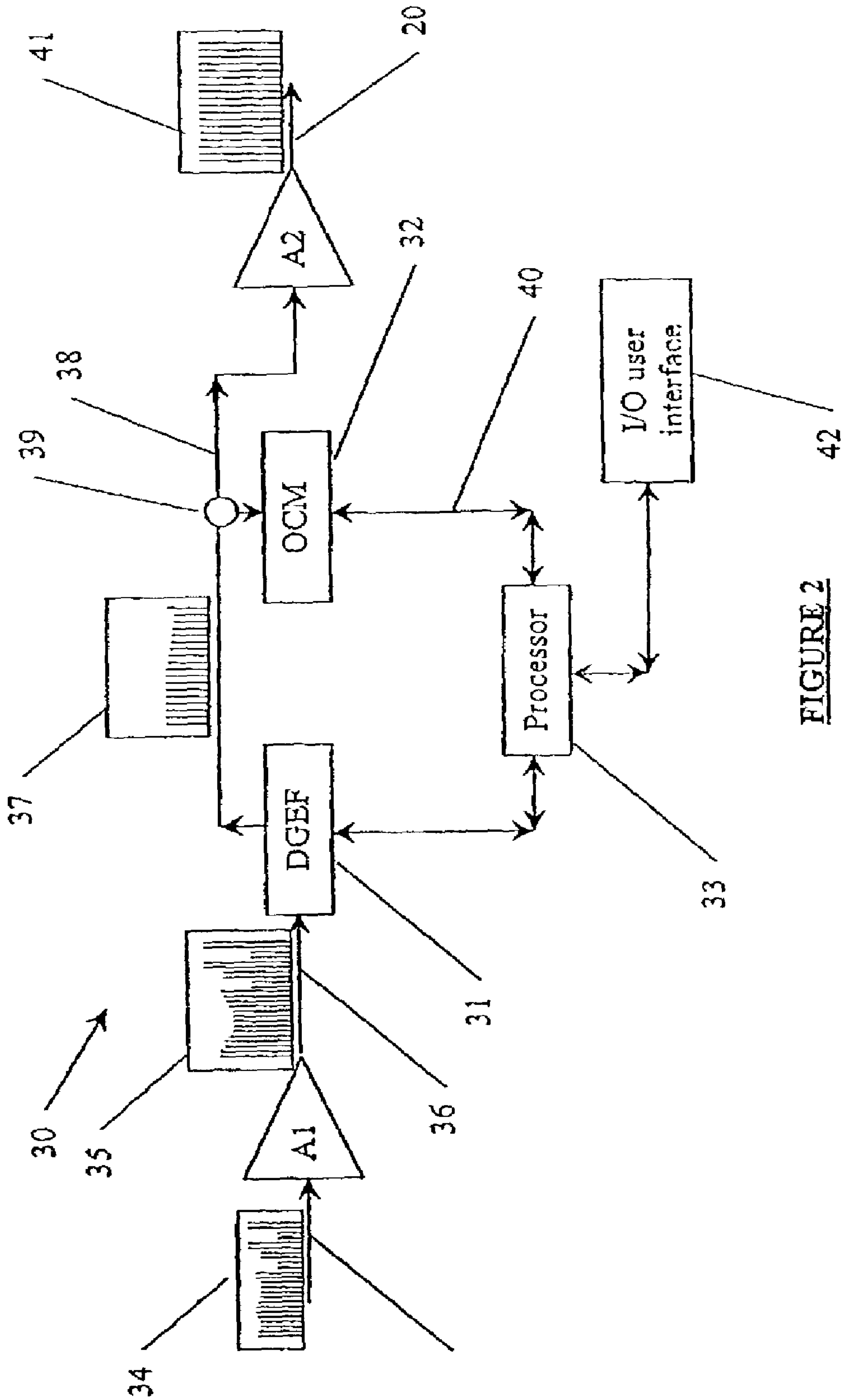
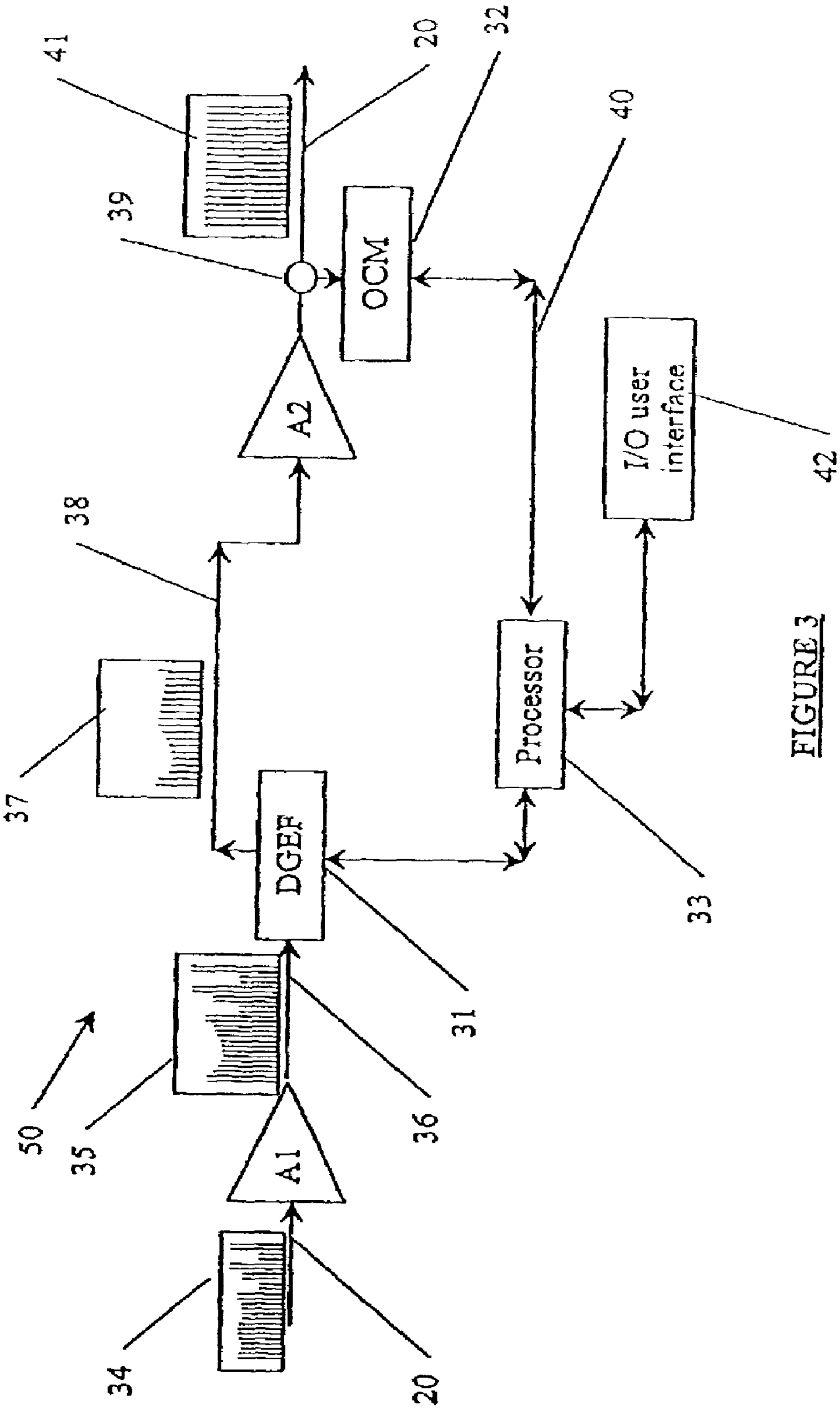


FIGURE 1



A1
A2
DGEF
OCM
Processor
I/O user interface
30
31
32
33
34
35
36
37
38
39
40
41
42
20

FIGURE 2



A1
A2
DGEF
OCM
Processor
I/O user interface
20
31
32
33
34
35
36
37
38
39
40
41
42
50

FIGURE 3

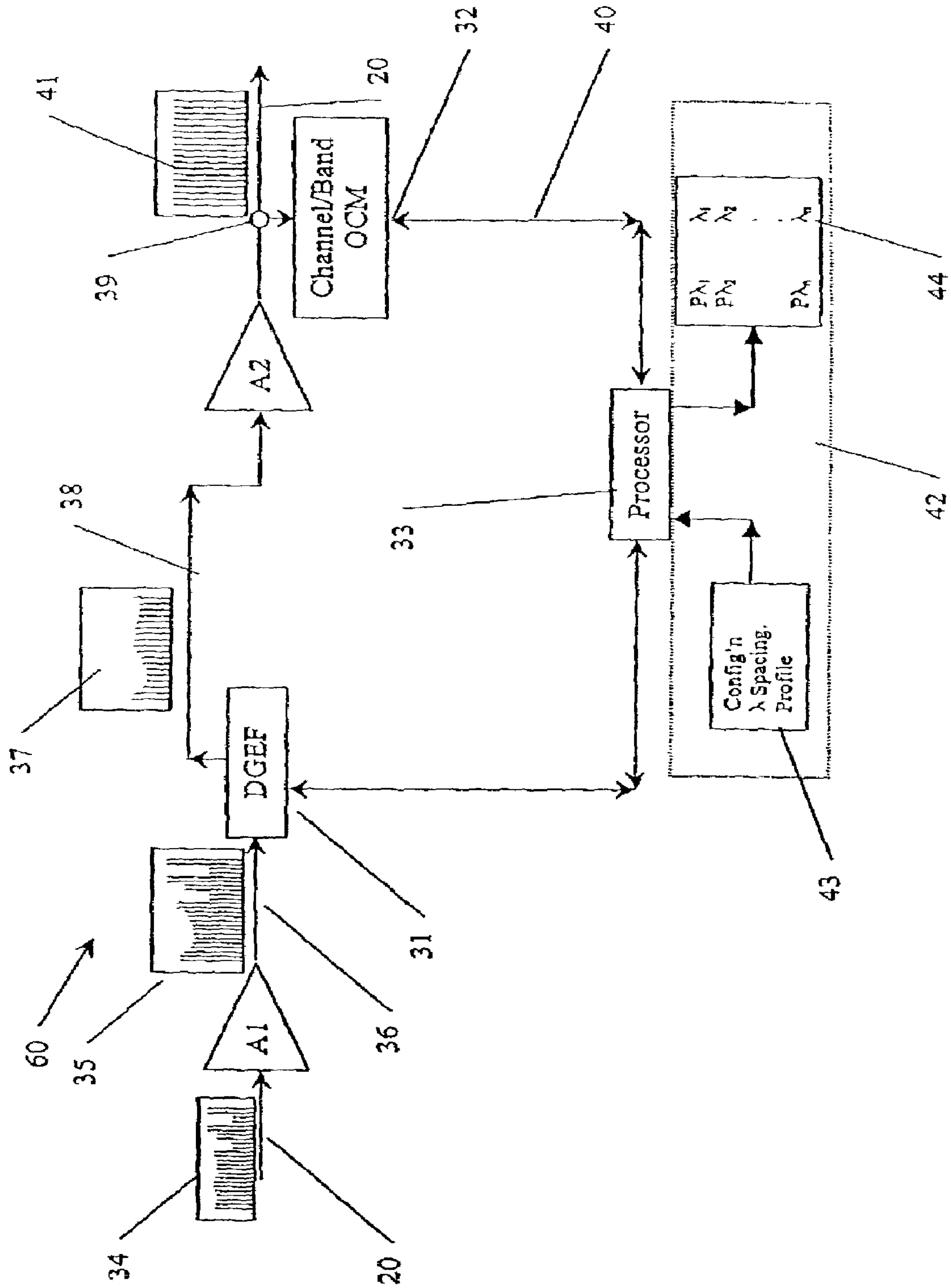

A1
A2
DGEF
Channel/Band OCM
Processor
Config'n λ Spacing, Profile
Pλ1 Pλ2 Pλn
λ1 λ2 λn
20
31
32
33
34
35
36
37
38
39
40
41
42
43
44
60

FIGURE 4

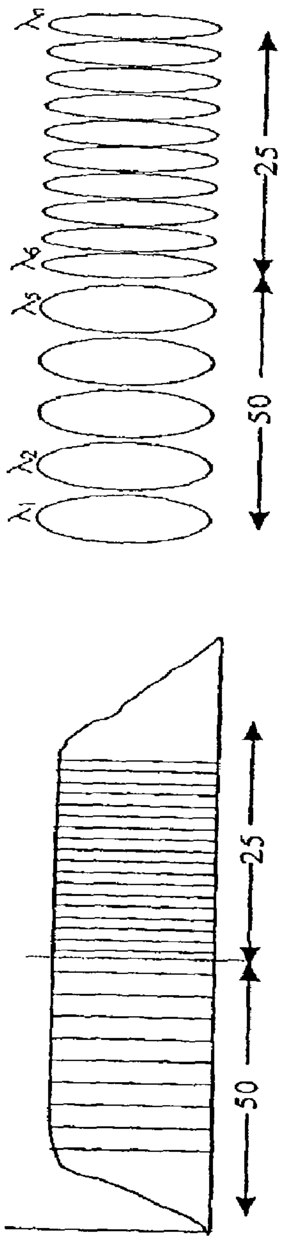


FIGURE 5

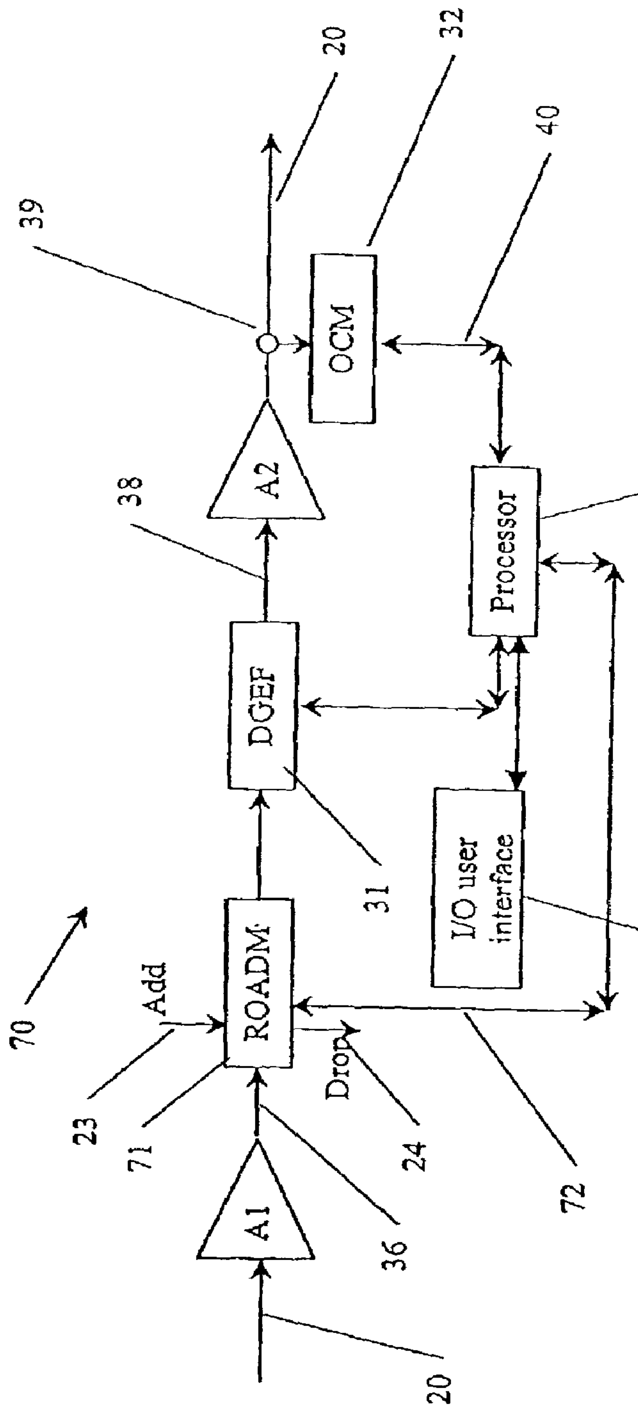


FIGURE 6

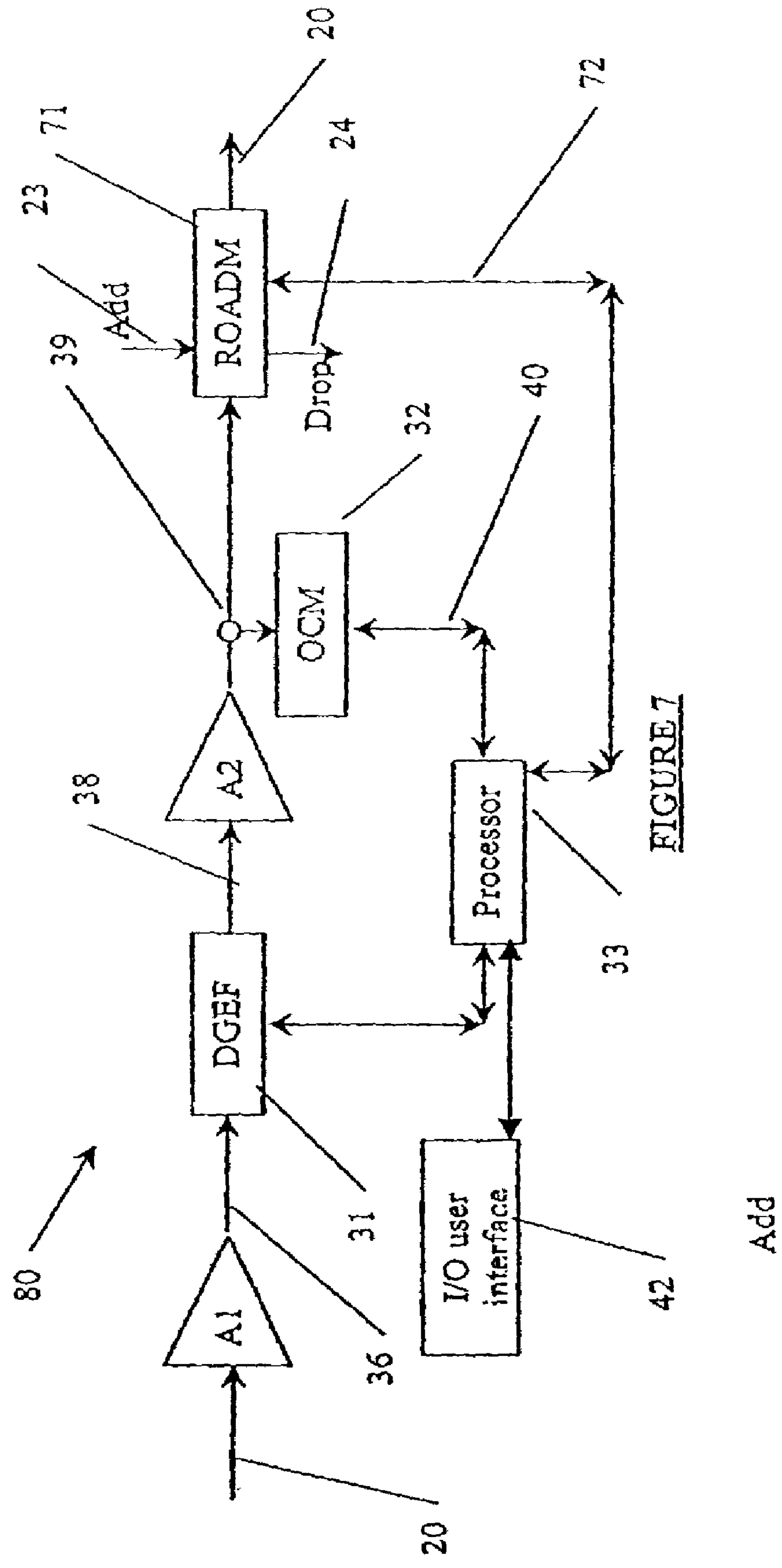
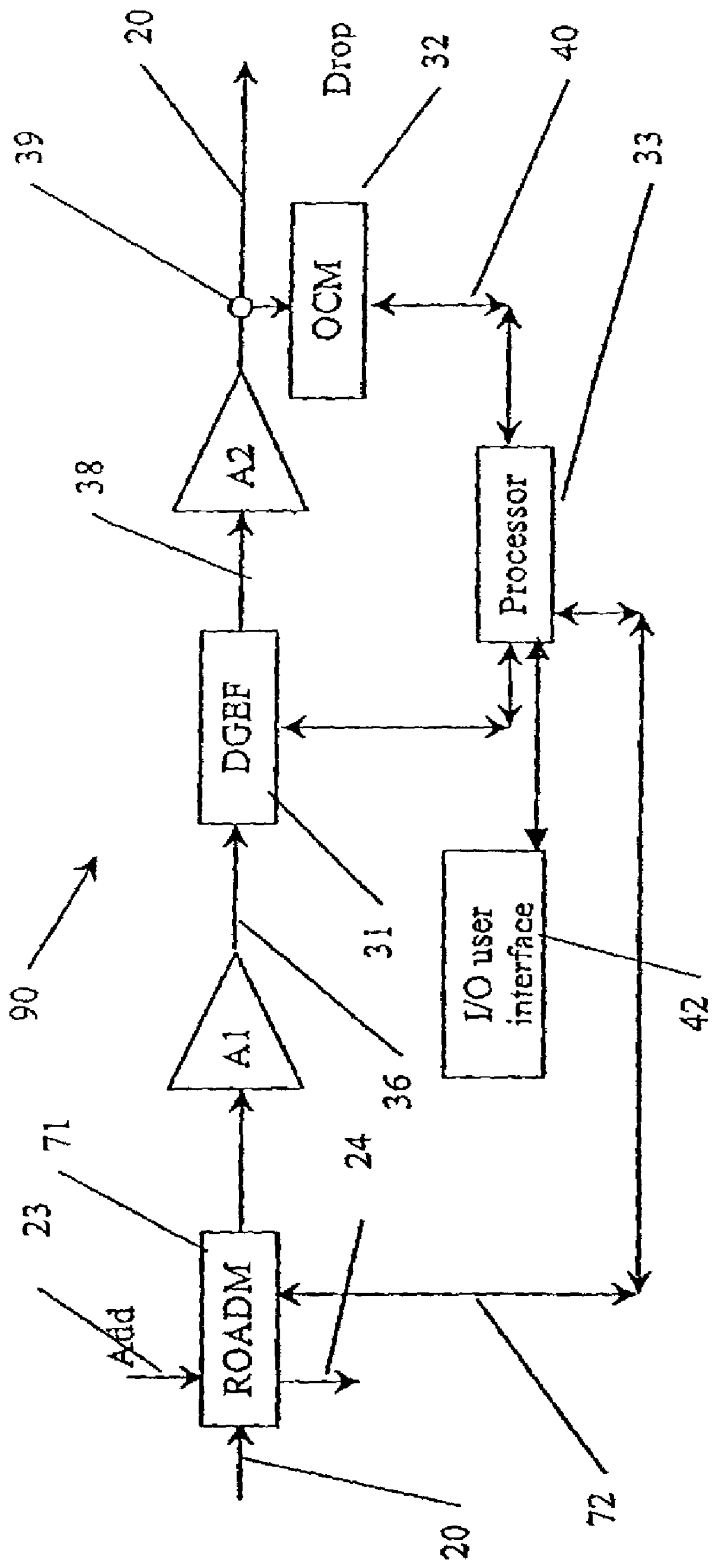

ROADM
Add
Drop
OCM
A2
A1
DGEF
Processor
I/O user interface
Add
80
20
36
31
38
39
23
71
24
20
72
32
40
33
42

FIGURE 7



20
Drop
32
40
39
33
OCM
38
A2
Processor
DGEF
90
31
A1
I/O user interface
42
36
71
23
24
Add
ROADM
20
72

FIGURE 8

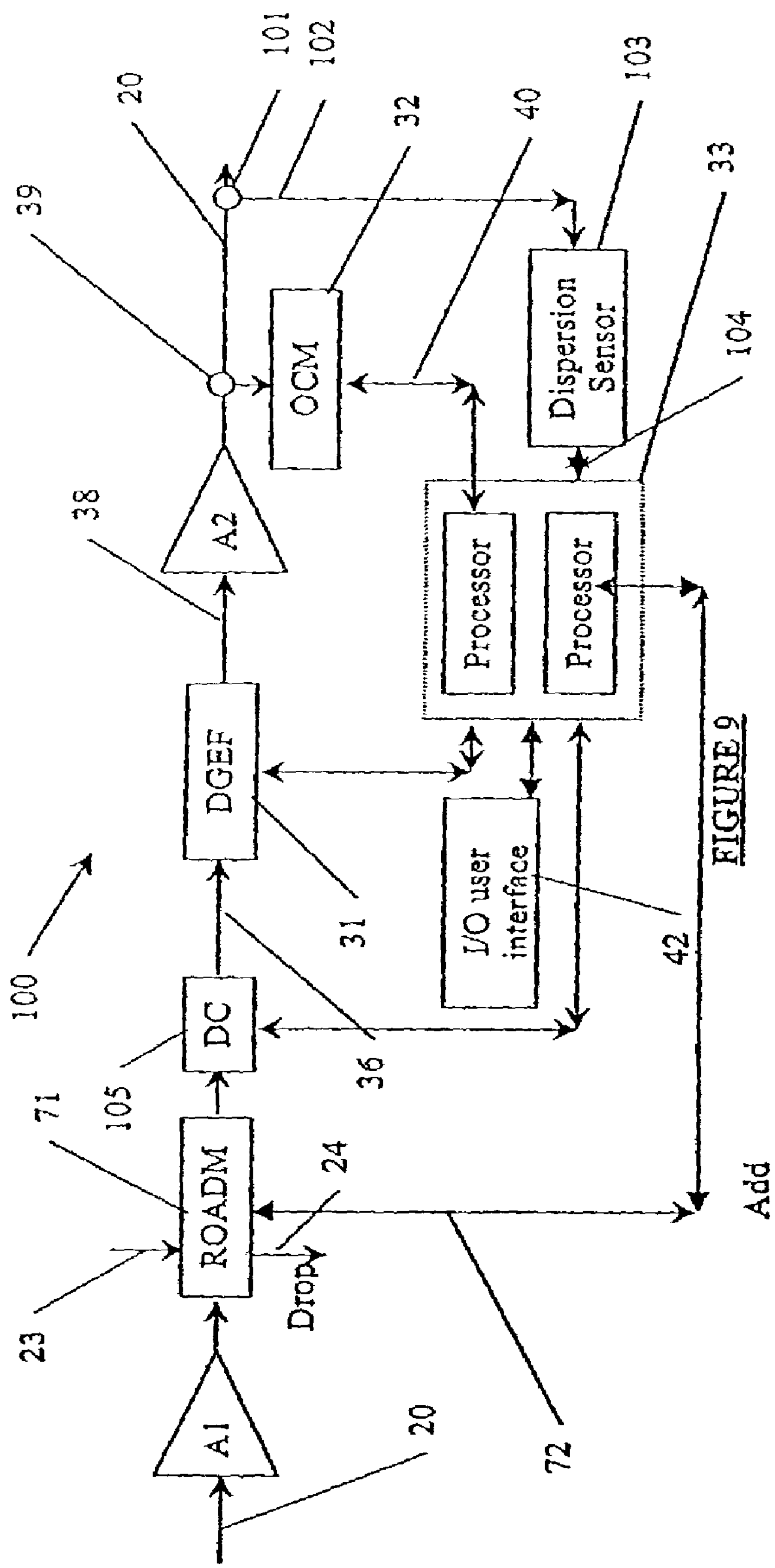
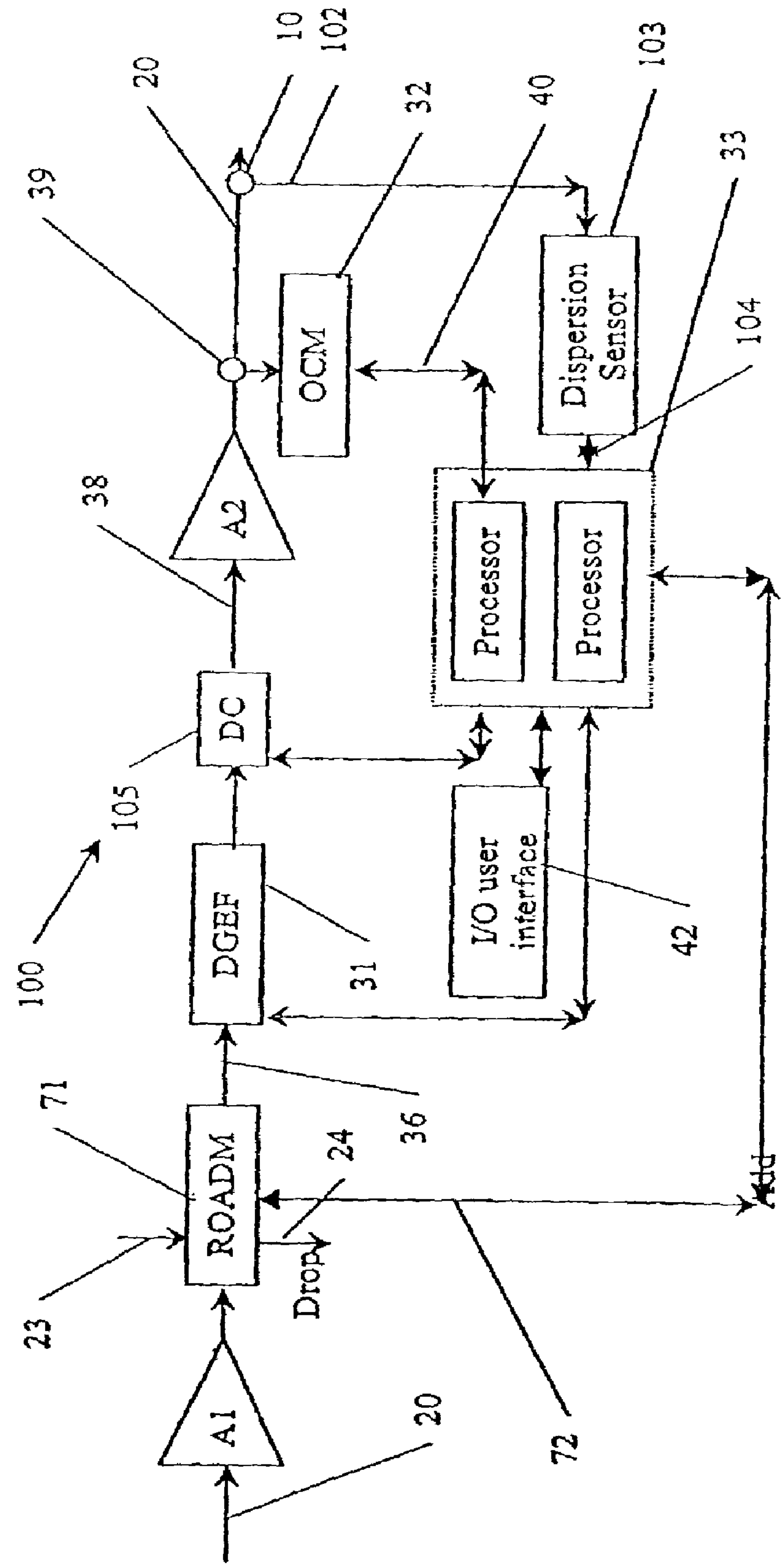

A1
A2
ROADM
DC
DGEF
OCM
Dispersion Sensor
Processor
Processor
I/O user interface
Drop
Add
20
23
24
71
72
100
105
36
31
38
39
20
101
102
32
40
103
33
104
42

FIGURE 9


100
A1
ROADM
DGEF
DC
A2
OCM
Dispersion Sensor
Processor
Processor
I/O user interface
Drop
Add
20
23
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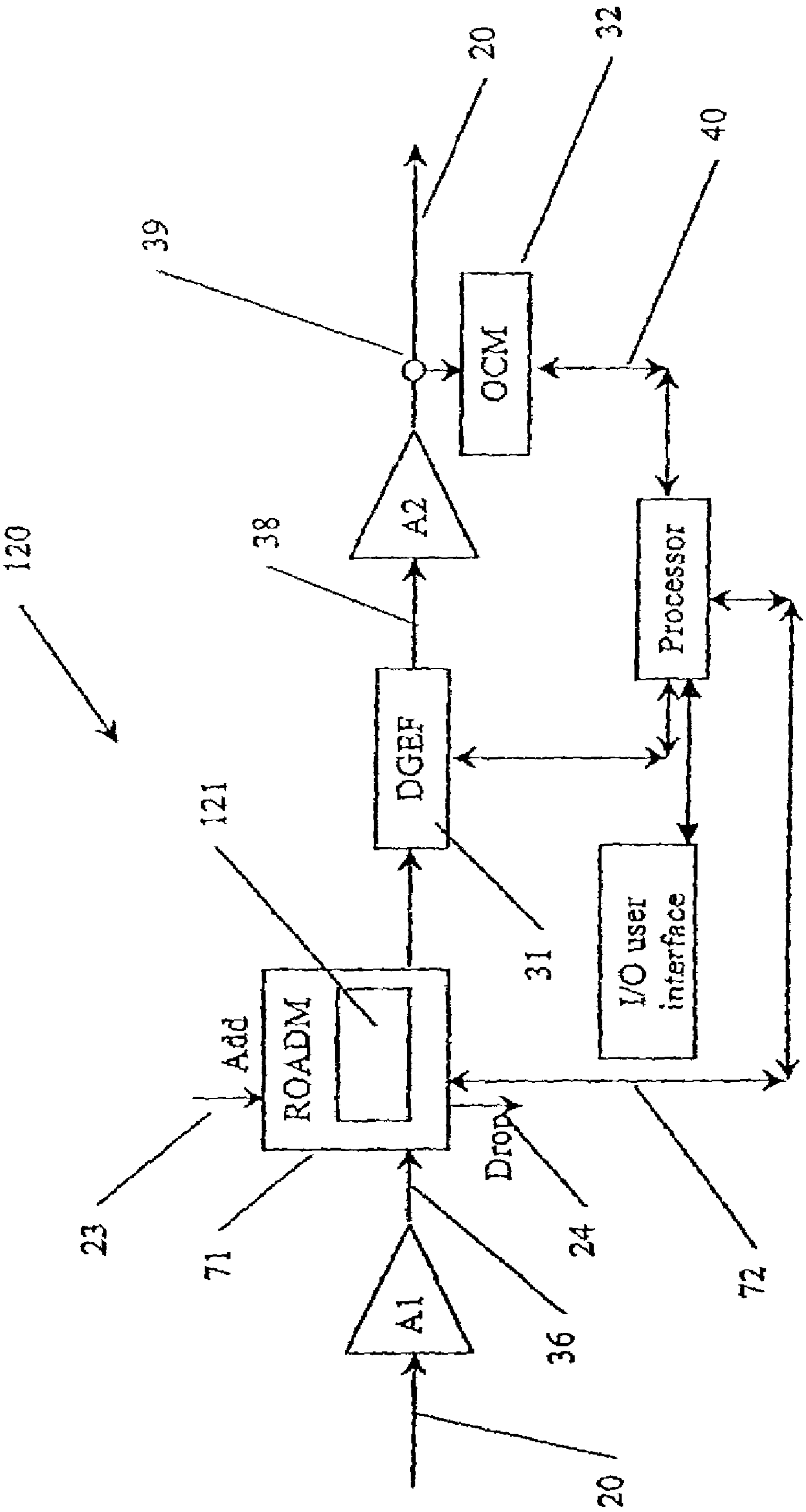
71
72
36
31
105
38
39
32
40
10
102
103
33
104
42

FIGURE 10



120
20
32
40
39
OCM
38
A2
Processor
121
DGEF
Add
ROADM
31
I/O user interface
Drop
23
71
24
72
A1
36
20

FIGURE 11

DYNAMICALLY RECONFIGURABLE OPTICAL SMART NODE

CROSS-REFERENCE TO RELATED APPLICATION

This application claims benefit to provisional patent application Ser. No. 60/310,991, filed Aug. 9, 2001, as well as 60/354,794, filed Feb. 6, 2002 (CiDRA file no. CC-0385).

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to wavelength division multiplexed optical communication systems, and more particularly, to wavelength division multiplexed optical communication systems which include smart nodes having dynamic optical signal manipulation devices in combination with sensing devices and processors to provide real time closed and open loop control of various channels of the network.

2. Description of Related Art

Optical communication networks need links having nodes which include dynamically reconfigurable optical signal manipulation devices in combination with other sensing devices and processors to provide real time closed and open loop control of various channels of network.

SUMMARY OF THE INVENTION

The present invention provides a smart node for use in an optical communications network having optical signals. The smart node features continuous, real time, autonomous feedback and correction with closed and/or open loop control of the optical signals in the optical communications network.

The smart node may include (1) an input amplifier for amplifying the optical signals; (2) an equalization filter for filtering the optical signals in response to a feedback processor signal; (3) a coupler for coupling filtered optical signals; (4) a channel monitor for monitoring a feedback portion of the filtered optical signals; (5) a processor for processing a channel monitor signal from the channel monitor, and providing the feedback processor signal to the equalization filter; and (6) an output amplifier for amplifying the filtered optical signals and providing a dynamically reconfigurable filtered and amplified output signal.

The smart node may also include an input/output user interface for receiving input signals from an outside user and providing user input interface signals to the processor, and for receiving user output signals from the processor and providing user output interface signals to the user. For example, the input/output user interface may include an input user interface for receiving inputs from the outside user for dynamically changing the configuration of the smart node, including timing, traffic or other distinct attribute basis. The input/output user interface may include an output user interface for providing outputs containing information that may cause the outside user to dynamically change the configuration of the smart node. The outputs may include the power levels of various bands or channels, the band or channel spacing, channel drift, the degree of attenuation taking place, and along with other sensors or devices, the amount of dispersion/correction, empty channels, or a combination thereof.

In one embodiment, the output amplifier may be arranged after the coupler, while in an alternative embodiment the output amplifier may be arranged between the equalization filter and the coupler.

The optical signals may include different wavelengths, bands or channels, as well as wavelength division multiplexed signals having various levels of power.

The equalization filter may include a dynamic gain equalization filter that selectively attenuates one or more wavelengths, bands or channels to provide a dynamic gain equalization filter signal, such as a pixelated optical filter, a Mach Zender/Fourier interference filter, acoustic filter, array waveguide or variable optical attenuator.

The channel monitor provides a signal that is indicative of a profile of the power levels of the various wavelengths, channels or bands of the optical signals, and may include a micromirror device, an optical channel monitor (OCM), an optical channel analyzer (OCA), or optical power meter capable of accurately monitoring power levels. The channel monitor may include either a band attenuation mode or a channel-by-channel mode, and may be constructed independent of any particular channel plan.

The processor may include software and hardware capable of dynamically controlling the equalization filter to equalize the power spectrum of wavelengths, channels or bands entering the equalization filter. In operation, upon receiving information from the channel monitor, the processor provides commands to the equalization filter to selectively attenuate preselected wavelengths, channels or bands to provide a preselected spectrum output. The processor may also operate to either attenuate each of the optical signals by substantially the same amount, controllably attenuate the optical signals so that the output amplifier is provided with a preselected gain profile for each of the optical signals, correct the gain tilt of the output amplifier, or a combination thereof.

The coupler may include an optical tap or splitter.

The output amplifier provides a second stage of amplification. The input amplifier, output amplifier or a combination thereof may include an erbium doped fiber amplifier.

The smart node may also include a reconfigurable optical add/drop multiplexer for adding and dropping one or more of the optical signals to and from the smart node. In operation, the processor, either through programmed software, firmware, or by other means, may command the reconfigurable optical add/drop multiplexer to add certain channels and/or drop other certain channels. In one embodiment, the reconfigurable optical add/drop multiplexer is arranged between the input amplifier and the equalization filter. In alternative embodiments, the reconfigurable optical add/drop multiplexer may be arranged either after the coupler, or before the input amplifier.

The smart node may also include a dispersion sensor and a dispersion compensator that combine to provide the ability to dynamically compensate for dispersion within the various bands or channels, as well as a second coupler arranged after the coupler connected to the output amplifier. The dispersion sensor is arranged between the second coupler and the processor, receives a small portion of the filter optical signals from the coupler, and determines the dispersion among the various channels or bands. The dispersion compensator may be arranged between the reconfigurable optical add/drop multiplexer and the equalization filter and compensates for the dispersion of the various channels. The dispersion sensor and the dispersion compensator are controlled by the processor. The dispersion sensor may include a bit error rate detector, an open eye diagram or other devices suitable for detecting chromatic dispersion, polarization mode dispersion or dispersion slope. The dispersion compensation device may include a chromatic dispersion compensator (CDC), a polarization mode dispersion compensator (PMDC) or a dispersion slope compensator. In an alternative embodiment, the dispersion compensator may be arranged between the equalization filter and the output amplifier to compensate for the dispersion of the various channels.

The smart node may also include a wavelength conversion device optically coupled to the reconfigurable optical add/drop multiplexer, which provides for the ability to dynamically add a channel regardless of its wavelength. The wavelength conversion device comprises a tunable laser by controlled the processor.

BRIEF DESCRIPTION OF THE DRAWING

The drawing, not drawn to scale, includes the following Figures:

FIG. **1** is a schematic diagram of a link of a fiber optic communications network having a smart node that is the subject matter of the present invention.

FIG. **2** is a schematic diagram of one embodiment of a smart node according to the present invention.

FIG. **3** is an alternative embodiment of the smart node of FIG. **2** according to the present invention.

FIG. **4** is an alternative embodiment of the smart node of FIG. **3** in accordance with the present invention including dynamic reconfigurability.

FIG. **5** is a graphical representation of one aspect of the reconfigurability of the embodiment of FIG. **4**.

FIG. **6** is a schematic diagram of a smart node including a DGEF, OCM and ROADM in accordance with the present invention.

FIG. **7** is an alternative embodiment of the smart node of FIG. **6** in accordance with the present invention.

FIG. **8** is an alternative embodiment of the smart node of FIG. **6** in accordance with the present invention.

FIG. **9** is a schematic diagram of the smart node including a DGEF, OCM, ROADM, dispersion sensor and dispersion compensator in accordance with the present invention.

FIG. **10** is an alternative embodiment of the smart node of FIG. **9** in accordance with the present invention.

FIG. **11** is an alternative embodiment of the smart node of FIG. **6** including a wavelength conversion device in accordance with the present invention.

In the drawing, similar elements in FIGS. **2**–**4** and **6**–**11** are labelled with similar reference numerals throughout the patent application.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1: The Smart Link

FIG. **1** shows an optical communications network in the form of a smart link generally indicated as **1**. The smart link comprises an express line **20** and at least one pair of terminals **10**, **19** having a plurality of smart nodes **11**–**18** positioned therebetween. The link **1** may be part of a larger link or optical network (not shown). The terminals **10**, **19** may operate for both transmission and receiving of optical signals along the express line **20** which may comprise one or more fiber optic transmission cables. The terminals **10**, **19** provide a number of optical signals, or channels, each at a distinct wavelength as is known in the industry. The terminals may be separated by a relatively large physical distance **21** necessitating amplification at the smart nodes **11**–**18**. As shown, the smart nodes **11**–**18** are separated by a shorter physical distance **22** than the terminals **10**, **19**, typically between 50 and 100 kilometers (about 30 and 60 miles). In addition to various optical signals carried along the express line **20**, between terminals **10** and **19** optical signals on optical lines **23**, **24** may be added and/or dropped from the network at any of the smart nodes **11**–**18**.

As is known, losses occur during the transmission of optical signals along lengths of fiber **20** that result in various network problems. To overcome the losses, optical amplifiers (see FIG. **2**) are positioned in the various nodes along the network. It is in combination with these optical amplifiers that certain configurations of smart nodes, or dynamic nodes, **11**–**18** of the present invention are embodied. Although shown by way of illustration as part of the link **1** in FIG. **1**, a smart node of the present invention is not limited thereto and may simply be a stand-alone device as described herein below.

Moreover, the smart nodes **11**–**18** in accordance with the present invention includes dynamic optical signal manipulation devices in combination with sensing devices and processors to provide real time closed and open loop control of various channels of network. These devices, as will be described more fully herein below, include singularly, or in combination, a dynamic gain equalization filter (DGEF), a dynamic reconfigurable optical add/drop multiplexer (ROADM), an optical cross connect (OXC), an optical channel monitor (OCM), an optical channel analyzer (OCA), a band selector, a wavelength converter (including a tunable laser and a modulator), a chromatic dispersion compensator, a polarization mode dispersion compensator, a scanning Fourier transform interferometer, a dynamic variable multiplexer (V-Mux), a dynamic variable attenuator (VOA) and a tunable bandpass filter (TBF).

FIG. 2: Dynamically Reconfigurable Optical Smart Node

FIG. **2** shows in detail the smart nodes **11**–**18** shown in FIG. **1**. The smart node in FIG. **2** is generally indicated as **30**. The smart node **30** has a pair of optical input and output amplifiers A**1**, A**2**, a DGEF **31** and an OCM **32** arranged in conjunction with a processor **33**, a tap or coupler **39**, and an input/output interface **42**. In the smart node **30**, the DGEF **31**, the OCM **32** and the processor **33** combine to provide a continuous, real time, autonomous feedback and correction in the form of a dynamic closed-loop control in accordance with the present invention, consistent with that described below.

The basic operation of the smart node **30** works as follows:

The input amplifier A**1** receives a plurality of optical signals, each at a respective one of wavelengths λ_1–λ_n typically within a range of 1500 to 1610 nm, or inclusive of channels or bands, such as the C band, L band, as well as the S band. The plurality of optical signals, which may include wave division multiplexed (WDM) signals, enter the smart node **30** via the express line **20** (see also FIG. **1**) and have various levels of power as depicted by an input power spectrum **34**. The input power spectrum **34** is intended to be illustrative of a typical spectrum of individual channels λ_1–λ_n depicted by the plurality of vertical lines representing various power levels. The input amplifier A**1** provides a power gain, typically on an order of 10–35 decibels (Db), to the channels and further typically introduces some gain tilt to the channels. The anomalous gain amplification profile or otherwise uneven amplification, referred to herein as gain tilt to the channels, is depicted by a power spectrum **35**.

The amplified channels are provided to the DGEF **31** via the express line **36** wherein preselected wavelengths, channels or bands are selectively attenuated to provide a dynamic gain equalization filtered signal of a preselected attenuated spectrum as depicted in a preselected spectrum output **37**. The DGEF **31** functions to trim or equalize the individual wavelengths, channels or bands of optical signals, and may comprise any known or contemplated device capable of performing these functions, such as a Mach Zender/Fourier interference filter, acoustic filter, array waveguide or variable optical attenuator. One embodiment of the DGEF **31** is discussed in further detail below.

The amplified and selectively attenuated wavelengths, channels or bands are provided to the output amplifier A**2** via the coupler **39** and a transmission line **38**, and a portion of the filtered signal is directed to the OCM **32** via the coupler **39**.

The OCM **32** provides an optical channel monitor signal, typically an electrical signal, to the processor **33** via line **40** that is indicative of the profile of the power levels of the various wavelengths, channels or bands of the spectrum. The OCM **32** may comprise any OCM, OCA, or optical power meter capable of accurately monitoring the power levels of the spectrum. One embodiment of the OCM **32** is discussed in further detail below.

The processor **33** includes software and hardware capable of dynamically controlling the DGEF **31** to equalize the power spectrum of the wavelengths, channels or bands entering the DGEF **31** via line **36**. The processor **33** upon receiving the information from the OCM **32** provides commands to the DGEF **31** to selectively attenuate preselected wavelengths, channels or bands to provide the preselected spectrum output **37**. The processor **33** variably controls the DGEF **31** with a control signal and attenuates each of the optical signals by substantially the same amount and controllably attenuates the optical signals so that the output amplifier A**2** is provided with a preselected gain profile for each of the optical signals.

In addition to dynamically correcting for the gain tilt of the input amplifier A**1**, the processor **33** also has information relating to the anticipated profile of the gain tilt from the amplifier A**2**. The gain tilt of the amplifier A**2** is corrected by the smart node **30** by commanding the processor **33** to attenuate the spectrum to present an optical signal profile having an inverse of the gain tilt of the amplifier A**2**. The result of this correction is shown in the power spectrum **37**. The signal emerging from the smart node **30** via the express line **20** would be of increased power and substantially equalized as shown in an output power spectrum **41**.

The optical signals are supplied from the DGEF **31** via the transmission line **38** to the amplifier A**2** containing a second segment of active optical fiber, which provides a second stage of amplification. The active optical fiber of the output amplifier A**2** is typically pumped with light from a laser (not shown) at a wavelength, e.g., 1480 nm, which is different than the optical signal wavelengths λ_1–λ_n. In addition, the second segment of active optical fiber is pumped in such a manner and has an appropriate composition that yields a high power output to the express line **20**. Although the various power of the input and output amplifiers A**1**, A**2** are given by way of example it is important to note that the combination of the amplifiers and various components of the smart node **30** must yield a signal having sufficient power for the transmission and use contemplated.

The output amplifier A**2** provides a power gain, typically on the order of 10–35 Db, to the channels and, similar to the input amplifier A**1**, typically introduces some gain tilt or otherwise uneven amplification to the channels. The power of optical signals provided to the output amplifier A**2** is typically significantly more than the power of optical signals supplied to the OCM **32**. For example, the power at output supplied to the OCM **32** can be approximately 2% of the power depicted in the power spectrum **37**, while the power supplied to the output amplifier A**2** can be approximately 98% of the power depicted in power spectrum **37** (neglecting coupler loss, for simplicity).

The pair of optical input and output amplifiers A**1**, A**2** may comprise an erbium doped fiber amplifier (EDFA) or other known amplifier. In an EDFA, the fiber is typically doped with the fluorescent material, erbium, and pumped with light at a wavelength different than the amplified optical signals, for example, 980–1480 nanometers (nm). A pump laser (not shown) is typically coupled to the active optical fiber of amplifiers in a known manner to excite the fluorescent material. The pump light is of sufficient magnitude and the composition of active optical fiber is such that the optical signals output from A**1** (and A**2** similarly) are amplified with high gain, but with relatively little noise.

In particular, the DGEF **31** may comprise a pixilated optical filter as disclosed in copending, commonly assigned, U.S. Patent Application Ser. No. 60/281,079, entitled "Reconfigurable Pixelated Optical Filter," filed Apr. 3, 2001, as well as U.S. Patent Application Ser. No. 60/311,002, filed Aug. 8, 2001, entitled "Dynamic Optical Filter having an Array of Micro-Mirrors," filed Aug. 8, 2001; Ser. No. 10/115,647, entitled "Dynamic Optical Filter Having a Spatial Light Modulator", filed Apr. 3, 2002; Ser. No. 10/159,370, entitled "Optical Channel Monitor", filed May 31, 2002; Ser. No. 60/332,318, entitled "Chromatic dispersion compensation device having an array of micromirrors", filed Nov. 16, 2001; Ser. No. 60/325,065, entitled "Reconfigurable Optical Add/Drop Multiplexer having an Array of micromirrors", filed Sep. 25, 2001; Ser. No. 60/325,068, entitled "Optical Cross-connect having an array of micromirrors", filed Sep. 21, 2001; Ser. No. 60/325,066, entitled "Optical Channel monitor having an Array of Micromirros", filed Sep. 25, 2001; Ser. No. 60/325,064, entitled "Optical Interleaver/deinterleaver device having an array of micromirrors", filed Sep. 25, 2001; Ser. No. 60/344,585, entitled "Optical blocking filter having an array of micromirrors", filed Dec. 28, 2001; Ser. No. 60/352,297, entitled "Multifunctional optical device having spatial light modulator", filed Jan. 28, 2002; Ser. No. 10/115,648, entitled "Variable Optical Source", filed Apr. 3, 2002; Ser. No. 10/120,617, entitled "Adaptive filter/attenuator using pixilated reflector", filed Apr. 11, 2002, the disclosures all of which are hereby incorporated by reference in their entireties. In operation, the OCM **32** would provide a signal to the processor **33** that a certain channel centered at wavelength λ_2 needs to be attenuated. In order to attenuate the optical channel centered at wavelength λ_2, the processor **33** commands a predetermined number of micro-mirrors disposed in the area illuminated by the optical channel at λ_2 to tilt to reflect a portion of the light of the optical channel away from the return path. In this manner, the OCM **32** provides signals indicative of the power profile of the entire spectrum, including the anticipated gain tilt of the output amplifier A**2**, and the processor **33** in turn commands the DGEF **31** to selectively attenuate the channels or bands having power levels above a predetermined threshold in order to provide the preselected channel profile depicted in the spectrum **37**.

In addition, the OCM **32** may comprise a micro-mirror device as set forth in the copending U.S. patent applications referenced above. In such a micro-mirror based OCM **32**, the micro-mirrors may be tilted such that all but one optical channel is dropped, and therefore, a single optical channel is reflected back through the optics making the device useful as either an OCM or an optical power monitor (OPM). The output optical signal may be provided to a photodetector or charge coupled device (CCD) array to determine certain characteristics of the optical channel(s), such as power, wavelength, signal-to-noise ratio, etc. In such a configuration, a controller (not shown) of the OCM **32** sequentially tilts each group of the micro-mirrors illuminated by each optical channel to sequentially return each optical channel back to the optics, to effectively scan across the spectral range to analyze each optical channel. The OCM **32** based on the micro-mirror device is capable of switching between a first and second position in approximately 16 microseconds.

The coupler **39** may be a conventional optical tap or splitter, which supplies each of the plurality of optical signals to both the OCM **32** and the output amplifier A**2**.

In addition, the smart node **30** may include an input/output (I/O) user interface **42** to remotely link the smart node **30** to the outside world. The I/O interface **42** enhances the usefulness of smart node **30** by, for instance, allowing for external motoring of the network's health and correction thereto via remote manipulation of the node, and the network thereby, by a network manager.

FIG. **3**: The Smart Node **50**

FIG. **3** shows an alternative embodiment of a smart node generally indicated as **50**, in which the amplifier A2 is arranged after the coupler **39**.

In operation, the OCM **32** is positioned after both the input and output amplifiers A**1** and A**2** and therefore the gains and gain tilt, among other signal inequities, of the A**1**, A**2** amplifiers are determined, and adjusted by varying the attenuation the various optical channels via the DGEF **31** so that output spectrum **41** corresponds to a uniform spectral gain. As shown, the coupler **39** taps a portion of the power of the optical signals from transmission line **20** to supply the OCM **32**. Consistent with that discussed above, the OCM **32** provides an output signal indicative of the power levels of the various wavelengths, channels or bands of the spectrum. The processor **33** analyzes the output of the OCM **32** and through proper algorithms outputs a control command to the DGEF **31** to attenuate certain of the signals to output the predetermined spectrum **37**. In the embodiment shown, the gain tilt of the output amplifier A**2** is dynamically controlled wherein the DGEF **31** responds to the output from the OCM **32** and provides the output spectrum **37** having an inverse of the gain tilt of the output A**2**. In this embodiment, the smart node **50** dynamically compensates for any drift in the input and output amplifiers A**1**, A**2**, loss in the various components or fibers or other power fluctuations, and provides the output spectrum **41** having a substantially uniform gain.

FIG. **4**: The Smart Node **60**

FIG. **4** shows a smart node generally indicated as **60**, in which the OCM **32** has band and channel-by-channel attenuation modes and the I/O user interface **42** has user input/output functionality. The smart node **60** takes particular advantage of the dynamic agility of the underlying design by allowing for operation not only in a band attenuation mode or channel-by-channel manipulation/attenuation mode as described herein above, but also by accommodating the varying spacing between bands or channels.

For example, the DGEF **31** and the OCM **32** may be controlled through an input user interface **43** of the I/O user interface **42** to the processor **33**, or other processor means (not shown), to operate in the channel-by-channel manipulation mode so that the output from the smart node **60** would yield an equalized spectrum **41** across all channels. The OCM **32** monitors at least the power level of each band and provides an output monitoring signal indicative thereof to the processor **33** via the line **40**. The processor **33** through suitable algorithms commands the DGEF **31** to attenuate certain channels to provide the output spectrum **37** which is typically the inverse of the gain tilt of the product of A**1** and A**2** (i.e. A**1**×A**2**).

In addition, the format of the channel count and/or spacing of the DGEF **31** and the OCM **32** could be controlled through the input user interface **43** to the processor **33** so that the channel spacing differs across the spectrum. The channel plan independence may be accomplished using a micro-mirror based DGEF and OCM as described herein above wherein the various channel spacings are accommodated by utilizing different numbers and positions of micro-mirrors. In one such embodiment, the DGEF **31** and the OCM **32** may share a common digital micro-mirror device (DMD). In such a smart node **60**, the performance is spectrally independent of the underlying channel plan.

The present invention is described in a specific example with reference to FIG. **5** wherein two distinct channel spacings are accommodated. In this particular example, channels centered about wavelengths λ_1–λ_5 are each positioned on approximately 1000 mirrors at a channel spacing of 50 Ghz and channels centered at wavelengths λ_6–λ_n are positioned on approximately 500 mirrors at a channel spacing of 25 Ghz. In this configuration, the OCM **32** monitors at least the power level and channel wavelength position of channel and provides an output signal indicative thereof to the processor **33** via the line **40**.

The processor **33** through suitable algorithms commands the DGEF **31** to attenuate certain of the channels to provide an output spectrum **37** which is typically the inverse of the gain tilt of the product of input and output amplifiers A**1** and A**2** (A**1**×A**2**). The resultant output of the smart node **60** would yield a substantially equalized gain of all channels λ_1–$\lambda_n$at the various predetermined channel spacing.

Further, the DGEF **31** and the OCM **32** (and smart node **60** thereby) could be controlled through the processor **33** to operate in the band-by-band manipulation mode so that the output from smart node **60** would yield an equalized gain spectrum **41** across all bands. In this case, the OCM **32** monitors at least the power level of each band and provides an output signal indicative thereof to the processor **33** via the line **40**. The processor **33** through suitable algorithms commands the DGEF **31** to attenuate certain bands to provide the output spectrum **37** which is typically the inverse of the gain tilt of the product of amplifiers A1 and A2 (A**1**×A**2**) on a band by band basis.

The profile of the output spectrum **41** of the smart node **60** may also be advantageously reconfigured through the input user interface **43**. For example, if certain channels or bands need not be attenuated for certain predetermined reasons those particular channels or bands could be selectively treated through discrete commands by the processor **33**. In particular, if it were determined that a particular channel at λ_j required maximum gain as transmitted from the smart node **60**, then an input through the input user interface **43** could allow for minimal or diminished attenuation of channel λ_j, The output spectrum **41** in this particular instance would not be substantially equalized but will be of a predetermined profile to match the requirements of the input to the smart node **60** via the input user interface **43**. Other various predetermined output spectra **41** are contemplated by the present invention such as if the link includes the S band and there is gain tilt from a Raman amplifier or other S-band amplifier.

In the above examples, the input user interface **43** is described as receiving discrete input from an outside user. However, the input user interface **42** is illustrative of an input into the smart node **60** and may take on various forms such as a separate processor input or one that is integral to the smart node **60**. For instance, an input to the smart node **60** may take place on a timing, traffic or other distinct attribute basis to dynamically change the configuration as contemplated by the various embodiments of the present invention.

The smart node **60** (as well as any other contemplated embodiment) may also include an output user interface **44** in addition to the input user interface **43**. The output user interface **44** may advantageously allow an operator or system to monitor the operation and or health of the smart node **60**, link **1** (FIG. **1**) or the network (not shown). For instance, the output user interface **44** may output the power levels of the various bands or channels, the band or channel spacing, channel drift, the degree of attenuation taking place, and along with other sensors or devices (as discussed herein) the amount of dispersion/correction, or empty channels, etc.

Such output may also be useful for downstream manipulation of the signals by other various smart nodes or links. For instance, if it were reported to the smart node **11** of FIG. **1** that a channel was missing at λ_2 then a channel could be added at that particular wavelength at the smart node **13** comprising an ROADM via line **23** as will be described more fully below. Alternatively, if the channel were found to be missing due to a network error at node **11**, a diagnostic routine could be run at the network level to determine the cause for the missing channel. In addition, the OCM **32** of the smart node **11** could determine that a particular channel was missing and report that error to the network via the input user interface **43**.

The scope of the invention is intended to include other configurations in addition to those discussed above in relation to FIG. **4**. The above configuration can also be utilized as a tunable filter and can be configured to fulfill various applications. In its most fundamental form the smart node **60** may comprise an arbitrary filter function formed by actuating components of a micro-mirror device corresponding to the spectral filter function desired. The light from these mirrors is collected and directed to an output fiber where it can be acted upon by a variety of devices. Due to the very fast actuation times associated with MEMS micro-mirror devices, this operation can be performed on time scales faster than milliseconds. In addition, the micro-mirrors can be actuated in a sequential fashion to permit scanning of the input optical spectrum across the output fiber. A detector located at this position could serve to detect the optical power and provide an OCM or OSA functionality. Various algorithms could be employed to calculate values for wavelength, power and OSNR from the detected power. One very powerful feature of this system is its ability to vary the filter function. A variable bandwidth (VBW) filter function could be obtained that could change depending on the requirements of the system or network. Along these lines a single device could be configured to operate on 100 Ghz or 50 Ghz spaced channels. In addition, if the variable bandwidth feature is utilized, a system that is mixed with various channel spacing could be interrogated. An additional example of the potential use of the variable bandwidth feature is a combined OSA and drop unit. In this system a wide BW filter would be used to drop a channel to minimize the degradation of the channel. In the OCA mode a narrow filter function would be employed to provide accurate powers, wavelength and optical signal-to-noise ratio (OSNR).

FIG. **6**: The Smart Node **70**

FIG. **6** shows an embodiment of a smart node generally indicated as **70** that includes an ROADM **71** arranged between the amplifier A**1** and the DGEF **31** and controlled by the processor **33**. ROADM's are generally known in the industry and serve to allow the dynamic addition and removal of a preselected channel(s) from the express line **20**. In addition to the ability of the smart node **70** to provide all of the spectra manipulation discussed herein, the smart node **70** further allows the dynamic reconfigurability of the ROADM **71** and the subsequent equalization and other manipulation of the added channel(s).

In operation, the OCM **32** senses channel presence, wavelengths and power levels and sends a signal indicative of such information to the processor **33** via line **40**. The processor **33** then either through programmed software, firmware, or by other means, commands the ROADM **71** to add certain channels via an optical line **23** and/or drop other certain channels via an optical line **24**. In addition, the I/O user interface **42** may be used to provide the output from the processor **33** regarding channel count, spacing, presence and further provide the smart node **70** with the ability to reconfigure the channels as described herein above.

In another aspect of the present invention, the processor **33** may further command the ROADM **71** via line **72** to add and/or drop certain channels based on the output from the I/O user interface **42** or from an input from a user or other smart node **11**–**18**, link **1** (FIG. **1**), or network (not shown).

As discussed, the smart node of the embodiment allows for the manipulation and trimming/equalization of channels or bands added via the optical line **23** but does not provide any signal conditioning to the dropped channels exiting the smart node **70** via the optical line **24**. In addition, the channels added via the optical line **23** do not benefit from the first stage of amplification provided by the amplifier A**1**.

In this particular embodiment, the smart node **70** may also include the ability to reconfigure the operation of the DGEF **31** to ignore the possibility that the added channel(s) may be weaker than others. In so doing, for example, the DGEF **31** may work to equalize all other channels except the added channel(s) and provide an output spectrum **41** that is somewhat higher in overall gain than would otherwise be possible if the added channel(s) were considered.

In embodiments of the present invention that utilize DMD technology, a single DMD chip can be multiplexed to perform multiple manipulation functions at the same time or on the same "real estate". For instance, in one particular embodiment of a DGEF approximately 20% of the DMD chip may be utilized, leaving about 80% of the chip for other functions.

FIG. **7**: The Smart Node **80**

FIG. **7** shows a smart node generally indicated as **80**, in which the ROADM **71** is arranged after the amplifier A**2** and the coupler **39** and controlled by the processor **33**. The smart node **80** is an alternative embodiment to that shown in FIG. **6**, in which the ROADM **71** is arranged after the amplifier A**1**. In the smart node **80**, all the functionality similar to the smart nodes **60** (FIG. **4**) and the smart node **70** (FIG. **6**) is preserved except for the ability to equalize the channels added via line **23**. In FIG. **7**, the added channel(s) do combine with the output spectrum and exit the node via the express line **20**.

FIG. **8**: The Smart Node **90**

FIG. **8** shows a smart node generally indicated as **90**, in which the ROADM **71** is arranged prior to the first stage of amplification A**1** and controlled by the processor **33**. In this particular embodiment, all of the functionality in terms of signal manipulation and configuration control and of smart nodes **60** (FIG. **4**), **70** (FIG. **6**) with the additional enhancement of introducing added channel(s) via the optical line **23** prior to the first stage of amplification A**1**. In this particular embodiment the DGEF **31**, the OCM **32** and the processor **33** cooperate to provide an output spectrum **41** having a maximum overall gain for all channels including those optical signals added via the optical line **23**.

FIG. **9**

FIG. **9** shows a smart node generally indicated as **100** that includes a dispersion sensor **103** and a dispersion compensator **105**. The dispersion sensor **103** is arranged between a coupler **101** and the processor **33** after the amplifier A**1**. The dispersion compensator **105** is arranged between the ROADM **71** and the DGEF **31** and controlled by the processor **33**. As is known, most of the various components along a link or fiber in a link contribute in some way to dispersion. The dispersion sensor **103** and the dispersion compensator **105** combine to provide the ability to dynamically compensate for dispersion within the various bands or channels.

In operation, the smart node **100** includes the optical coupler **101**, similar to optical coupler **39** described herein above, to direct a small portion of the output spectrum **41** via the line **102** to the dispersion sensor **103**. The dispersion sensor **103** determines the dispersion among the various channels or bands and provides an output signal indicative of such dispersion to the processor **33** via a line **104**. The processor **33** then either through programmed software, firmware, or by other means, commands the dispersion compensator **105** to compensate the dispersion of the various channels, including those channel(s) added by the ROADM **71**. The smart node **100** is dynamically reconfigurable to provide a predetermined output spectrum **41** to the express line **20** that manipulates the signals as described for the various embodiments above with the additional ability to dynamically compensate for various dispersion effects. As a person skilled in the art would appreciate, the ROADM **71** may also be arranged prior to the amplifier Al as described herein above without departing from the scope of the present invention.

The dispersion sensor **103** may comprise a bit error rate detector, an open eye diagram or other known or contemplated devices that are capable of detecting chromatic dispersion (or the absence thereof), polarization mode dispersion or dispersion slope accurately enough to enable the present invention.

The dispersion compensation device **105** may comprise a chromatic dispersion compensator (CDC), a polarization mode dispersion compensator (PMDC) or a dispersion slope compensator.

FIG. **10**

FIG. **10** shows a smart node generally indicated as **110** which is an alternative embodiment of the present invention. In this embodiment, the dispersion compensator **105** is arranged between the DGEF **31** and the amplifier A**2**. In this particular embodiment, all the functionality of the smart node **100** of FIG. **9** is preserved. In addition, the dispersion compensator **105** in combination with dispersion sensor **103** accommodates any dispersion caused by the various components within the smart node **110**.

FIG. **11**

FIG. **11** shows a smart node generally indicated as **120** that includes a wavelength conversion device **121** optically coupled to the ROADM **71**. In this particular embodiment, the smart node **120** has the ability to dynamically add channel(s) to the express line **20** regardless of their wavelength.

The wavelength conversion device **121** may comprise a tunable laser that is commanded by processor **33**. The ROADM **71** comprises a device wherein the channel drop portion of a micro-mirror based device permits a single channel to be selected that will be wavelength converted and dropped from the full dense wavelength division multiplexed (DWDM) data stream from the express line **20**. The tunable laser permits any new wavelength to be selected and sent out of the device.

In one aspect of this particular configuration, the OCM **32** operates as set forth herein above and provides a signal indicative of channel power and wavelength. The processor **33** then, prompted by a request or need to add another channel via ROADM **71** directs wavelength converter **121** to add the channel(s) to the express line **20** at an available wavelength. With the smart node **120** operating in this manner a channel may be added to the link **1** (FIG. **1**) without conflicting with another channel already operating on the link.

In another aspect of the invention, the smart node **120** includes the capability of dropping a channel via the line **24** as described herein before. The added advantage of the wavelength converter **121** is that the processor **33** may command the conversion of any particular channel to be dropped to an appropriate wavelength for addition to another node, smart node, link or other area of a network as appropriate.

THE SCOPE OF THE INVENTION

While the foregoing invention has been described in terms of the embodiments discussed above, numerous variations are possible. Accordingly, modifications and changes such as those suggested above, but not limited thereto, are considered to be within the scope of the following claims.

The invention claimed is:

1. A smart node for use in an optical communications network having optical signals, the smart node providing continuous, real time, autonomous feedback and correction with closed and/or open loop control of the optical signals in the optical communications network, the smart node comprises:

an equalization filter for filtering the optical signals in response to a feedback processor signal;

a coupler for coupling filtered optical signals;

a channel monitor for monitoring a feedback portion of the filtered optical signals; and a processor for processing a channel monitor signal from the channel monitor, and providing the feedback processor signal to the equalization filter.

2. A smart node according to claim **1**, wherein the smart node further comprises:

an input/output user interface for receiving input signals from a user and providing user input interface signals to the processor, and for receiving user output signals from the processor and providing user output interface signals to the user.

3. A smart node according to claim **1**, wherein the optical signals include different wavelengths, bands or channels.

4. A smart node according to claim **1**, wherein the optical signals include wavelength division multiplexed signals having various levels of power.

5. A smart node according to claim **1**, wherein the equalization filter is a dynamic gain equalization filter that selectively attenuates one or more wavelengths, bands or channels to provide a dynamic gain equalization filter signal.

6. A smart node according to claim **5**, wherein the dynamic gain equalization filter is either a pixelated optical filter, a Mach Zender/Fourier interference filter, acoustic filter, array waveguide or variable optical attenuator.

7. A smart node according to claim **1**, wherein the channel monitor signal is indicative of a profile of the power levels of the various wavelengths, channels or bands of the optical signals.

8. A smart node according to claim **1**, wherein the channel monitor is a micromirror device, an optical channel monitor (OCM), an optical channel analyzer (OCA), or optical power meter capable of accurately monitoring power levels.

9. A smart node according to claim **1**, wherein the processor includes software and hardware capable of dynamically controlling the equalization filter to equalize the power spectrum of wavelengths, channels or bands entering the equalization filter.

10. A smart node according to claim **1**, wherein the processor, upon receiving information from the channel monitor, provides commands to the equalization filter to selectively attenuate preselected wavelengths, channels or bands to provide a preselected spectrum output.

11. A smart node according to claim **1**, wherein the processor attenuates each of the optical signals by substantially the same amount and controllably attenuates the optical signals so that the output amplifier is provided with a preselected gain profile for each of the optical signals.

12. A smart node according to claim **1**, wherein the processor corrects the gain tilt of the output amplifier.

13. A smart node according to claim **1**, wherein the output amplifier provides a second stage of amplification.

14. A smart node according to claim **1**, wherein the coupler is an optical tap or splitter.

15. A smart node according to claim **1**, wherein the channel monitor has either a band attenuation mode or a channel-by-channel mode.

16. A smart node according to claim **2**, wherein the channel monitor has either a band attenuation mode or a channel-by-channel mode.

17. A smart node according to claim **16**, wherein the equalization filter and the channel monitor share a common digital micro-mirror device.

18. A smart node according to claim **2**, wherein the input/output user interface includes an input user interface for receiving inputs from an outside user for dynamically changing the configuration of the smart node, including timing, traffic or other distinct attribute basis.

19. A smart node according to claim **2**, wherein the input/output user interface includes an output user interface for providing outputs containing information that may cause an outside user to dynamically change the configuration of the smart node.

20. A smart node according to claim **2**, wherein the outputs include the power levels of various bands or channels, the band or channel spacing, channel drift, the degree of attenuation taking place, and along with other sensors or devices, the amount of dispersion/correction, empty channels, or a combination thereof.

21. A smart node according to claim **1**, wherein the smart node includes a reconfigurable optical add/drop multiplexer for adding and dropping one or more of the optical signals to and from the smart node.

22. A smart node according to claim **21**, wherein the processor either through programmed software, firmware, or by other means, commands the reconfigurable optical add/drop multiplexer to add certain channels and/or drop other certain channels.

23. A smart node according to claim **1**, wherein the smart node comprises:

an input amplifier for amplifying the optical signals; and

an output amplifier for amplifying the filtered optical signals and providing a dynamically reconfigurable filtered and amplified output signal.

24. A smart node according to claim **1**, wherein the smart node comprises:

an input amplifier for amplifying the optical signals.

25. A smart node according to claim **1**, wherein the smart node comprises:

an output amplifier for amplifying the filtered optical signals and providing a dynamically reconfigurable filtered and amplified output signal.

26. A smart node according to claim **23**, wherein the input amplifier, output amplifier or a combination thereof is an erbium doped fiber amplifier.

27. A smart node according to claim **23**, wherein the output amplifier is arranged between the equalization filter and the coupler.

28. A smart node according to claim **27**, wherein the smart node includes a reconfigurable optical add/drop multiplexer for adding and dropping one or more of the optical signals to and from the smart node.

29. A smart node according to claim **28**, wherein the reconfigurable optical add/drop multiplexer is arranged between the input amplifier and the equalization filter and controlled by the processor.

30. A smart node according to claim **29**, wherein the reconfigurable optical add/drop multiplexer provides subsequent equalization and other manipulation of an added channel.

31. A smart node according to claim **27**, wherein the reconfigurable optical add/drop multiplexer is arranged after the coupler and controlled by the processor.

32. A smart node according to claim **27**, wherein the reconfigurable optical add/drop multiplexer is arranged before the input amplifier and controlled by the processor.

33. A smart node according to claim **29**, wherein the smart node includes a dispersion sensor and a dispersion compensator that combine to provide the ability to dynamically compensate for dispersion within the various bands or channels.

34. A smart node according to claim **33**, wherein

the smart node includes a second coupler arranged after the coupler connected to the output amplifier;

the dispersion sensor is arranged between the second coupler and the processor, receives a small portion of the filter optical signals from the coupler, and determines the dispersion among the various channels or bands; and

the dispersion compensator is arranged between the reconfigurable optical add/drop multiplexer and the equalization filter and compensates for the dispersion of the various channels.

35. A smart node according to claim **34**, wherein the dispersion sensor and the dispersion compensator are controlled by the processor.

36. A smart node according to claim **34**, wherein the dispersion sensor comprises a bit error rate detector, an open eye diagram or other devices suitable for detecting chromatic dispersion, polarization mode dispersion or dispersion slope.

37. A smart node according to claim **34**, wherein the dispersion compensation device comprises a chromatic dispersion compensator (CDC), a polarization mode dispersion compensator (PMDC) or a dispersion slope compensator.

38. A smart node according to claim **33**, wherein

the smart node includes a second coupler arranged after the coupler connected to the output amplifier;

the dispersion sensor is arranged between the second coupler and the processor, receives a small portion of the filter optical signals from the coupler, and determines the dispersion among the various channels or bands; and

the dispersion compensator is arranged between the equalization filter and the output amplifier and compensates for the dispersion of the various channels.

39. A smart node according to claim **28**, wherein the smart node includes a wavelength conversion device optically coupled to the reconfigurable optical add/drop multiplexer.

40. A smart node according to claim **39**, wherein the wavelength conversion device provides for the ability to dynamically add a channel regardless of its wavelength.

41. A smart node according to claim **39**, wherein the wavelength conversion device comprises a tunable laser controlled by the processor.

42. A smart node according to claim **39**, wherein the reconfigurable optical add/drop comprises a device for providing a single channel to be selected that will be wavelength converted and dropped from a full dense wavelength division multiplexed data stream.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 7,123,833 B2
APPLICATION NO. : 10/216000
DATED : October 17, 2006
INVENTOR(S) : Szczepanek et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 6, line 35 “Micromirros” should be -- Micromirrors --

Signed and Sealed this

Twenty-third Day of March, 2010

David J. Kappos

David J. Kappos
Director of the United States Patent and Trademark Office

EXHIBIT C

US007126740B2

(12) United States Patent
Szczepanek et al.

(10) **Patent No.: US 7,126,740 B2**
(45) **Date of Patent: Oct. 24, 2006**

(54) **MULTIFUNCTIONAL OPTICAL DEVICE HAVING A SPATIAL LIGHT MODULATOR WITH AN ARRAY OF MICROMIRRORS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **10/353,772**

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Related U.S. Application Data

(63) Continuation-in-part of application No. 10/327,695, filed on Dec. 19, 2002, now Pat. No. 6,956,687, and a continuation-in-part of application No. 10/298,264, filed on Nov. 15, 2002, now Pat. No. 6,934,069, and a continuation-in-part of application No. 10/255,141, filed on Sep. 25, 2002, now abandoned, and a continuation-in-part of application No. 10/255,133, filed on Sep. 25, 2002, and a continuation-in-part of application No. 10/255,132, filed on Sep. 25, 2002, now Pat. No. 6,922,277, and a continuation-in-part of application No. 10/255,129, filed on Sep. 25, 2002, now abandoned, and a continuation-in-part of application No. 10/216,000, filed on Aug. 8, 2002, and a continuation-in-part of application No. 10/120,617, filed on Apr. 11, 2002, now abandoned, and a continuation-in-part of application No. 10/115,648, filed on Apr. 3, 2002, and a continuation-in-part of application No. 10/115,647, filed on Apr. 3, 2002.

(60) Provisional application No. 60/365,741, filed on Mar. 18, 2002, provisional application No. 60/365,682, filed on Mar. 18, 2002, provisional application No. 60/365,461, filed on Mar. 18, 2002, provisional application No. 60/365,446, filed on Mar. 18, 2002, provisional application No. 60/354,794, filed on Feb. 6, 2002, provisional application No. 60/352,297, filed on Jan. 28, 2002, provisional application No. 60/344,585, filed on Dec. 28, 2001, provisional application No. 60/332,319, filed on Nov. 16, 2001, provisional application No. 60/332,318, filed on Nov. 16, 2001, provisional application No. 60/325,068, filed on Sep. 25, 2001, provisional application No. 60/325,066, filed on Sep. 25, 2001, provisional application No. 60/325,065, filed on Sep. 25, 2001, provisional application No. 60/325,064, filed on Sep. 25, 2001, provisional application No. 60/310,991, filed on Aug. 9, 2001, provisional application No. 60/311,002, filed on Aug. 8, 2001, provisional application No. 60/283,197, filed on Apr. 11, 2001, provisional application No. 60/281,079, filed on Apr. 3, 2001.

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(52) **U.S. Cl.** **359/290**; 359/298; 385/18; 398/81; 398/86; 398/87; 398/88

(58) **Field of Classification Search** 359/290, 359/301, 302, 315, 318, 320, 618, 629, 634, 359/639, 850, 872, 223–224, 291, 107, 108, 359/298; 385/11, 15–18, 24, 1–3, 31, 10, 385/36, 37; 398/86–88, 81, 82, 84
See application file for complete search history.

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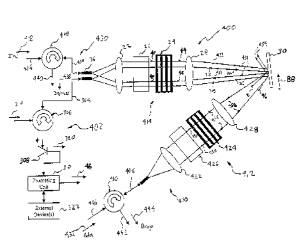

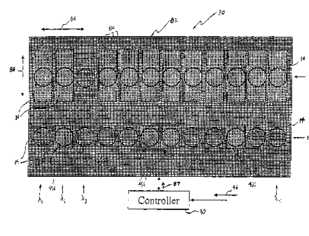

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Assistant Examiner—Joseph Martinez

(57) **ABSTRACT**

A reconfigurable multifunctional optical device has an optical arrangement for receiving an optical signal, each having optical bands or channels, and a spatial light modulator for reflecting the at least one optical signal provided thereon. The optical arrangement features a free optics configuration with a light dispersion element for spreading each optical signal into one or more respective optical bands or channels for performing separate optical functions on each optical signal. The spatial light modulator includes a micro-mirror device with an array of micro-mirrors, and the respective optical bands or channels reflect off respective micro-mirrors. The free optics configuration includes a common set of optical components for performing each separate optical function on each optical signal. The separate optical functions reflect off separate non-overlapping areas on the spatial light modulator. The separate optical functions include optical switching, conditioning or monitoring functions.

51 Claims, 26 Drawing Sheets

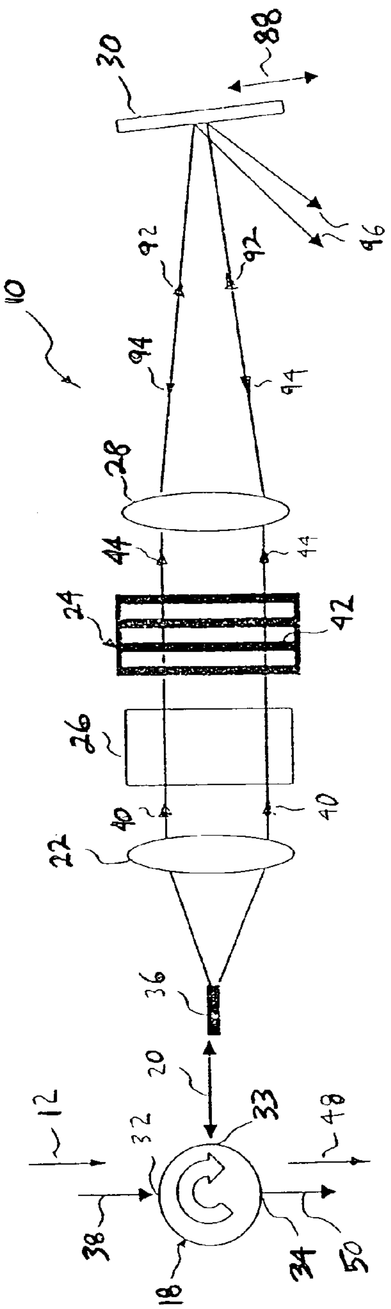


Fig. 1

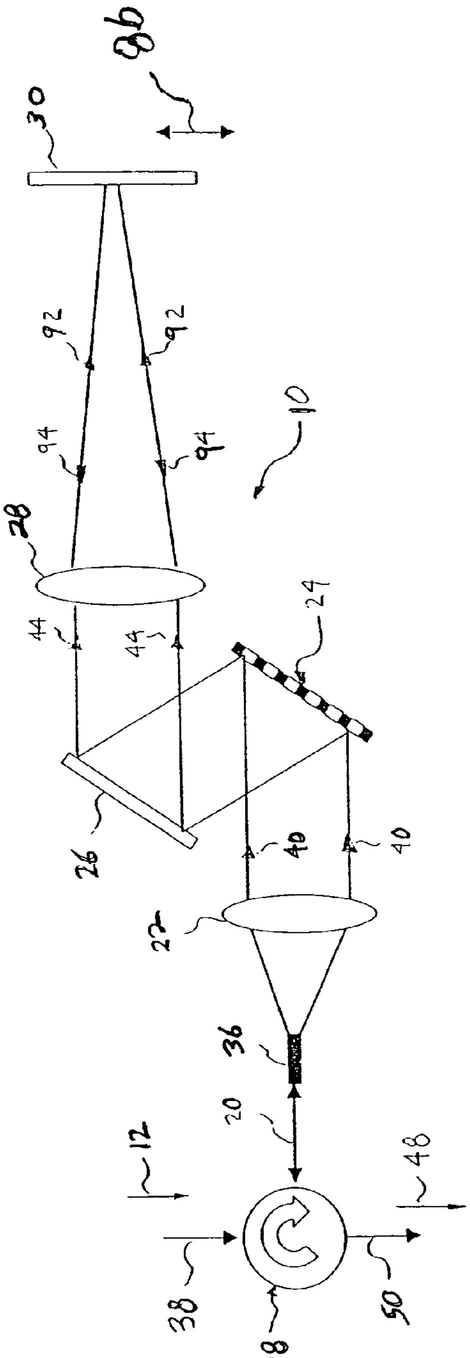


Fig. 2

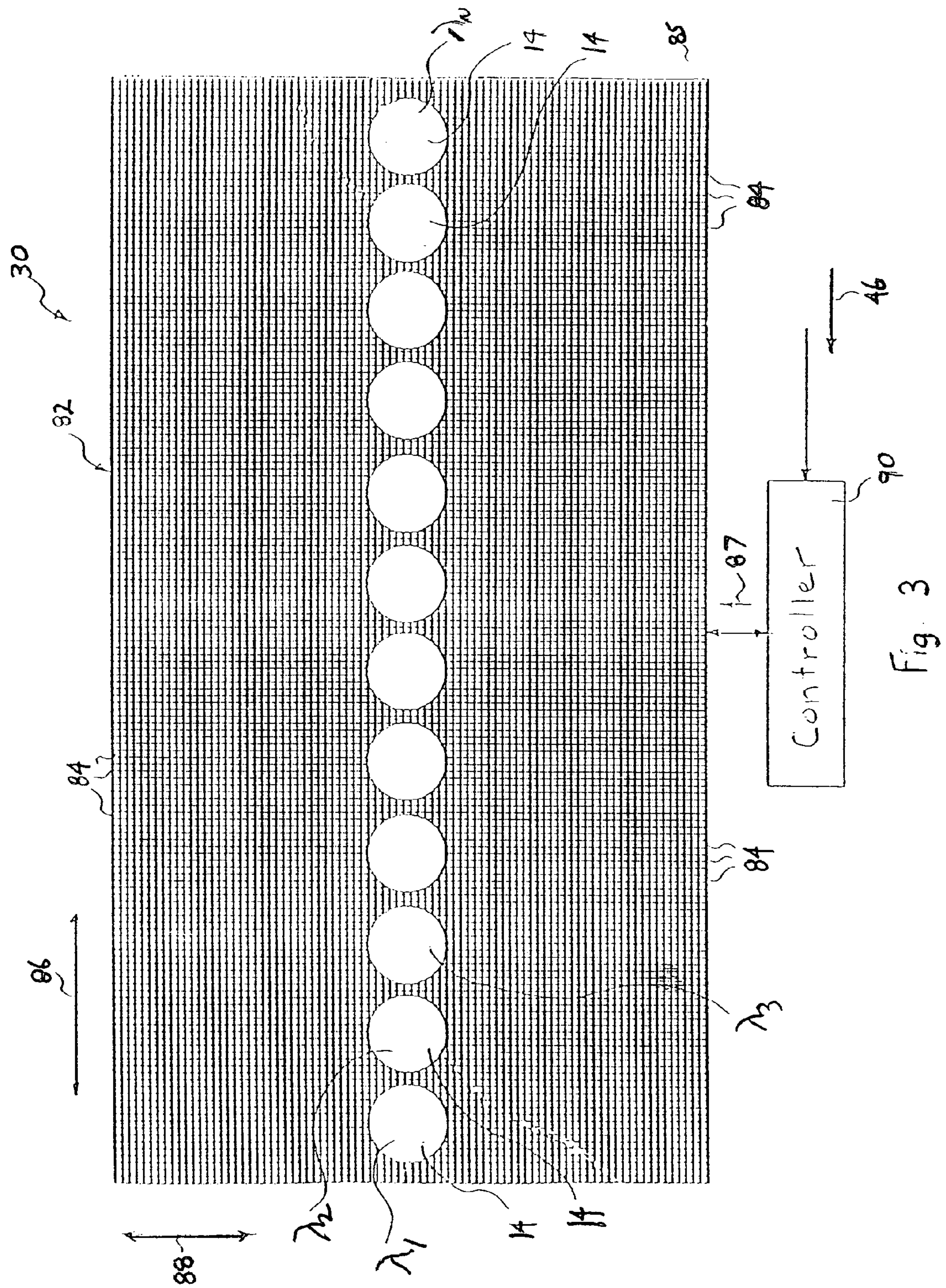


Fig. 3

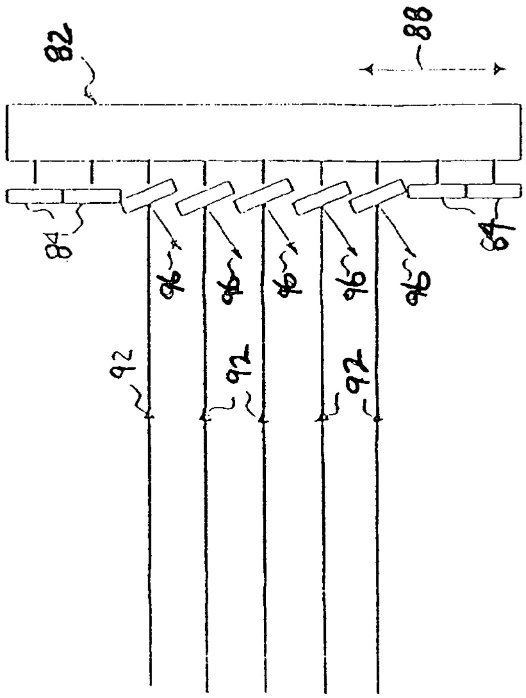


Fig. 4b

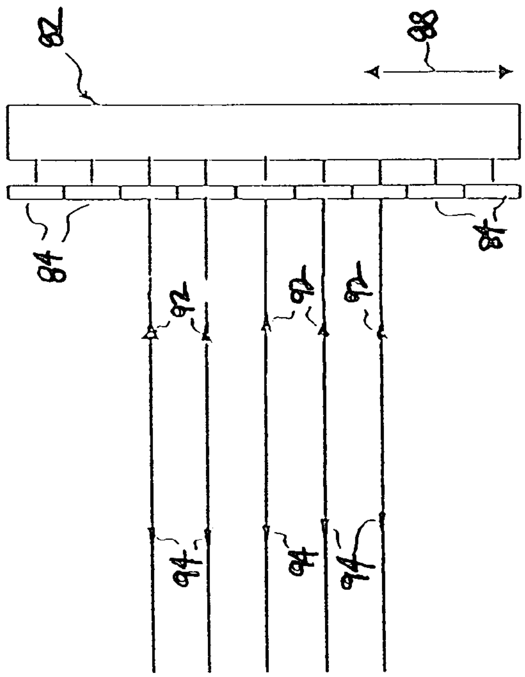


Fig. 4a

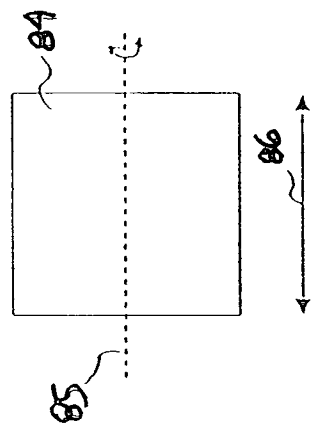


Fig. 5

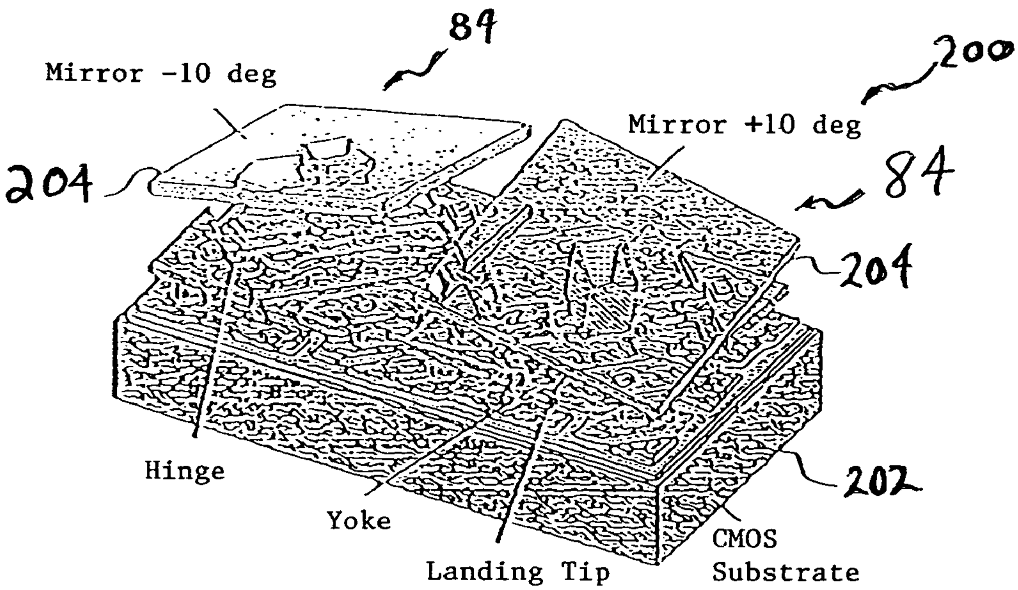


Fig. 6 (Prior Art)

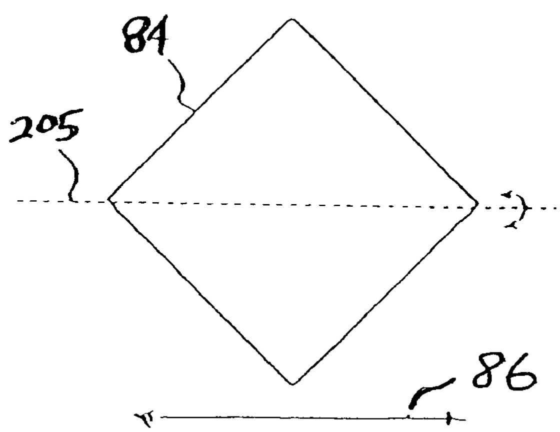


Fig. 7

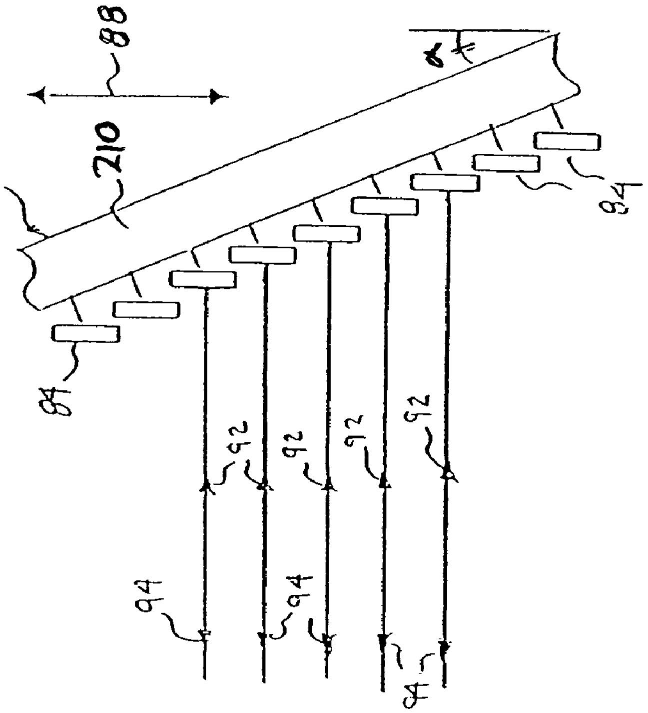


Fig. 8b

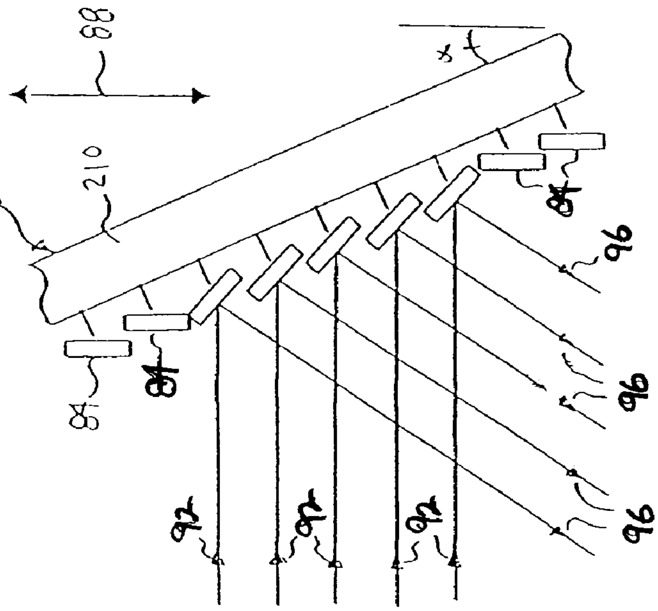


Fig. 8a

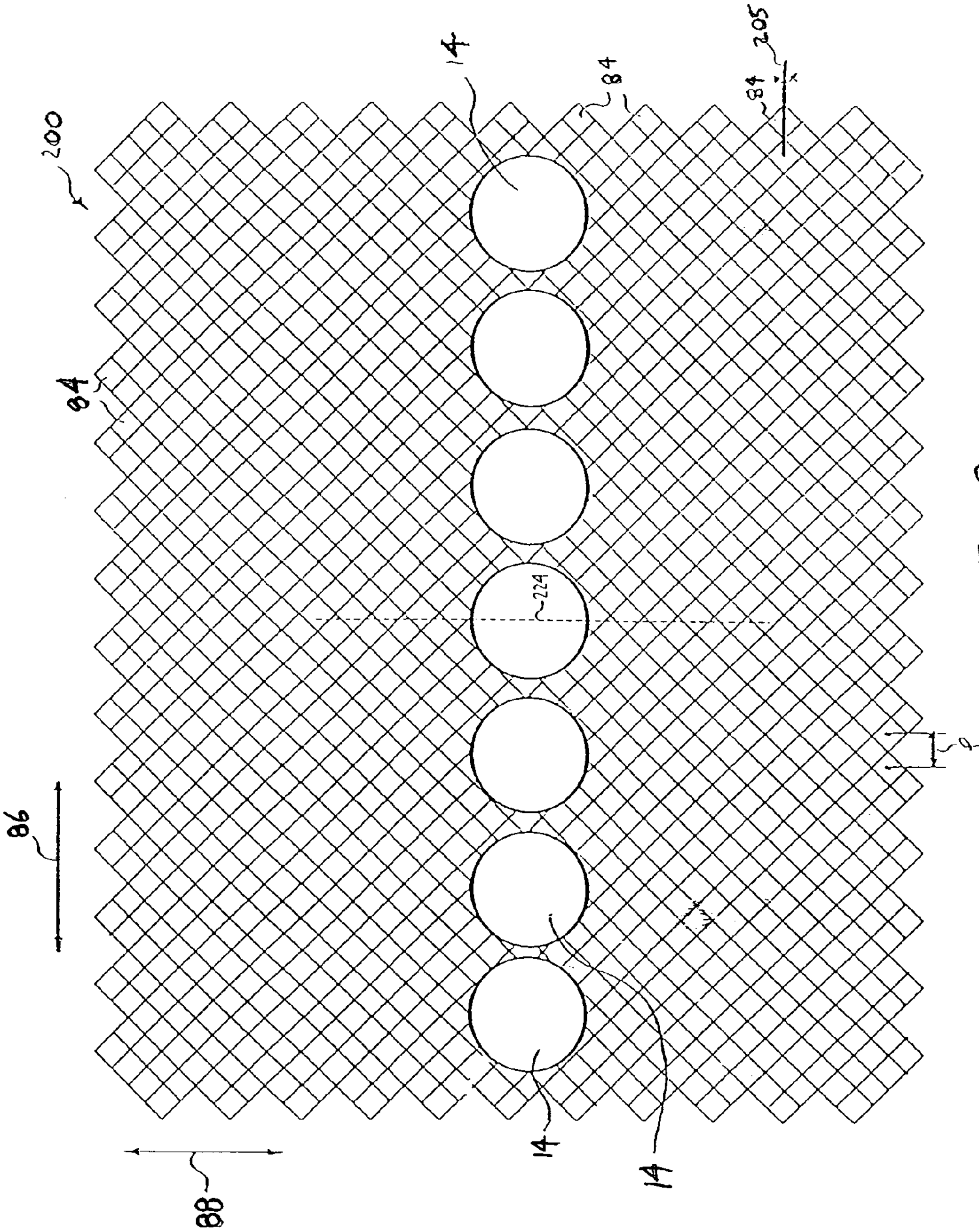


Fig. 9a

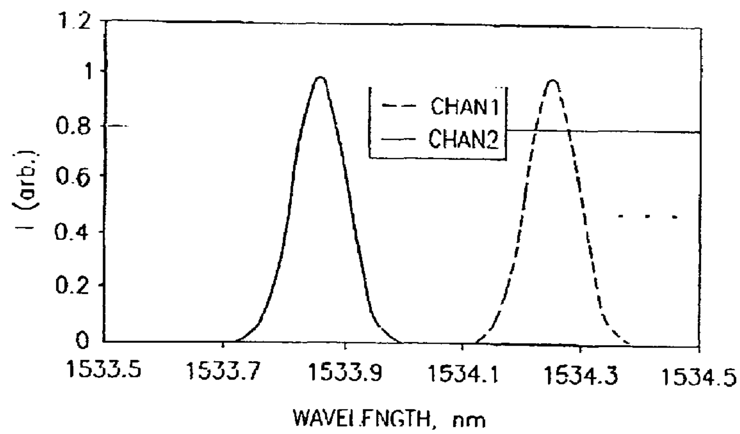


FIG. 9b

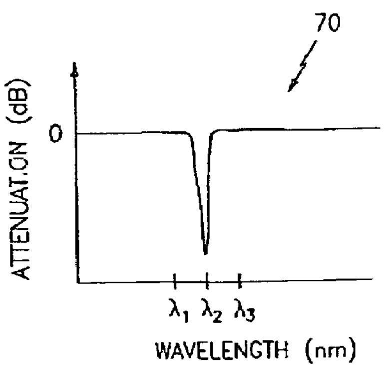


FIG. 9c

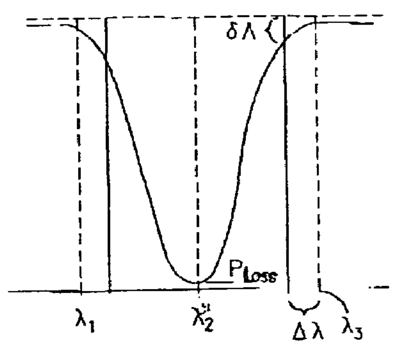


FIG. 9d

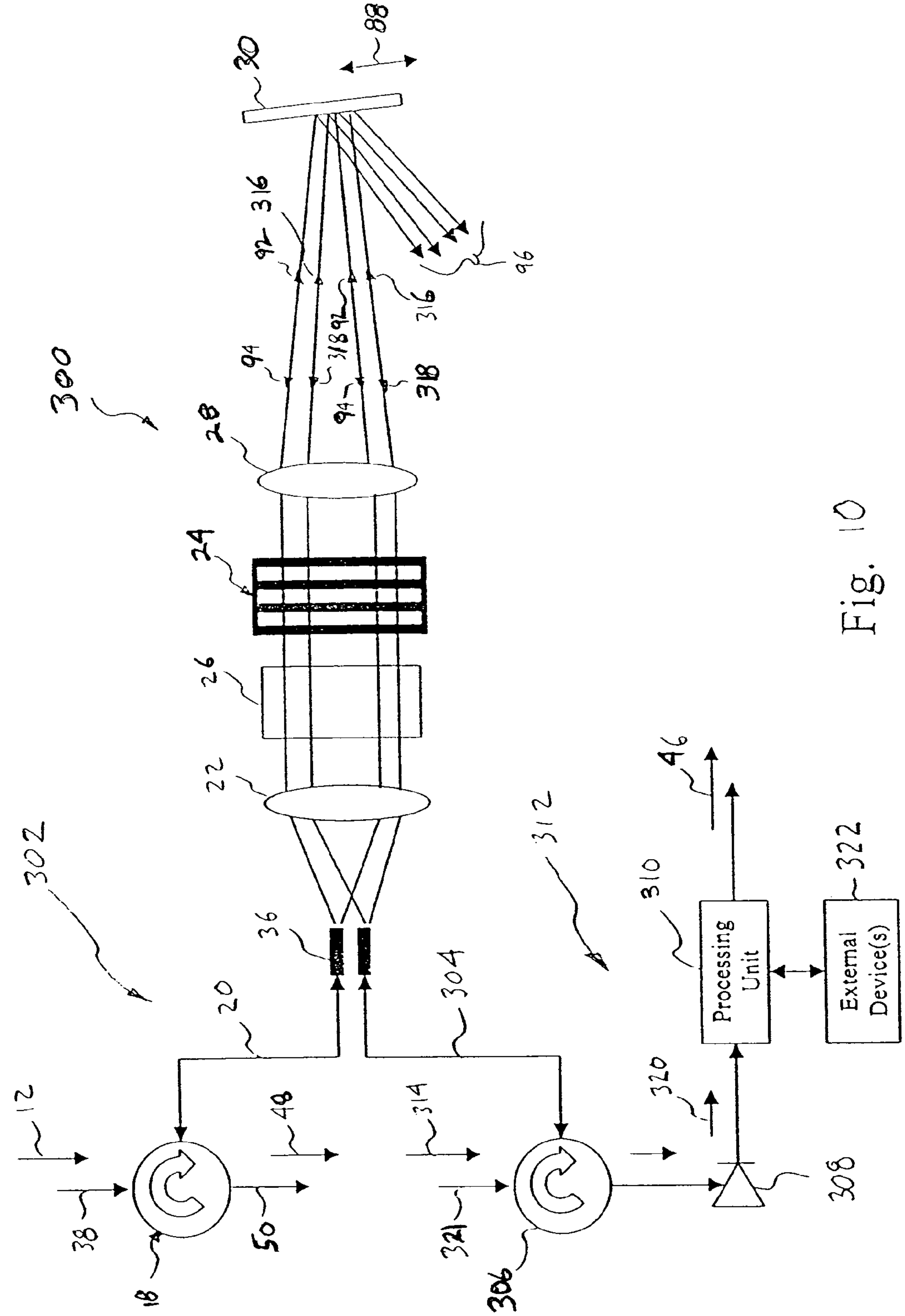
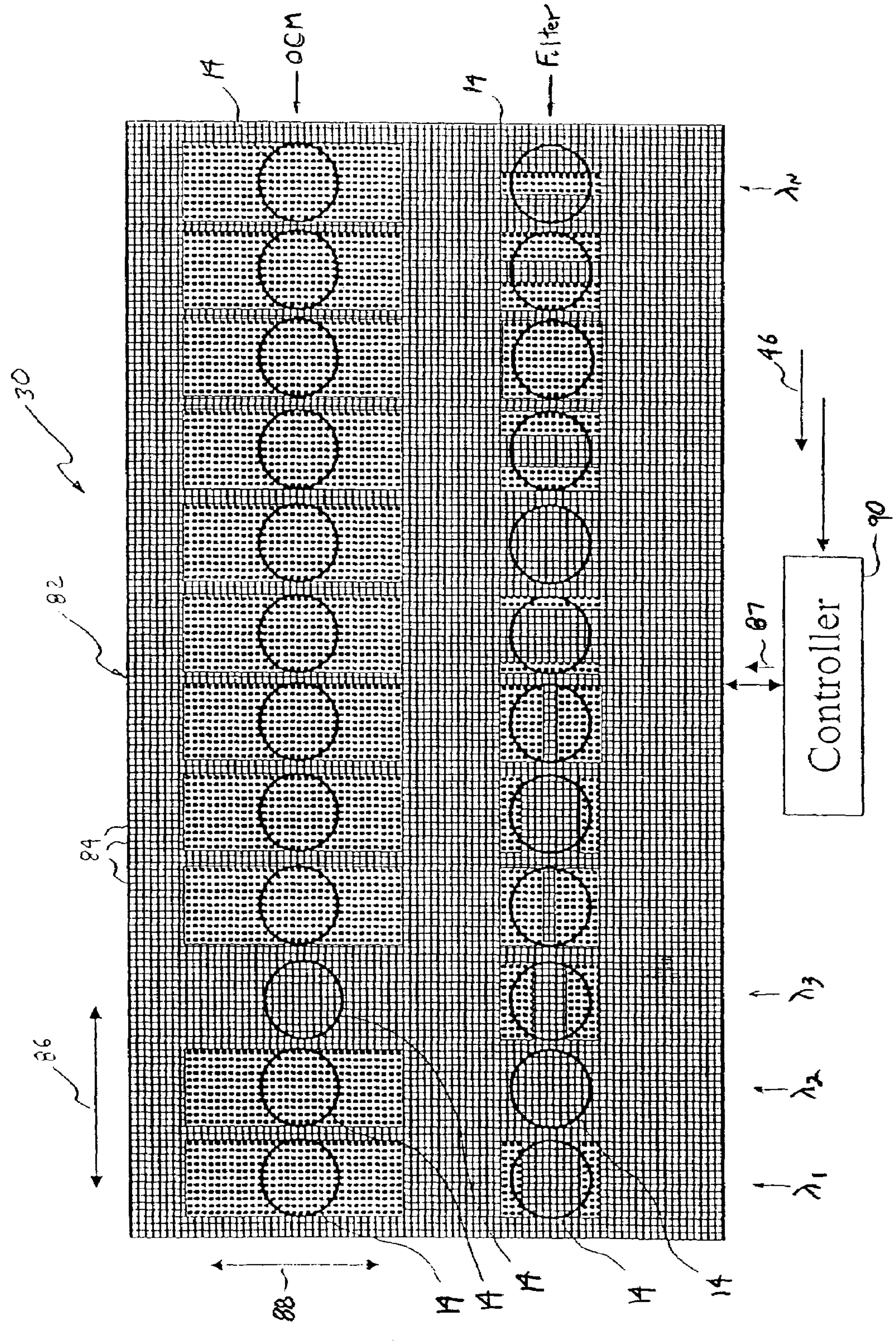

300
302
312
Processing Unit
External Device(s)
310
322
46
30
88
96
316
92
94
318
28
24
26
22
36
20
304
12
38
18
48
50
314
321
306
320
308

Fig. 10



OCM
Filter
14
30
82
84
86
88
46
90
87
Controller
λ_1
λ_2
λ_3
λ_N

Fig. 11

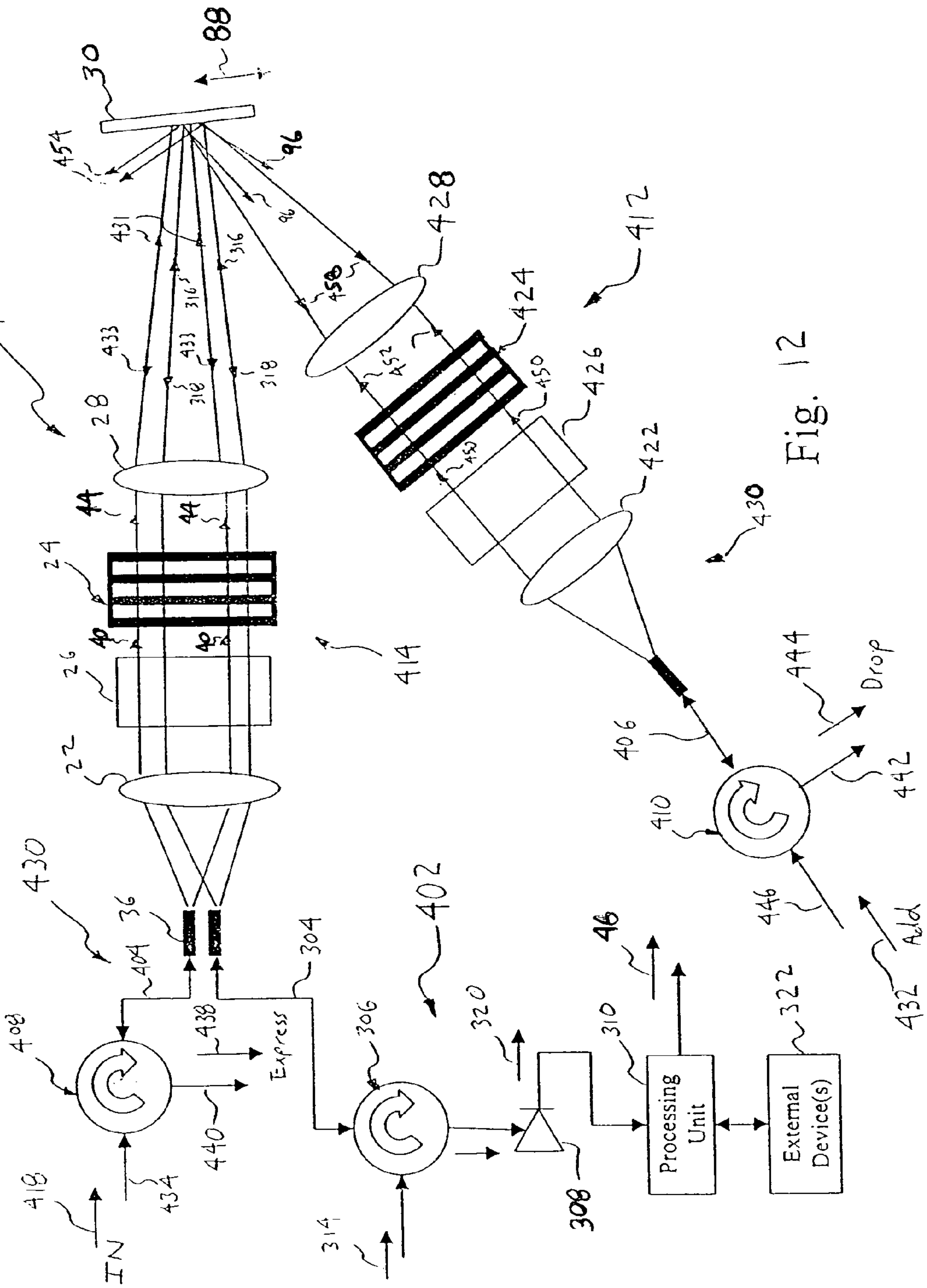
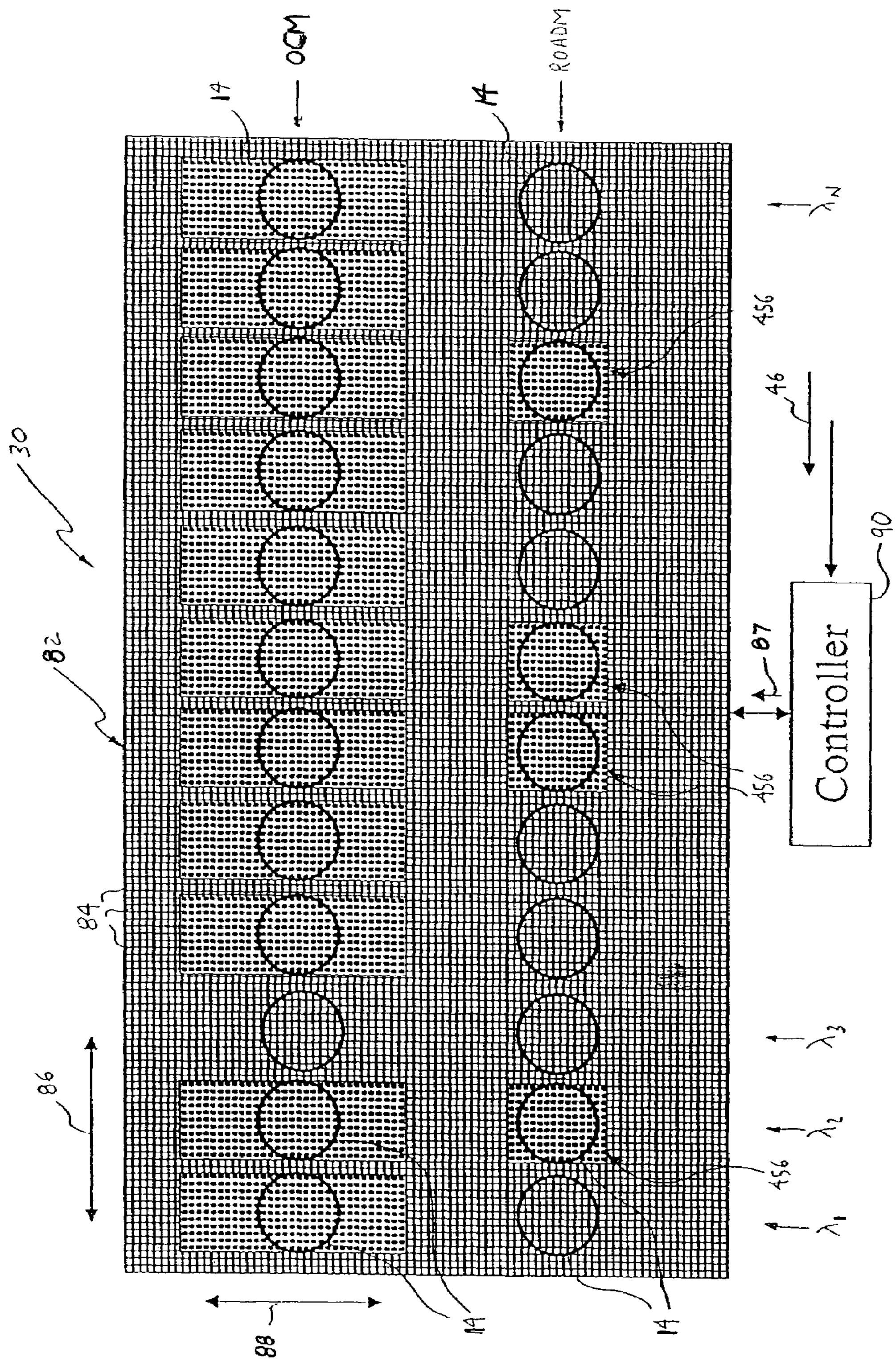

400
30
88
454
96
428
412
431
316
433
318
28
44
24
40
26
22
414
424
426
450
452
458
422
430
406
444
Drop
442
410
446
Add
432
402
304
36
404
408
438
Express
440
306
320
310
Processing Unit
46
External Device(s)
322
308
314
IN
418
434

Fig. 12



OCM
ROADM
30
82
84
86
88
14
456
46
87
90
Controller
λ_N
λ_3
λ_2
λ_1

Fig. 13

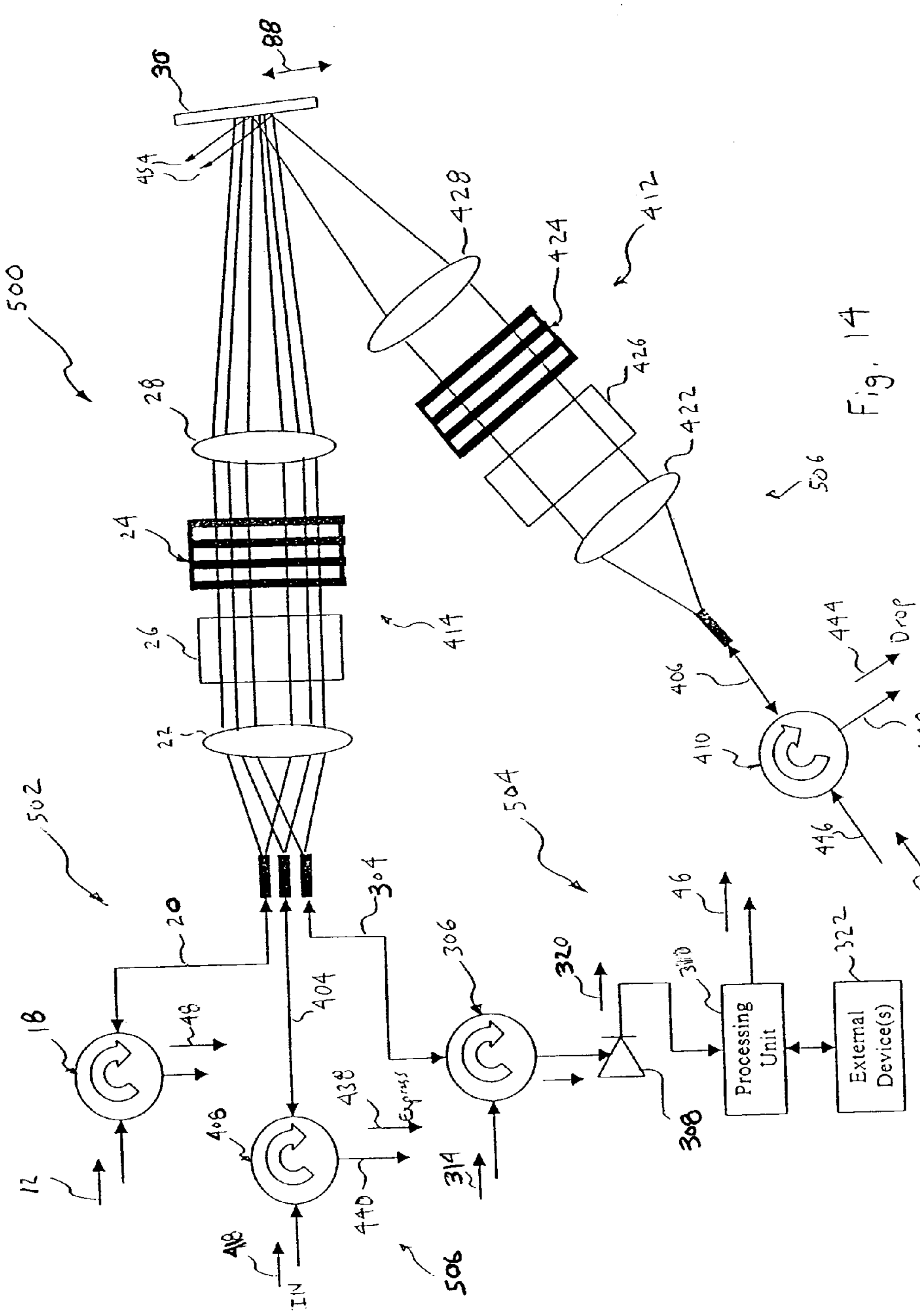

500
502
504
506
12
18
20
48
404
406
408
IN
438
Express
440
304
306
314
320
308
310
Processing Unit
External Device(s)
322
46
22
26
24
28
30
88
454
428
424
426
422
412
414
410
444
Drop
442
446
ADD
432

Fig. 14

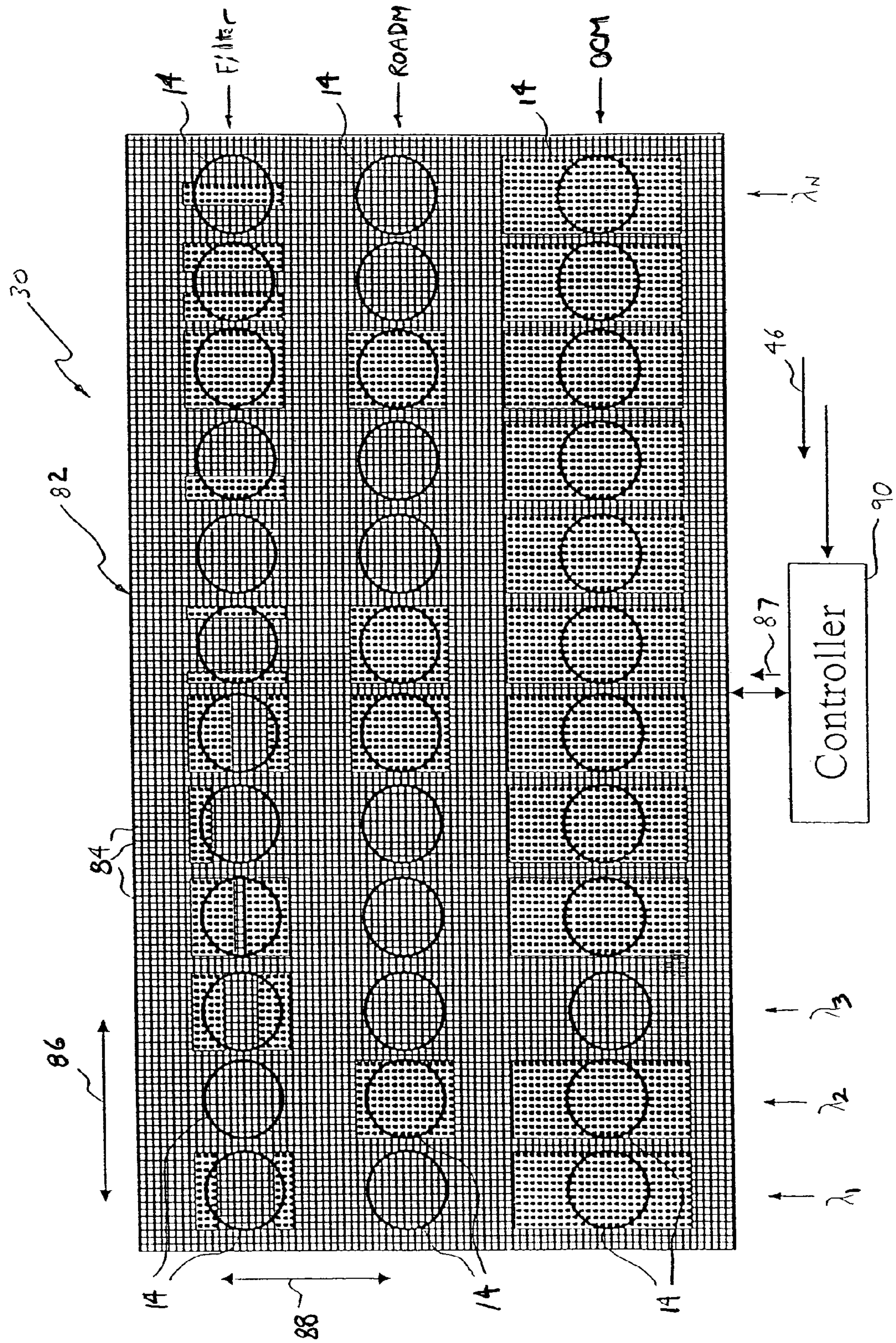

Filter
ROADM
OCM
Controller
30
82
84
86
87
88
90
46
14
λ1
λ2
λ3
λN

Fig. 15

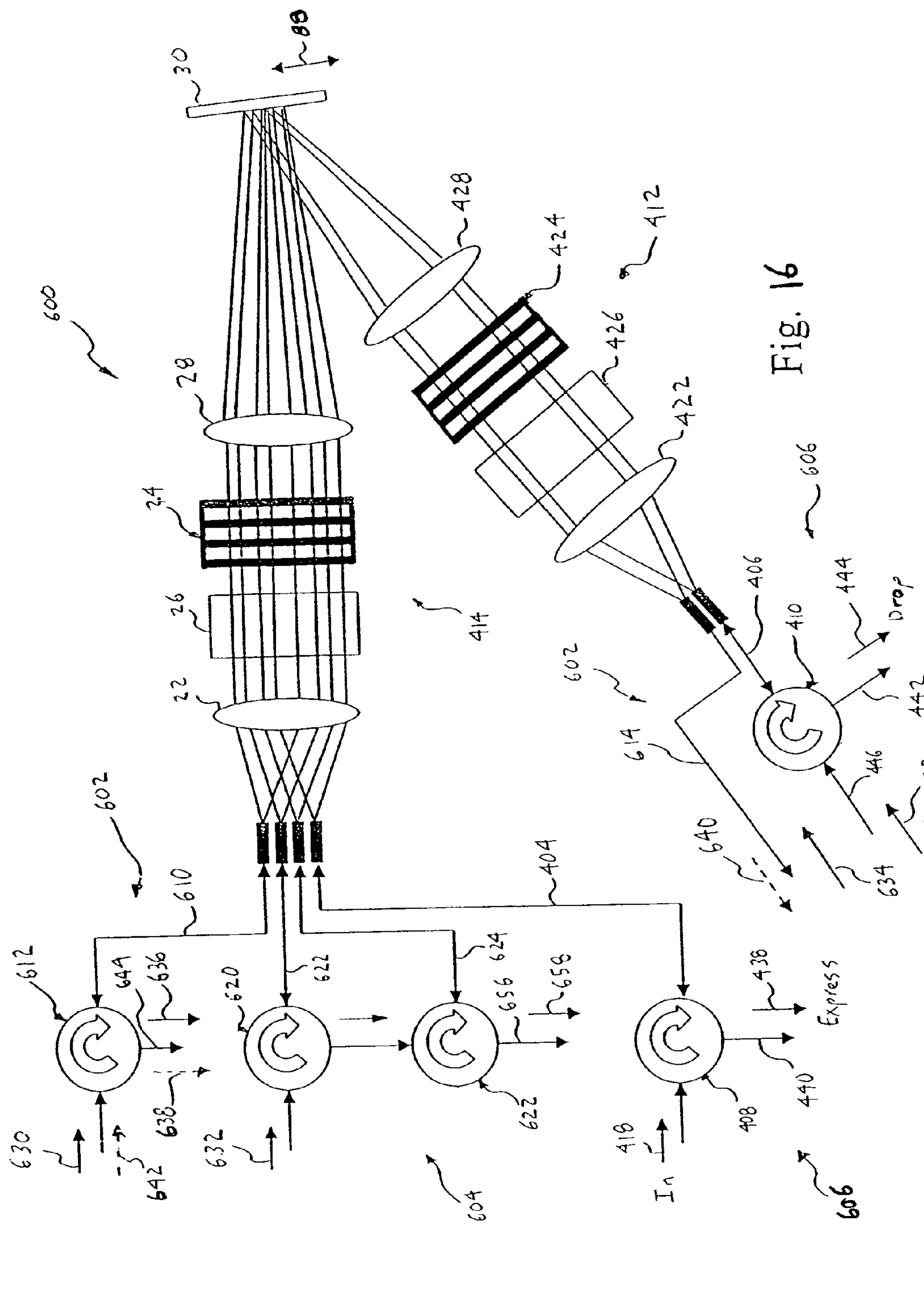


Fig. 16

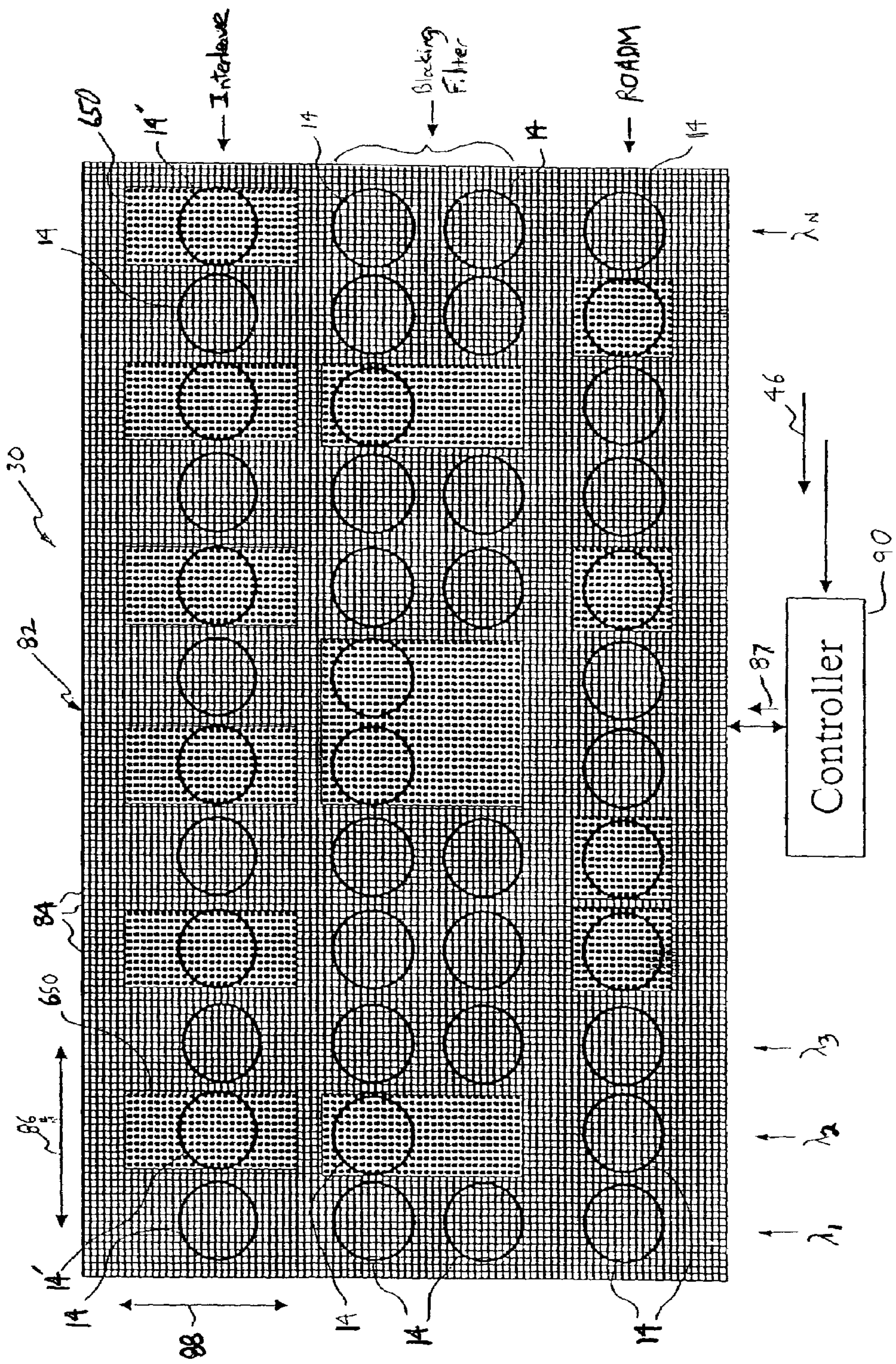

Interleave
Blocking Filter
ROADM
Controller
30
82
84
86
87
88
90
46
650
14
14'

Fig. 17

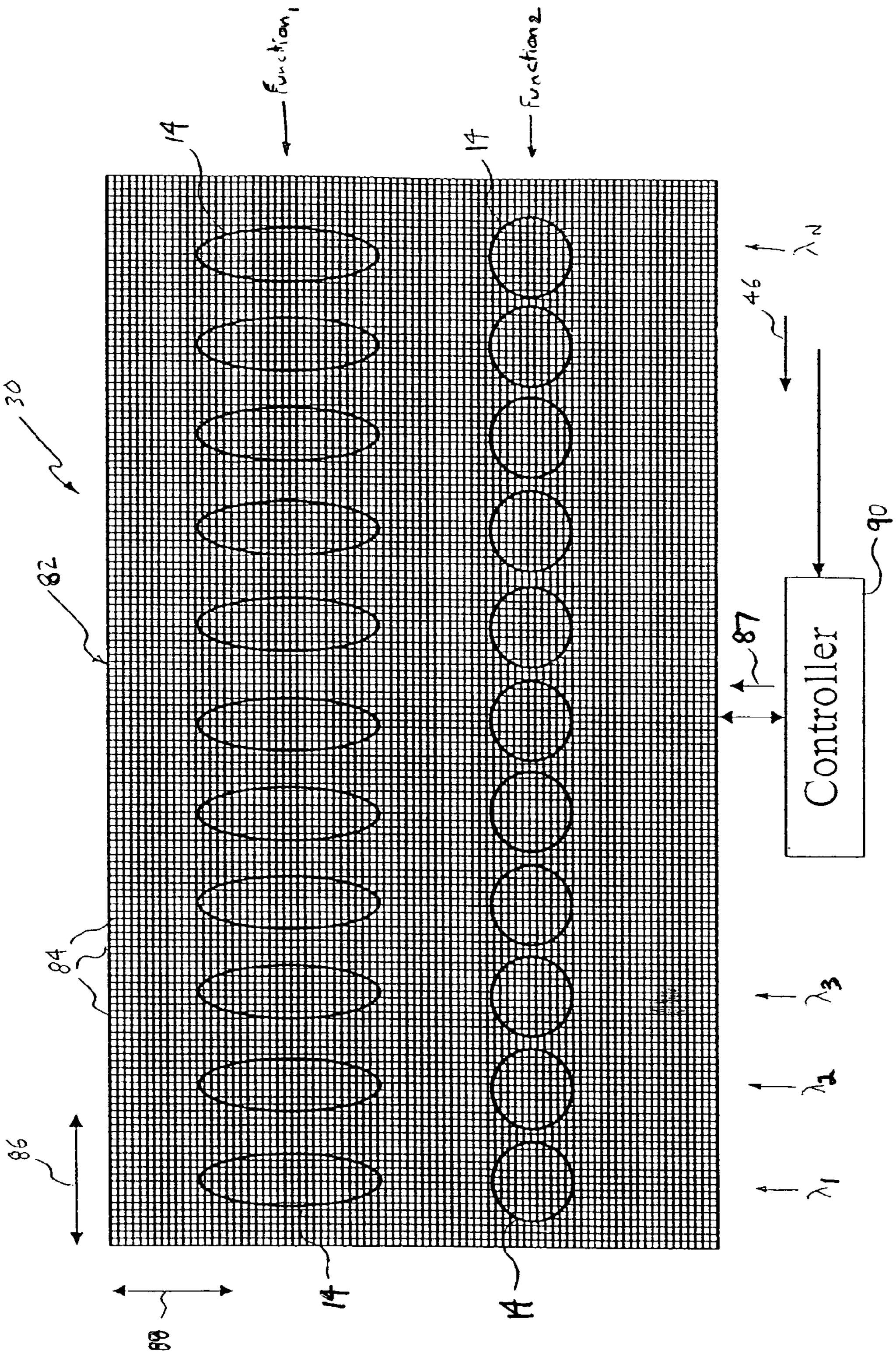

Function1
Function2
14
14
14
14
30
82
84
84
86
88
46
87
90
λ1
λ2
λ3
λN
Controller

Fig. 18

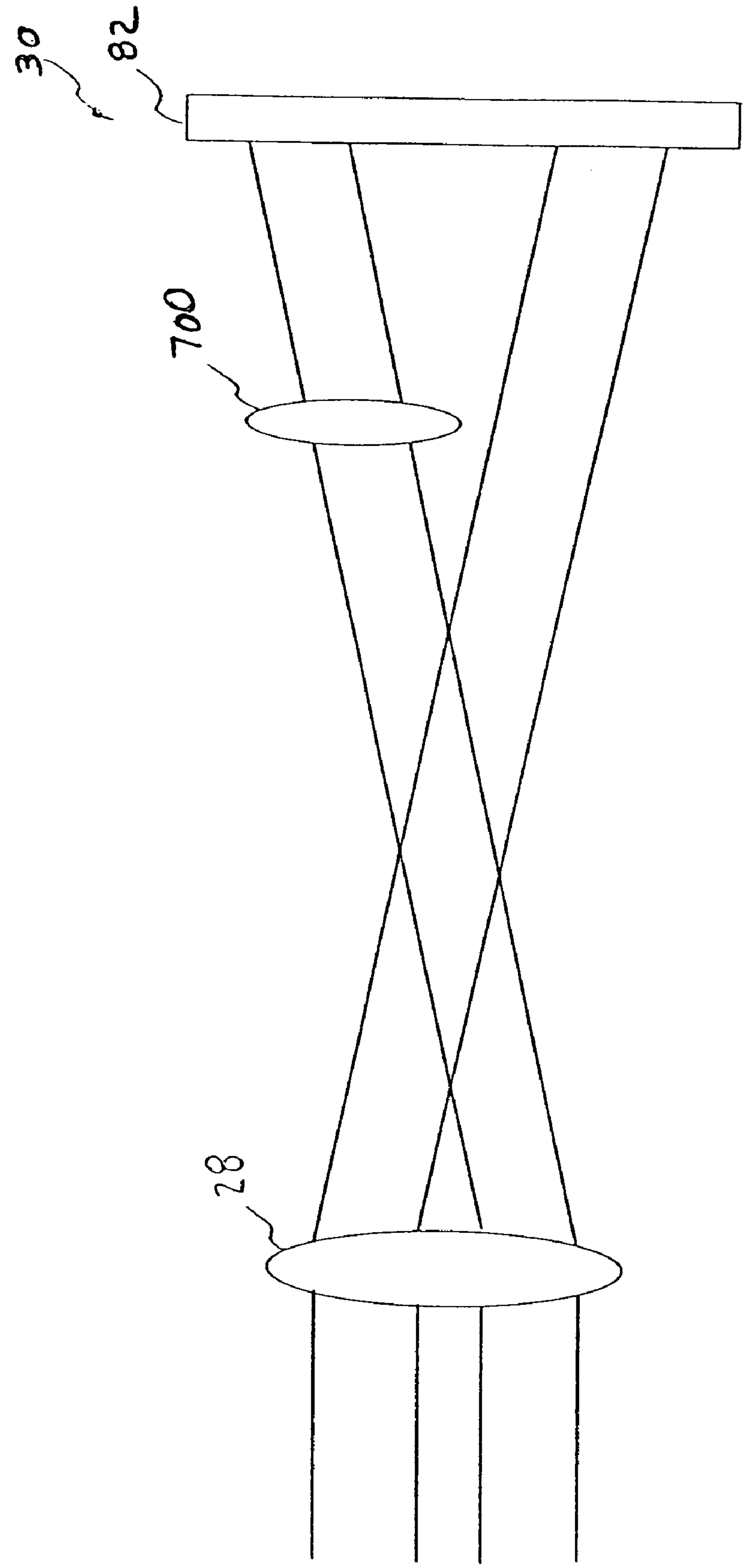


Fig. 19

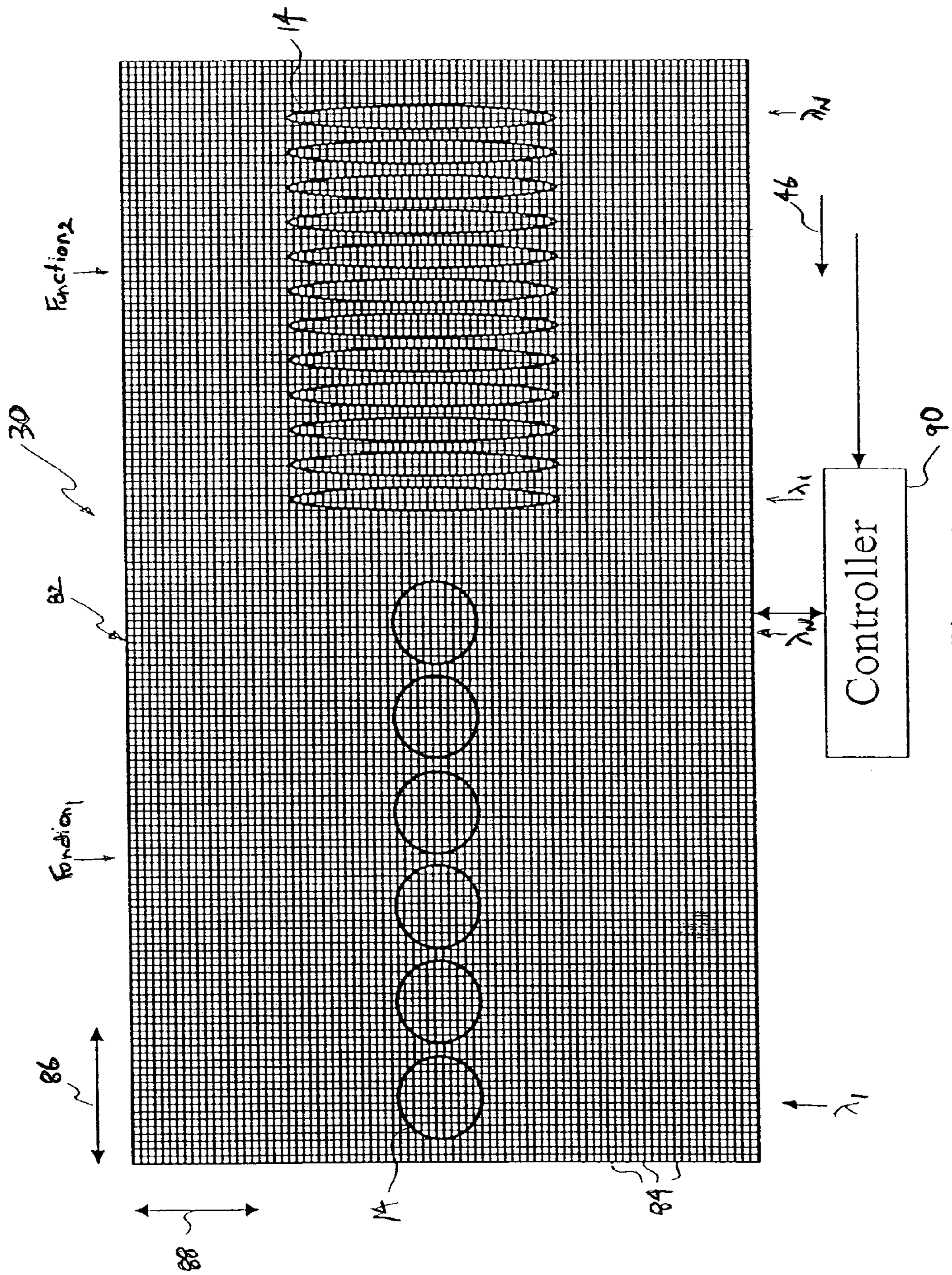


Fig. 20

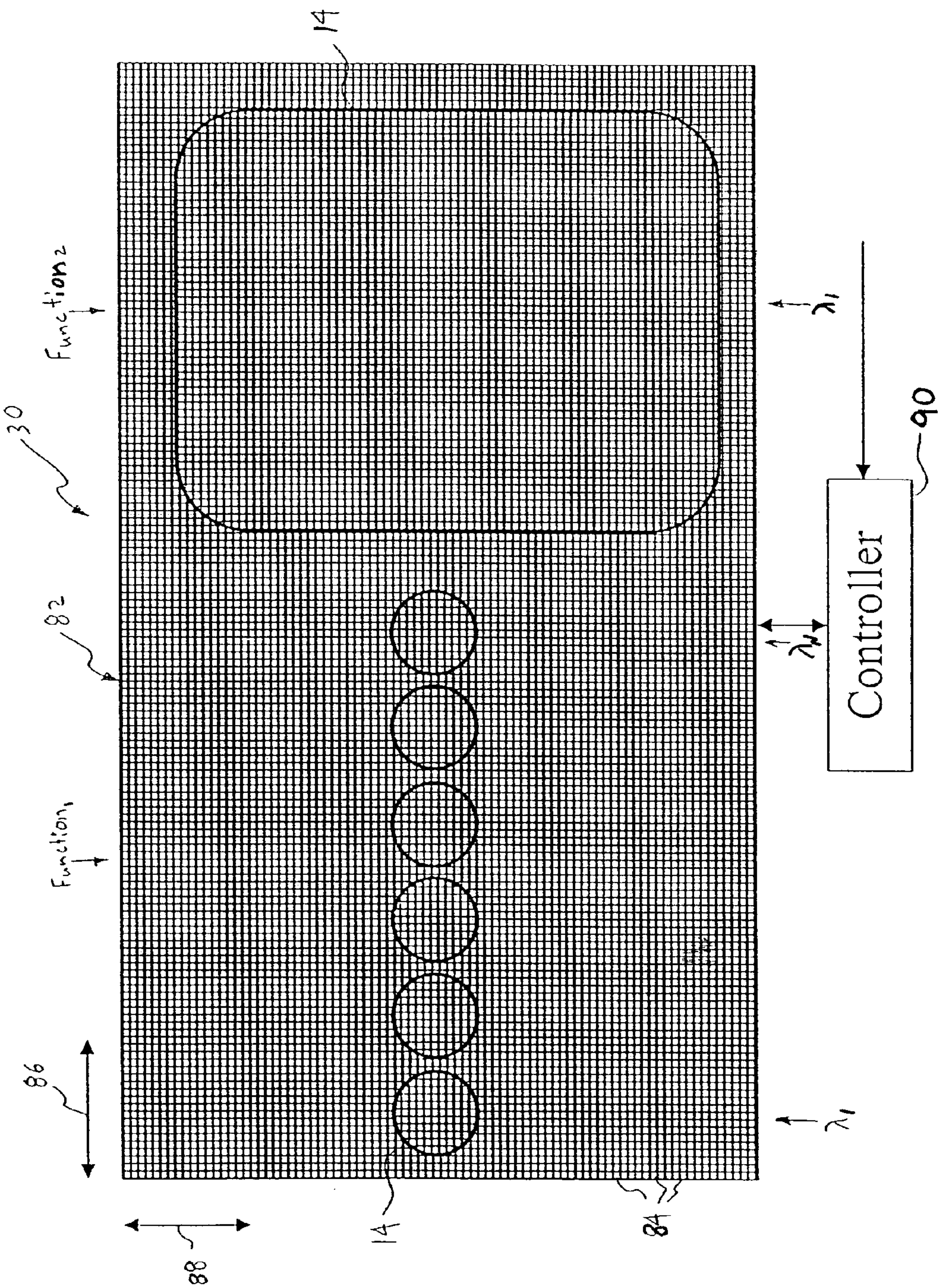

14
Function2
30
82
Function1
86
88
14
84
λ1
λ2
λ1
Controller
90

Fig. 21a

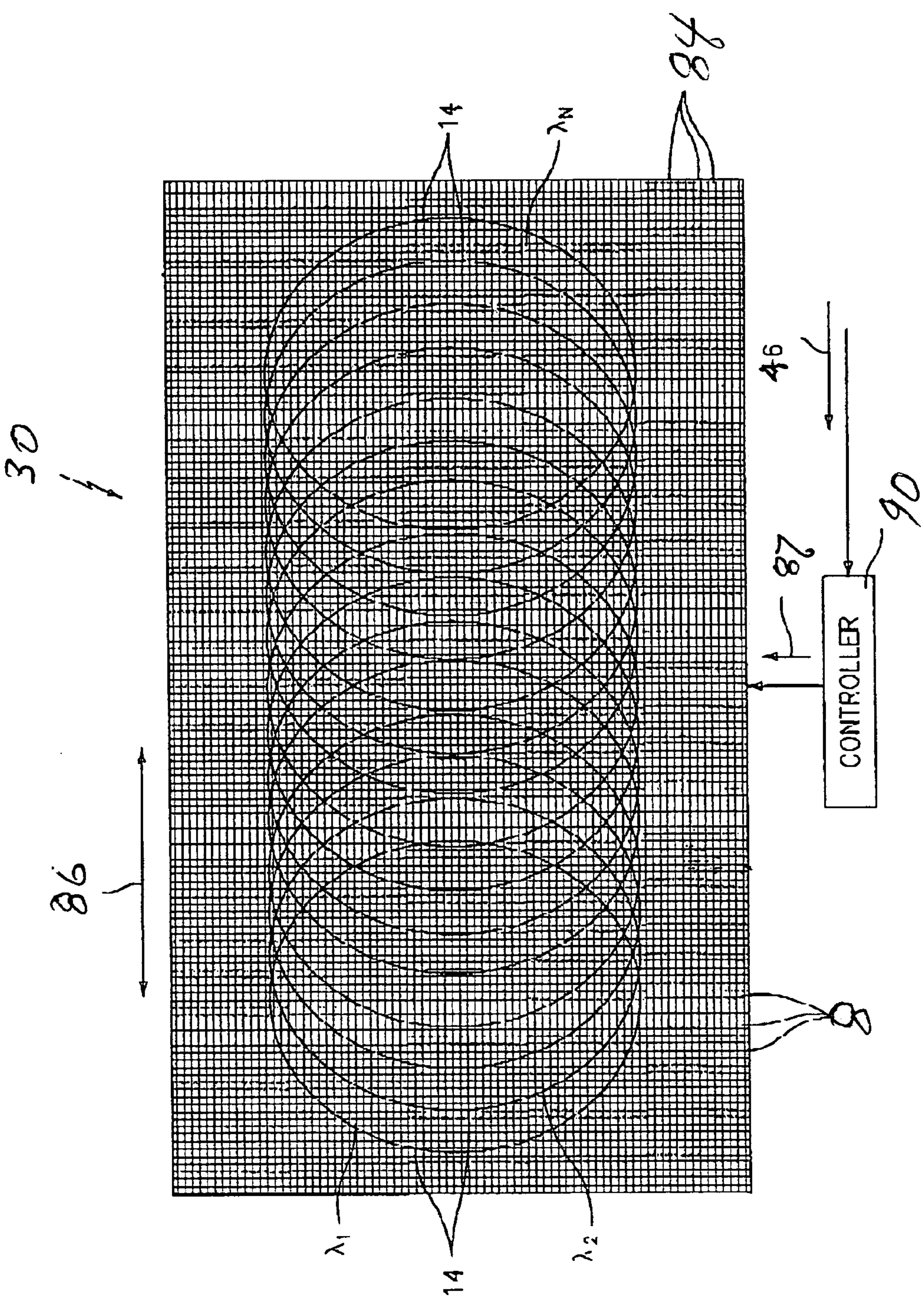


FIG. 21b

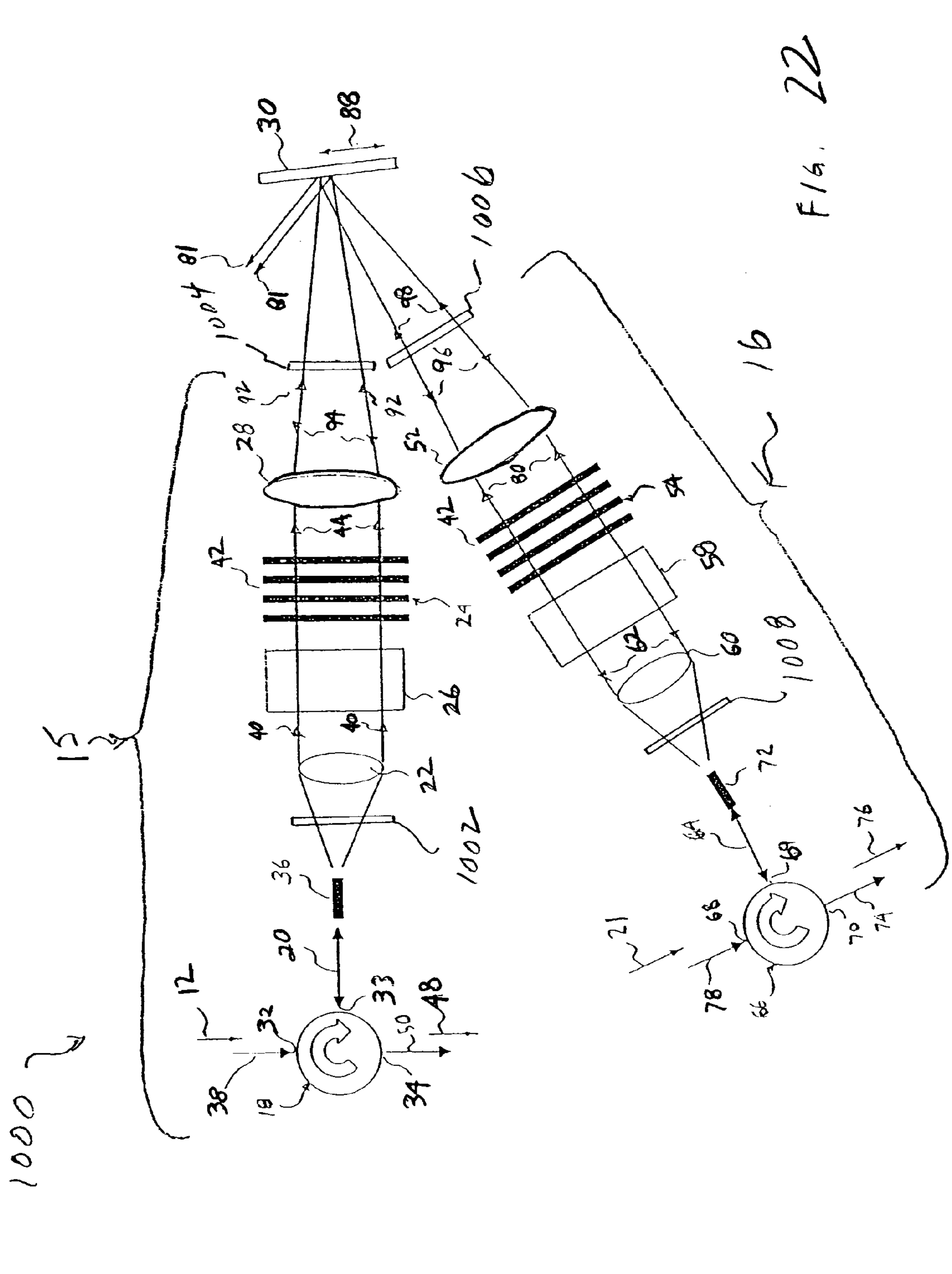

1000
15
12
32
38
18
33
20
34
50
48
36
1002
22
40
26
24
42
44
28
94
92
1004
81
30
88
1006
98
96
52
80
54
58
62
60
1008
72
64
69
68
66
78
21
70
74
76
16

FIG. 22

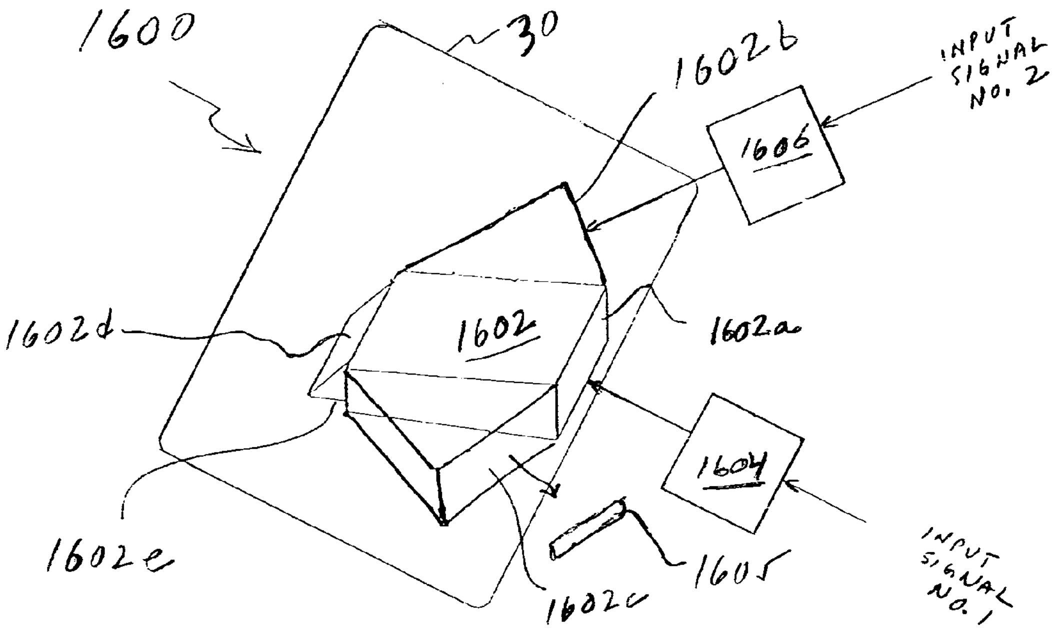
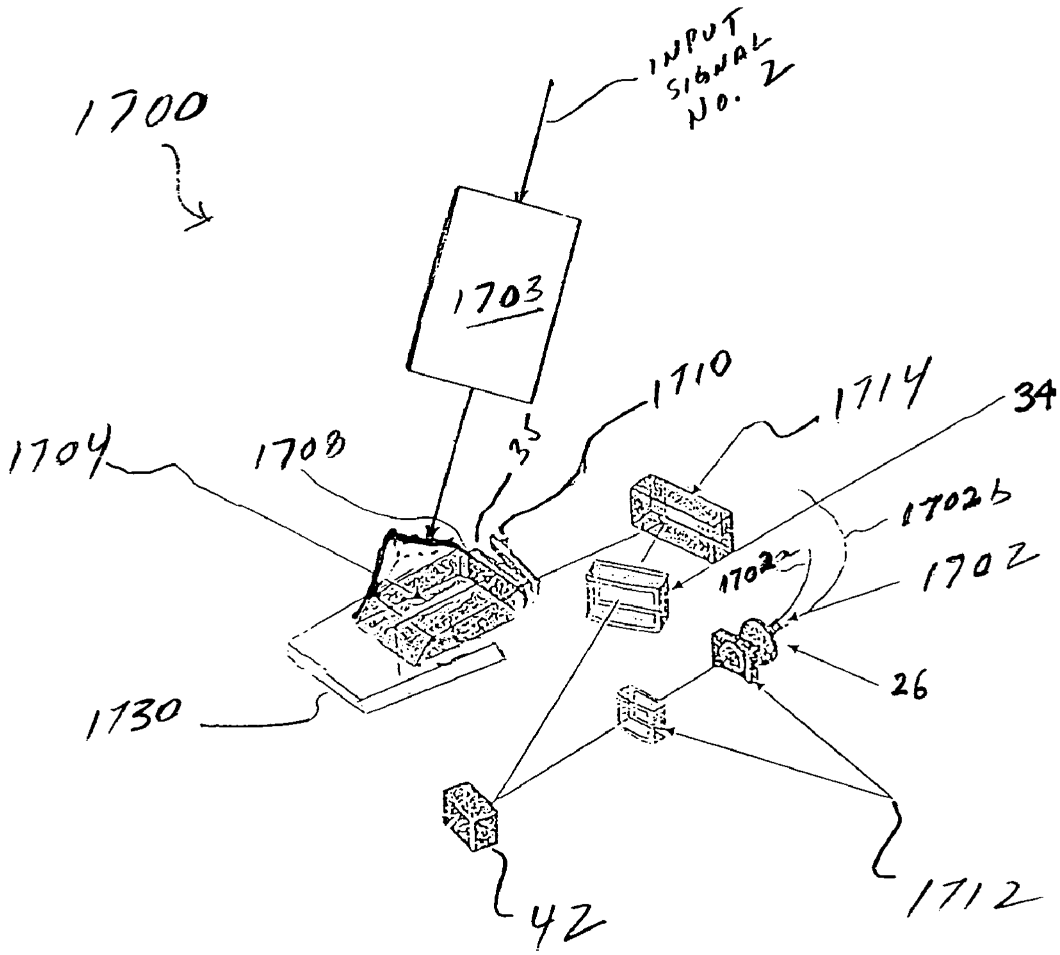

1600
30
1602b
INPUT SIGNAL NO. 2
1606
1602
1602d
1602a
1604
1602e
1605
1602c
INPUT SIGNAL NO. 1

FIGURE 23



1700
INPUT SIGNAL NO. 2
1703
1710
1714
34
1704
1708
35
1702b
1702a
1702
26
1730
42
1712

FIG. 24

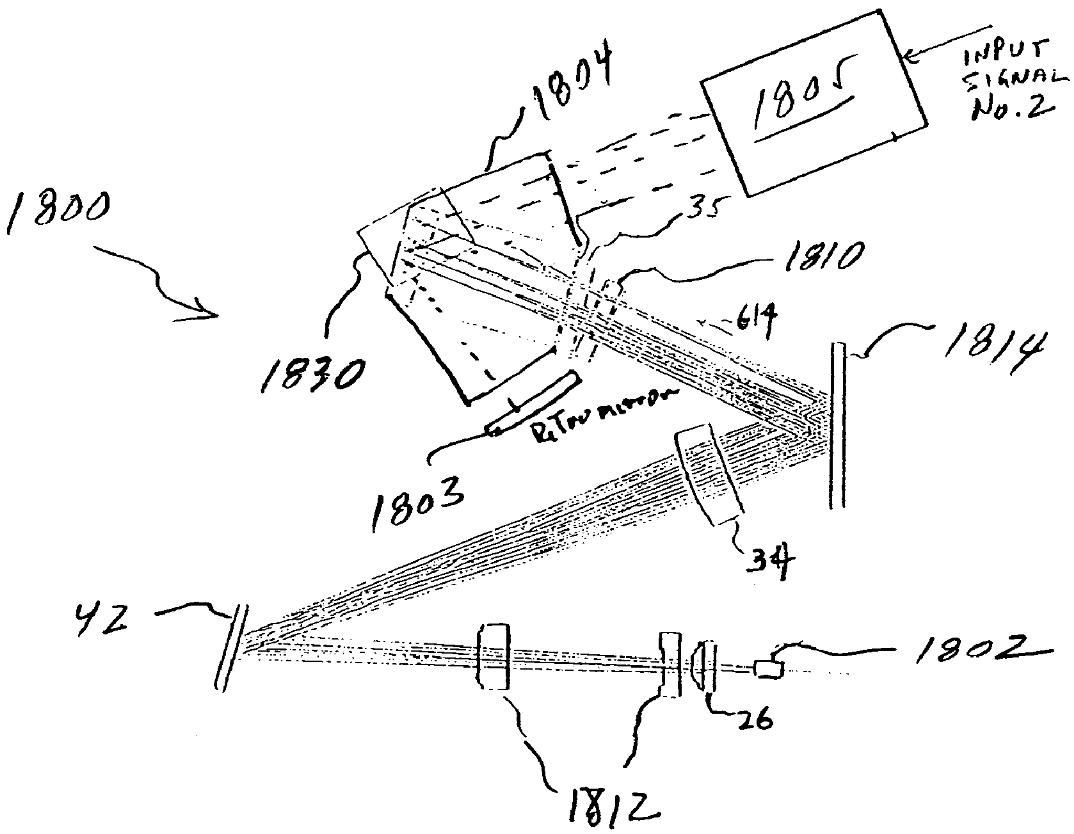

1800
1804
1805
INPUT SIGNAL No. 2
35
1810
614
1830
1814
1803
34
42
1802
26
1812

FIG. 25

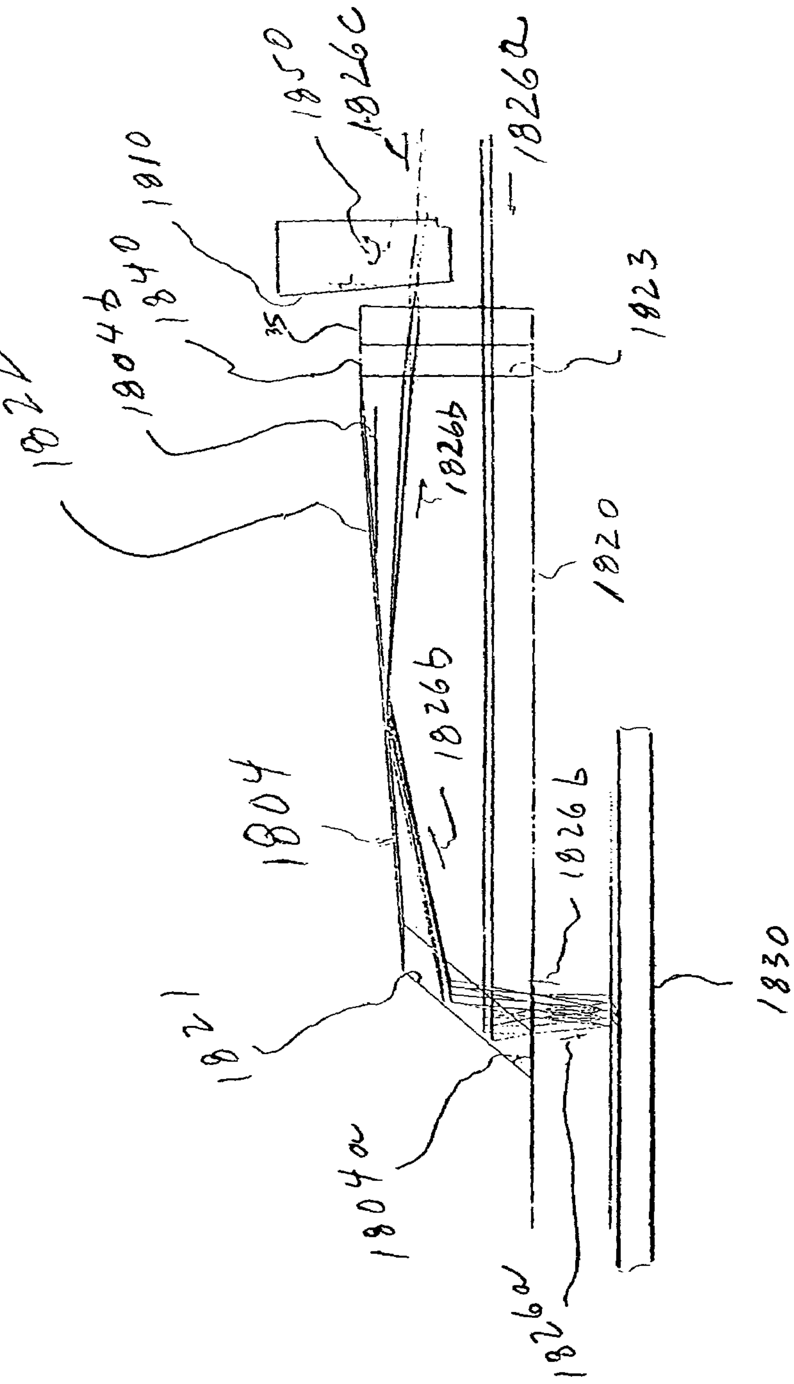

1822
1804b
1840
1810
1850
1826c
1826a
1823
1820
1826b
1804
1821
1804a
1830

FIG. 26

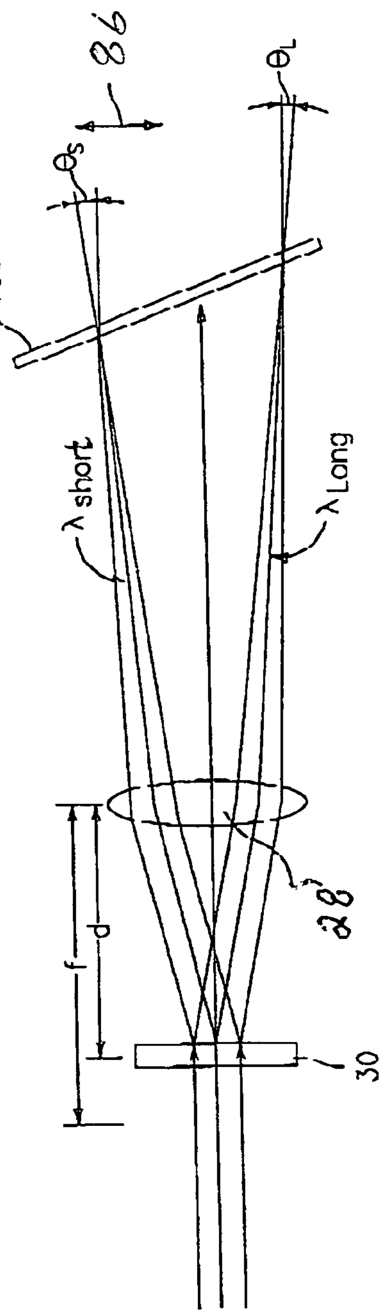


FIG. 27a

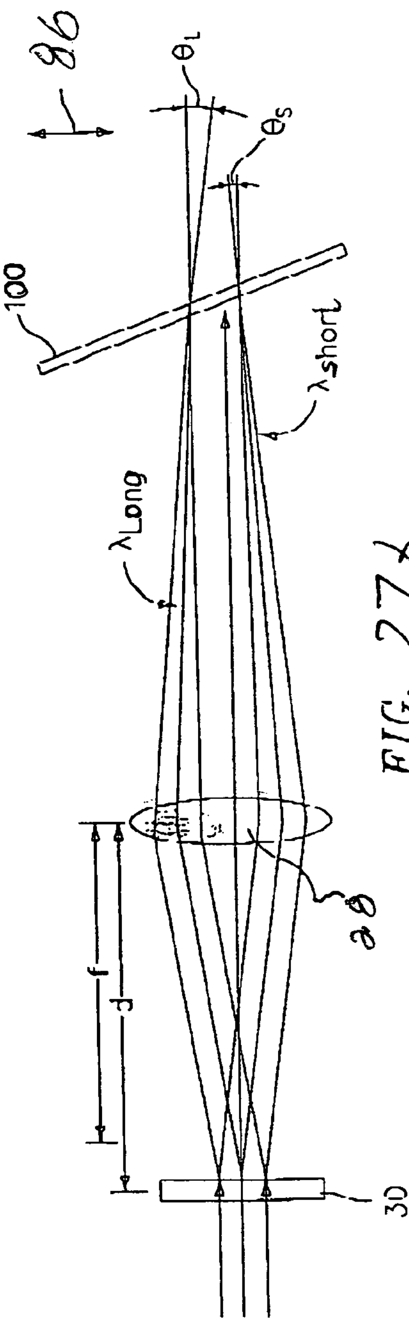


FIG. 27b

MULTIFUNCTIONAL OPTICAL DEVICE HAVING A SPATIAL LIGHT MODULATOR WITH AN ARRAY OF MICROMIRRORS

CROSS REFERENCE TO RELATED APPLICATIONS

This patent claims the benefit of U.S. Provisional Patent Application Ser. No. 60/352,297, filed Jan. 28, 2002; and is a continuation-in-part of U.S. patent application Ser. No. 10/115,647, filed Apr. 3, 2002, which claims the benefit of U.S. Provisional Patent Application Ser. No. 60/281,079, filed Apr. 3, 2001, U.S. Provisional Patent Application Ser. No. 60/311,002, filed Aug. 8, 2001, U.S. Provisional Patent Application Ser. No. 60/332,319, filed Nov. 16, 2001 U.S. Provisional Patent Application Ser. No. 60/365,741, filed Mar. 18, 2002, and U.S. Provisional Patent Application Ser. No. 60/365,461, filed Mar. 18, 2002; and is a continuation-in-part of U.S. patent application Ser. No. 10/120,617, filed Apr. 11, 2002 now abandoned, which claims the benefit of U.S. Provisional Patent Application Ser. No. 60/283,197, filed Apr. 11, 2001; and is a continuation-in-part of U.S. patent application Ser. No. 10/115,648, filed Apr. 3, 2002, which claims the benefit of U.S. Provisional Patent Application Ser. No. 60/365,682, filed Mar. 18, 2002, and U.S. Provisional Patent Application Ser. No. 60/365,446, filed Mar. 18, 2002; and is a continuation-in-part of U.S. patent application Ser. No. 10/216,000, filed Aug. 8, 2002, which claims the benefit of U.S. Provisional Patent Application Ser. No. 60/310,991, filed Aug. 9, 2001, and U.S. Provisional Patent Application Ser. No. 60/354,794, filed Feb. 6, 2002; and is a continuation-in-part of U.S. patent application Ser. No. 10/255,141, filed Sep. 25, 2002now abandoned, which claims the benefit of U.S. Provisional Patent Application Ser. No. 60/325,065, filed Sep. 25, 2001; and is a continuation-in-part of U.S. patent application Ser. No. 10/255,133, filed Sep. 25, 2002, which claims the benefit of U.S. Provisional Patent Application Ser. No. 60/325,066, filed Sep. 25, 2001; and is a continuation-in-part of U.S. patent application Ser. No. 10/255,129, filed Sep. 25, 2002now abandoned, which claims the benefit of U.S. Provisional Patent Application Ser. No. 60/325,068, filed Sep. 25, 2001; and is a continuation-in-part of U.S. patent application Ser. No. 10/298,264, filed Nov. 16, 2002now U.S. Pat. No. 6,934,069, which claims the benefit of U.S. Provisional Patent Application Ser. No. 60/332,318, filed Nov. 16, 2001; and is a continuation-in-part of U.S. patent application Ser. No. 10/255,132, filed Sep. 25, 2002now U.S. Pat. No. 6,922,277, which claims the benefit of U.S. Provisional Patent Application Ser. No. 60/325,064, filed Sep. 25, 2001; and is a continuation-in-part of U.S. patent application Ser. No. 10/327,695, filed Dec. 19, 2002now U.S. Pat. No.6,956,687, which claims the benefit of U.S. Provisional Patent Application Ser. No. 60/344,585, filed Dec. 28, 2001, all of which are incorporated herein by reference in their entirety.

BACKGROUND OF THE INVENTION

1. Technical Field

The present invention relates to tunable optical devices, and more particularly to a reconfigurable multifunctional optical device including a spatial light modulator to selectively attenuate, condition and/or redirect at least one optical channel of a wavelength division multiplexing (WDM) optical signal.

2. Description of Related Art

MEMS micro-mirrors have been widely explored and used for optical switching and attenuation applications. The most commonly used application is for optical cross-connect switching. In most cases, individual micro-mirror elements are used to 'steer' a beam (i.e., an optical channel) to a switched port or to deflect the beam to provide attenuation on a channel-by-channel basis. Each system is designed for a particular 'wavelength plan'—e.g. "X" number of channels at a spacing "Y", and therefore each system is not 'scalable' to other wavelength plans.

Further, dynamic gain equalization (or "flattening") is a critical technology for deployment of next-generation optical network systems. Dynamic gain equalizing filters (DGEF's) function by adding varying amounts of attenuation at different spectral locations in the signal spectrum of optical fiber communication systems. For instance, a DGEF may be designed to operate in the "C-band" (~1530–1565 nanometers (nm)) of the communication spectrum that is capable of selectively attenuating spectrally concatenated "bands" of some preselected spectral width (e.g., 3 nm). The total number of bands within the DGEF is determined by the width of an individual band.

In the networking systems, it is often necessary to route different channels (i.e., wavelengths) between one fiber and another using a reconfigurable optical add/drop multiplexer (ROADM) and/or an optical cross-connect device.

One issue with the above optical MEMs device is that it is not "channel plan independent". In other words, each MEMs device is limited to the channel spacing (or channel plan) originally provide. Another concern is that if the absolute value of a channel wavelength changes, a respective optical signal may begin to hit an edge of a corresponding mirror leading to large diffraction losses. Further, since each channel is aligned to an individual mirror, the device must be carefully adjusted during manufacturing and kept in alignment when operated through its full temperature range in the field.

It would be advantageous to provide an optical switching or attenuating device using a spatial light modulator and to combine multiple optical functions using a single spatial light modulator.

SUMMARY OF THE INVENTION

An object of the present invention is to provide a multifunctional optical device using a single spatial light modulator.

The invention provides a new and unique reconfigurable multifunctional optical device comprising an optical arrangement for receiving at least one optical signal, each optical signal having one or more optical bands or channels, and a spatial light modulator for reflecting the at least one optical signal provided thereon. The optical arrangement features a free optics configuration with a light dispersion element for spreading each optical signal into one or more respective optical bands or channels for performing separate optical functions on each optical signal. In one embodiment, the spatial light modulator may include a micro-mirror device with an array of micro-mirrors, and the one or more respective optical bands or channels reflect off a respective plurality of micro-mirrors. In effect, the free optics configuration includes a common set of optical components for performing each separate optical function on each optical signal.

The separate optical functions reflect off separate non-overlapping areas on the spatial light modulator and may include different optical functions. The separate optical functions include optical switching, conditioning or monitoring functions such as either an optical add/drop multiplexer (OADM) function, an optical channel monitor (OCM) function, an optical cross-connect (CC) function, an optical interleaver/deinterleaver (INT/DEINT), a dynamic gain equalization filter (DGEF) or dynamic spectral equalizer (DSE), or some combination thereof. The at least one optical signal typically includes two or more optical input signals, on which a respective function is performed. The scope of the invention is also intended to include performing an optical function on one optical input signal, and performing a second optical function on the output signal from the first optical function.

The one or more light dispersion elements include either a diffraction grating, an optical splitter, a holographic device, a prism, or a combination thereof.

In accordance with an embodiment of the present invention, the multifunctional optical device may include a collimator that collimates a first and second optical input signal. Each of the first and second optical input signals includes a plurality of optical input channels. Each optical input channel is centered at a central wavelength. A light dispersion element substantially separates the optical channels of the collimated first and second input signals. A spatial light modulator reflects each of the first and second optical input channels along a respective first optical path or second optical path, in response to a control signal. The spatial light modulator comprises a micro-mirror device that includes an array of micro-mirrors selectively disposable between a first and a second position in response to the control signal. Each separated optical input channel of each of the first and second input signals is incident on a respective group of micro-mirrors. Each separated optical channel is incident on the respective group of micro-mirrors, wherein each respective separated optical input channel reflects along the respective first optical path when the micro-mirrors are disposed in the first position, or along the respective second optical path when the micro-mirrors are disposed in the second position. A controller generates the control signal in accordance with a switching algorithm.

BRIEF DESCRIPTION OF THE DRAWING

The drawing includes the following Figures:

FIG. **1** is a plan view of a block diagram of a reconfigurable optical filter including a spatial light modulator in accordance with the present invention;

FIG. **2** is a side elevational view of a block diagram of the optical filter of FIG. **1**;

FIG. **3** is a block diagram of a spatial light modulator of the optical filter of FIG. **1**, wherein the optical channels of a WDM input signal are distinctly projected onto the micro-mirror device, in accordance with the present invention;

FIG. **4***a* is a pictorial cross-sectional view of the micro-mirror device of FIG. **3** showing a partial row of micro-mirrors, when the micro-mirrors are disposed in a first position perpendicular to the light beam of the input signal in accordance with the present invention;

FIG. **4***b* is a pictorial cross-sectional view of the micro-mirror device of FIG. **3** showing a partial row of micro-mirrors, when the micro-mirrors are disposed in a second position non-orthogonal to the light beam of the input signal in accordance with the present invention;

FIG. **5** is a plan view of a micro-mirror of the micro-mirror device of FIG. **3** in accordance with the present invention;

FIG. **6** is a perspective view of a portion of a known micro-mirror device;

FIG. **7** is a plan view of a micro-mirror of the micro-mirror device of FIG. **6**;

FIG. **8***a* is a pictorial cross-sectional view of the micro-mirror device of FIG. **6** showing a partial row of micro-mirrors, when the micro-mirrors are disposed in a second position non-orthogonal to the light beam of the input signal in accordance with the present invention;

FIG. **8***b* is a pictorial cross-sectional view of the micro-mirror device of FIG. **6** showing a partial row of micro-mirrors, when the micro-mirrors are disposed in a first position perpendicular to the light beam of the input signal in accordance with the present invention;

FIG. **9***a* is a pictorial cross-sectional view of the micro-mirror device of FIG. **6** disposed at a predetermined angle in accordance with the present invention;

FIG. **9***b* is a plot of the power of the optical channels imaged onto the micromirror device, wherein the optical channels of a WDM input light are substantially dispersed onto the micro-mirror device as shown in FIG. **9***a* in accordance with the present invention;

FIG. **9***c* is a graphical representation of a transmission filter function of an optical filter, wherein the optical channels of a WDM input light are substantially dispersed onto the micro-mirror device as shown in FIG. **9***a*, in accordance with the present invention;

FIG. **9***d* is a plot of attenuation curve when a single channel is dropped from the optical input signal of the optical filter of FIG. **9***a;*

FIG. **10** is a plan view of a block diagram of a reconfigurable multi-function optical device having an OCM function and optical filter function;

FIG. **11** is a block diagram of the spatial light modulator of FIG. **10**, wherein the optical channels of the WDM input signals to the OCM and optical filter are distinctly projected onto the micro-mirror device, in accordance with the present invention;

FIG. **12** is a plan view of a block diagram of another multifunction optical device having an OCM function and reconfigurable optical add/drop multiplexer (ROADM) function;

FIG. **13** is a block diagram of the spatial light modulator of FIG. **12**, wherein the optical channels of the WDM input signals to the OCM and ROADM are distinctly projected onto the micro-mirror device, in accordance with the present invention;

FIG. **14** is a plan view of a block diagram of another multifunction optical device having an OCM function; ROADM function and optical filter function;

FIG. **15** is a block diagram of the spatial light modulator of FIG. **14**, wherein the optical channels of the WDM input signals to the OCM, ROADM and optical filter are distinctly projected onto the micro-mirror device, in accordance with the present invention;

FIG. **16** is a plan view of a block diagram of another multifunction optical device having an interleaver function, blocking filter function and ROADM function;

FIG. **17** is a block diagram of the spatial light modulator of FIG. **10**, wherein the optical channels of the WDM input signals to the interleaver device, blocking filter and ROADM are distinctly projected onto the micro-mirror device, in accordance with the present invention;

FIG. **18** is a block diagram of a spatial-light modulator of another embodiment of a multifunctional optical device, wherein the optical channels of a WDM input signal are distinctly projected onto the micro-mirror device, in accordance with the present invention;

FIG. **19** is an enlarged view of a portion of another embodiment of a multifunctional optical device, in accordance with the present invention;

FIG. **20** is a block diagram of a spatial light modulator of another embodiment of a multifunctional optical device, wherein the optical channels of a WDM input signal are distinctly projected onto the micro-mirror device, in accordance with the present invention;

FIG. **21***a* is a block diagram of a spatial light modulator of another embodiment of a multifunctional optical device, wherein the optical channels of a WDM input signal are distinctly projected onto the micro-mirror device, in accordance with the present invention;

FIG. **21***b* is a block diagram of a spatial light modulator of another embodiment of an optical filter having a micro-mirror device, wherein the optical channels of a WDM input light are overlappingly dispersed onto the micro-mirror device in various degrees of overlap, in accordance with the present invention;

FIG. **22** shows an alternative embodiment of a reconfigurable multifunctional optical device having one or more optic devices for minimizing polarization dispersion loss (PDL);

FIG. **23** shows an embodiment of a reconfigurable multifunctional optical device having a chisel prism in accordance with the present invention;

FIG. **24** shows an alternative embodiment of a reconfigurable multifunctional optical device having a chisel prism in accordance with the present invention;

FIG. **25** shows an alternative embodiment of a reconfigurable multifunctional optical device having a chisel prism in accordance with the present invention;

FIG. **26** is side elevational view of a portion of the reconfigurable multifunctional optical device of FIG. **40**;

FIG. **27***a* is a graphical representation of a portion of the optical filter wherein the grating order causes the shorter wavelengths of light to image onto the micromirror device that is closer than the section illuminated by the longer wavelengths, in accordance with the present invention; and

FIG. **27***b* is a graphical representation of a portion of the optical filter wherein the grating order causes the longer wavelengths of light to image onto the micromirror device that is closer than the section illuminated by the shorter wavelengths in accordance with the present invention.

BEST MODE FOR CARRYING OUT THE INVENTION

The present invention provides a multifunctional optical device that uses a single spatial modulator to provide multiple optical switching and/or conditioning of at least one optical input signal. For example, the optical device may function as both an optical filter and a reconfigurable optical add/drop device (ROADM). Another example is an optical device that may function as an optical channel monitor (OCM) and a dynamic gain equalizer filter (DGEF). In this manner, the functionality of the spatial light modulator can be efficiently utilized. To better understand the specific embodiments of the present invention, a reconfigurable optical filter **10** is first described in FIGS. **1**–**9**, which has a substantial number of components common to the specific multifunctional embodiments.

Referring to FIGS. **1**–**3**, the reconfigurable optical filter **10** selectively filters or attenuates a desired optical channel **14** of light (i.e., a wavelength band) of an optical WDM input signal **12**. The optical filter **10** is similar to that shown and described in co-pending U.S. Patent Application Ser. No. 60/281,079, U.S. Patent Application Ser. No. 60/311,002, and U.S. Patent Application Ser. No. 60/525,066, which are incorporated herein by reference in their entirety. Each optical channel **14** (see FIG. **3**) of the input signal **12** is centered at a respective channel wavelength ($\lambda_1, \lambda_2, \lambda_3, \ldots \lambda_N$).

FIG. **1** is a top plan view of the optical filter **10**. To better understand the optical filter **10** of FIG. **1**, a side elevational view of the filter is illustrated in FIG. **2**. As shown in FIG. **2**, the optics of the filter **10** is disposed in two tiers or horizontal planes. Specifically, the filter includes a three-port circulator **18**, an optical fiber or pigtail **20**, a collimator **22**, a light dispersive element **24**, a mirror **26**, and a bulk lens **28** (e.g., a Fourier lens) for directing light to and from a spatial light modulator **30**. As shown, the pigtail **20**, the collimator **22** and the light dispersive element **24** are disposed in a first tier or horizontal plane. The mirror **26**, bulk lens **28** and the spatial light modulator **30** are disposed in the second tier or second horizontal plane which is substantially parallel to the first horizontal plane.

Referring to FIGS. **1** and **2**, the three-port circulator **18** directs light from a first port **32** to a second port **33** and from the second port to a third port **34**. The optical fiber or pigtail **20** is optically connected to the second port of the circulator **18**. A capillary tube **36**, which may be formed of glass, is attached to one end of the pigtail **20** such as by epoxying or collapsing the tube onto the pigtail. The circulator **18** at the first port **32** receives the WDM input signal **12** tapped from an optical network (not shown) via optical fiber **38**, and directs the input light to the pigtail **20**. The input signal **12** exits the pigtail (into free space) and passes through the collimator **22**, which collimates the input signal. The collimator **22** may be an aspherical lens, an achromatic lens, a doublet, a GRIN lens, a laser diode doublet or similar collimating lens. The collimated input signal **40** is incident on the light dispersion element **24** (e.g., a diffraction grating or a prism), which separates spatially the optical channels of the collimated input signal **40** by diffracting or dispersing the light from (or through) the light dispersion element.

In one embodiment, the diffraction grating **24** is comprised of a blank of polished fused silica or glass with a reflective coating (such as evaporated gold or aluminum), wherein a plurality of grooves **42** (or lines) are etched, ruled or otherwise formed in the coating. The diffractive grating **24** has a predetermined number of lines, such as 600 lines/mm, 835 lines/mm and 1200 lines/mm. The resolution of the optical filter **10** improves as the number of lines/mm in the grating increases. The grating **24** may be similar to those manufactured by Thermo RGL, part number 3325FS-660 and by Optometrics, part number 3-9601. Alternatively, the diffraction grating may be formed using holographic techniques, as is well known in the art. Further, the light dispersion element may include a prism or optical splitter to disperse the light as the light passes therethrough, or a prism having a reflective surface or coating on its backside to reflect the dispersed light.

As best shown in FIG. **2**, the diffraction grating **24** directs the separated light **44** to the mirror **26** disposed in the second tier. The mirror **26** reflects the separated light **44** to the bulk lens **28**, which focuses the separated light onto the spatial light modulator **30**, as shown in FIG. **3**. In response to a switching algorithm and input command **46**, the spatial light modulator **30** selectively attenuates at least one optical input channel and reflects the channels (one of which is attenuated) back through the same optical path to the pigtail **20** as indicated by arrows **94**, and reflects the attenuated portion of optical input channels away from the bulk lens **28** as indicated by arrows **96**, as best shown in FIG. **1**. The attenuated and non-attenuated input channels propagate from the second port **33** to the third port **34** of the optical circulator **18** to provide an output signal **48** from optical fiber **50**.

As shown in FIG. **3**, the spatial light modulator **30** comprises a micro-mirror device **82** having a two-dimensional array of micro-mirrors **84**, which cover a surface of the micro-mirror device. The micro-mirrors **84** are generally square and typically 14–20μ wide with 1μ spaces between them. FIG. **4***a* illustrates a partial row of micro-mirrors **84** of the micro-mirror device **82**, when the micro-mirrors are disposed in a first position to reflect the light back along the return path **94** and provide the selected input channel **14** to the optical fiber **50**. FIG. **4***b* illustrates a partial row of micro-mirrors **84** when the micro-mirrors are disposed in a second position, and therefore reflected the attenuated portion of the optical input channels **14** away from the return path, as indicated by arrows **96**. The micro-mirrors may operate in a "digital" fashion. In other words, the micro-mirrors either lie flat in a first position, as shown in FIG. **4***a*, or be tilted, flipped or rotated to a second position, as shown in FIG. **4***b*.

As described herein before, the positions of the mirrors, either flat or tilted, are described relative to the optical path **92** wherein "flat" refers to the mirror surface positioned orthogonal to the optical path, either coplanar in the first position or parallel as will be more fully described hereinafter. The micro-mirrors flip about an axis **85** parallel to the spectral axis **86**, as shown in FIGS. **3** and **5**. One will appreciate, however, that the micromirrors may flip about any axis, such as parallel to the spatial axis **88** or at a 45 degrees angle to the spatial axis.

Referring to FIG. **3**, the micro-mirrors **84** are individually flipped between the first position and the second position in response to a control signal **87** provided by a controller **90** in accordance with a switching algorithm and an input command **46** from the processing unit **54**. The switching algorithm may provide a bit (or pixel) map indicative of the state (flat or tilted) of each of the micro-mirrors **84** of the array to attenuate the desired optical channel(s) **14** to provide the output signal **48** at optical fiber **50** (see FIG. **1**), and thus requiring a bit map for each configuration of channels to be dropped. Alternatively, each group of micro-mirrors **84**, which reflect a respective optical channel **14**, may be individually controlled by flipping the group of micro-mirrors to direct the channel along a desired optical path.

As shown in FIGS. **1** and **4***a*, the micro-mirror device **82** is oriented to reflect the focused light **92** of the input signal **12** back through the bulk lens **28** to the pigtail **20**, as indicated by arrows **94**, to provide the output signal **48**, when the micro-mirrors **84** are disposed in the first position. As shown in FIGS. **1** and **4***b*, the focused light **92** reflects away from the bulk lens **28**, as indicated by arrows **96**. This "digital" mode of operation of the micro-mirrors advantageously eliminates the need for any type of feedback control for each of the micro-mirrors. The micro-mirrors are either "on" or "off" (i.e., first position or second position), respectively, and therefore, can be controlled by simple binary digital logic circuits.

FIG. **3** further illustrates the outline of the optical channels **14** of the optical input signal **12**, which are dispersed off the diffraction grating **24** and focused by the bulk lens **28**, onto the array of micro-mirrors **84** of the micro-mirror device **82**. Each optical channel **14** is distinctly separated from other channels across the spectrum and has a generally circular cross-section, such that the input channels do not substantially overlap when focused onto the spatial light modulator **30**. The optical channels have a circular cross-section that project the beam over a multitude of micro-mirrors **84**, while keeping the optical channels separated by a predetermined spacing. One will appreciate though that the diffraction grating **24** and bulk lens **28** may be designed to reflect and focus any input channel or group of input channels with any desired cross-sectional geometry, such as elliptical, rectangular, square, polygonal, etc. Regardless of the cross-sectional geometry selected, the cross-sectional area of the channels **14** should illuminate a plurality of micro-mirrors **84**, which effectively pixelates the optical channels. In an exemplary embodiment, the cross sectional area of the input channels **14** is generally circular in shape, whereby the spectral width of the optical channel beam spans over approximately 12 micromirrors.

One will appreciate that while the spacing between the channels are predetermined, the spacing between may be non-uniform. For example, one grouping of channels may be spaced to correspond to a 100 GHz spacing, and another group of channels may be spaced to correspond to a 50 GHz spacing.

While the embodiment of an optical filter embodying the present invention described hereinbefore includes optics disposed in two planes, one will appreciate that the optics may be disposed in one plane, as described in co-pending U.S. Patent Application Ser. No. 60/281,079, U.S. Patent Application Ser. No. 60/311,002, and U.S. Patent Application Ser. No. 60/325,066.

The micro-mirror device **82** of FIGS. **1**–**3** is similar to the Digital Micromirror Device™ (DMD™) manufactured by Texas Instruments and described in the white paper entitled "Digital Light Processing™ for High-Brightness, High-Resolution Applications", white paper entitled "Lifetime Estimates and Unique Failure Mechanisms of the Digital Micromirror Device (DMD)", and news release dated September 1994 entitled "Digital Micromirror Display Delivering On Promises of 'Brighter' Future for Imaging Applications", which are incorporated herein by reference.

FIG. **6** illustrates a pair of micro-mirrors **84** of a micro-mirror device **200** manufactured by Texas Instruments, namely a digital micromirror device (DMD™). The micro-mirror device **200** is monolithically fabricated by CMOS-like processes over a CMOS memory **202**. Each micro-mirror **84** includes an aluminum mirror **204**, 16μ square, that can reflect light in one of two directions, depending on the state of the underlying memory cell **202**. Rotation, flipping or tilting of the mirror **204** is accomplished through electrostatic attraction produced by voltage differences between the mirror and the underlying memory cell. With the memory cell **202** in the on (1) state, the mirror **204** rotates or tilts approximately +10 degrees. With the memory cell in the off (0) state, the mirror tilts approximately −10 degrees. As shown in FIG. **7**, the micro-mirrors **84** flip about an axis **205**.

FIGS. **8***a* and **8***b* illustrate the orientation of a micro-mirror device **200** similar to that shown in FIG. **6**, wherein neither the first or second position (i.e., on or off state) of the micro-mirrors **84** is parallel to the base or substrate **210** of the micromirror device **200**, as shown in FIGS. **4***a* and **4***b*. Consequently as shown in FIG. **8***a*, the base **210** of the micro-mirror device **200** is mounted at a non-orthogonal angle α relative to the collimated light **83** to position the micro-mirrors **84**, which are disposed at the first position, perpendicular to the collimated light **44**, so that the light reflected off the micro-mirrors in the first position reflect substantially back through the return path, as indicated by arrows **94**, to provide the output signal **48** at optical fiber **50**. Consequently, the tilt angle of the mirror between the horizontal position and the first position (e.g., 10 degrees) is approximately equal to the angle α of the micro-mirror device. FIG. **8***b* is illustrative of the micro-mirror device **200** when the micro-mirrors **84** are disposed in the second position to drop an input channel **14** to the output signal **48** at optical fiber **50**.

As described hereinbefore, the micro-mirrors **84** of the micro-mirror device **200** flip about a diagonal axis **205** as shown in FIGS. **7** and **9***a*. In an exemplary embodiment of the present invention shown in FIG. **9***a*, the optical input channels **14** are focused on the micro-mirror device **200** such that the spectral axis **86** of the optical channels **14** is parallel to the tilt axis **205** of the micro-mirrors. This configuration is achieved by rotating the micro-mirror device 45 degrees compared to the configuration shown in FIG. **3**. Alternatively, the optical channels **14** may be focused such that the spectral axes **86** of the channels are perpendicular to tilt axis **205** of the micro-mirrors. Further, one will appreciate that the orientation of the tilt axis **205** and the spectral axis **86** may be at any angle.

As shown in FIGS. **9***a* and **9***b*, the optical channels **14** are dispersed, such that the optical channels do not substantially overlap spectrally when focused onto the spatial light modulator **36**. For example, as shown in FIGS. **9***a* and **9***c*, the optical channels **14** are sufficiently separated such that when a channel is substantially attenuated or dropped (e.g. approximately 30 dB power loss) the adjacent channels are attenuated less than approximately 0.1% for unmodulated signals and less than approximately 0.2% for a modulated signal. In other words, as shown in FIGS. **9***c* and **9***d*, the optical channels are substantially separated and non-overlapping when an optical channel is attenuated or dropped (P_{LOSS}) such that the power of the adjacent channel drops less than a predetermined level (dA) at a predetermined delta (§ f) from the center frequency (or wavelength) of the adjacent channels. For example, for a 50 GHz WDM input signal wherein an optical channel at λ_2 is attenuated (P_{LOSS}) greater than 30 dB, the loss (dA) at adjacent channels is approximately less than 0.2 dB at the channel center +/−10 GHz.

In FIG. **10**, an embodiment of a multi-functional optical device **300** in accordance with the present invention is shown. The device combines the functions of an optical channel monitor (OCM) and an optical filter using one spatial modulator including a micromirror device. The optical device includes an optical filter portion **302** substantially the same as the optical filter **10** of FIGS. **1**–**3** described hereinbefore, and therefore like components have the same reference numerals. The functionality of the OCM is added to the filter portion **302** by adding a second pigtail **304**, a second circulator **306**, a photodetector **308** and a processing unit **310**. Not only does the OCM use a common spatial light modulator **30** in this embodiment, the OCM uses common free-space optics, namely the collimator **22**, mirror **26**, diffraction grating **24** and Fourier lens **28**. The OCM portion **312** of the optical device **300** is substantially the same as the OCM described in co-pending U.S. Patent Application Ser. No. 60/325,066, which is incorporated herein by reference in its entirety.

The ends of the pigtails **20**, **304** are spaced in the spatial direction **88** so that the input light **12**, **314** of the filter portion **302** and OCM portion **312**, respectively, propagate along separate optical paths and intersect the micromirror device **82** in separate non-overlapping areas. As a result, the diffracted light **92**, **316** is spaced spatially on the micromirror device **82** as illustrated in FIG. **11**. As shown, the diffracted light **316** of the input light **314** of the OCM **312** is spread spectrally over the upper portion of the micromirror device **82**, and the diffracted light **92** of the input light **12** of the optical filter **302** is spread spectrally over the lower portion of the micro-mirror device.

For the OCM **304**, a portion of the micromirrors are tilted to the second position, as indicated by the black squares, to reflected the optical channels **14** at λ_1, λ_2 and λ_4–λ_N away from the return path **318** as indicated by arrows **96**. The other micromirrors associated with the optical channel **14** at λ_3 are tilted to the first position, as indicated by the white squares, to reflect the optical channel at λ_3 back along the return path **318** to the second pigtail **304**. The returned optical channel **14** at λ_3 passes through the second circulator **306** to the photodetector **308**, which provides an electrical signal **320** indicative of the returned optical channel to the processing unit **310**. The processing unit provides an output signal to an external device(s) **322** and a control signal **46** to controller **90** of the spatial light modulator **30** to control the flipping of the micromirrors **84** for reflecting any optical channel or channels **14** to the photodetector **308** for sensing.

The optical filter **302** substantially operates as described hereinbefore. As shown in FIG. **11**, the micromirrors **84** of the micromirror device **82** are selectively tilted to attenuate at least one optical channel **14**. For instance, the optical channel **14** at λ_1 attenuate the upper and lower portions of the channel by tilting the micromirrors disposed at the upper and lower portions of the channel to the second position, as indicated by the black squares, to reflect the corresponding portions of light away from the return path **94** as indicated by arrows **96**. The other micromirrors disposed over the remaining portion of the optical channel **14** at λ_1 are tilted to the first position, as indicated by the white squares, to reflect that portion of the optical channel back along the return path to the first pigtail **20** to provide an output signal **48** at optical fiber **50**. As shown in FIG. **11**, any pattern or number of micromirrors may be titled to the second position to attenuate a particular optical channel **14**. Further, the present invention contemplates that the micro-mirrors **84** of the optical filter **302** may be tilted to function as a blocking filter as described in U.S. Patent Application Ser. No. 60/344,585, which is incorporated herein by reference in its entirety. Further, it is also contemplated that the micromirrors of the optical filter **302** may be titled to function as a dynamic gain equalization filter (DGEF) as described in U.S. Patent Application Ser. Nos. 60/281,019 and 60/311,002, which are incorporated herein by reference in their entirety.

While the DGEF (or optical filter) **302** and the OCM **312** of the multifunctional device of FIG. **9***a* operate independently having separate inputs and outputs, the present invention contemplates providing the output **50** of the DGEF to the input **321** of the OCM to provide a closed loop DGEF for a smart node, similar to that described in U.S. Patent Application Ser. No. 60/354,794, which is incorporated herein by reference in its entirety. In the operation, the OCM detects the output signal **48** of the DGEF **302** and provides a feedback signal **46** to the spatial light modulator **30**. The controller **90** of FIG. **11** then flips the micromirrors **84** to adjust the attenuate of the channels **14** of the optical channels of the input signal **12** of the DGEF.

In FIG. **12**, an embodiment of a multifunctional optical device **400** in accordance with the present invention is shown. The optical device **400** combines the functions of an optical channel monitor (OCM) and a reconfigurable optical add/drop multiplexer (ROADM) using one spatial modulator **30** including a micromirror device **82**. The optical device includes an OCM portion **402** substantially the same as the OCM portion **312** of FIG. **10** described hereinbefore, and therefore like components have the same reference numerals. The functionality of the ROADM is added to the OCM **402** by adding second and third pigtails **404**, **406**, second and third circulators **408**, **410**, and a second set of free-space optics **412** similar to the first set of free-space optics **414**. The second set of free-space optics includes a collimator **422**, a mirror **426**, a diffraction grating **424** and a Fourier lens **428**. Similar to the optical device **300**, both the OCM and ROADM use the first set of free-space optics **414**, namely the collimator **22**, mirror **26**, diffraction grating **24** and Fourier lens **28**, and a common spatial light modulator **30**. The ROADM portion **430** of the optical device **400** is substantially the same as an ROADM described in co-pending U.S. Patent Application Ser. No. 60/325,065, which is incorporated herein by reference in its entirety.

The ends of pigtails **304**, **404** are spaced in the spatial direction **88** so that the input signal **314**, **418** of the OCM portion **402** and the ROADM portion **430**, respectively, propagate along separate optical paths. Consequently, the diffracted light **316**, **431** is spaced on the micromirror device **82** as illustrated in FIG. **13**. As shown, the diffracted light **316** of the input light **314** of the OCM **312** is spread spectrally over the upper portion of the micromirror device **82**, and the diffracted light **431** of the input light **12** of the ROADM **430** is spread spectrally over the lower portion of the micromirror device.

The OCM **402** substantially operates as described hereinbefore for the OCM **313** of FIGS. **10**, **11**. As shown in FIG. **13**, a portion of the micromirrors **84** are tilted to the second position, as indicated by the black squares, to reflected the optical channels **14** at λ_1, λ_2, and λ_4–λ_N away from the return path **31** as indicated by arrows **96**. The other micromirrors associated with the optical channel **14** at λ_3 are tilted to the first position, as indicated by the white squares, to reflect the optical channel at λ_3 back along the return path **318** to pigtail **304**. The returned optical channel at λ_3 passes through the circulator **316** to the photodetector **308**, which provides an electrical signal **320** indicative of the returned optical channel **14** to the processing unit **310**. The processing unit provides an output signal to an external device(s) **322** and a control signal **46** to controller **90** of the spatial light modulator **30** to control the flipping of the micromirrors **84** for reflecting any optical channel or groups/band(s) of channels **14** to the photodetector **308** for sensing.

Referring to FIG. **12**, the ROADM **430** comprises a pair of optical portions **412**, **414** wherein one portion receives the optical input signal **418** and the other portion **412** receives an optical add signal **432**. The optics of the optical portion **414** is disposed in two tiers or horizontal planes similar to that described in FIGS. **1** and **2**. Specifically, the optical portion **414** includes a three-port circulator **408**, an optical fiber or pigtail **404**, a collimator **22**, a light dispersive element **24**, a mirror **26**, and a bulk lens **28** for directing light to and from a spatial light modulator **30**.

The circulator **408** receives the WDM input signal (IN) **418** from an optical network (not shown) via optical fiber **434**, and directs the input light to the pigtail **404**. The input signal **418** exits the pigtail **404** (into free space) and passes through the collimator **22**, which collimates the input signal. The collimated input signal **40** is incident on the light dispersion element **24** (e.g., a diffraction grating or a prism), which separates spatially the optical channels of the collimated input signal **40** by diffracting or dispersing the light from (or through) the diffraction grating **24**.

The diffraction grating **24** directs the separated light **44** to the mirror **26**. The mirror **26** reflects the separated light **44** to the Fourier lens **28** which focuses the separated light onto the spatial light modulator **30**, as shown in FIG. **13**. In response to a switching algorithm and input command **46**, the spatial light modulator **30** reflects selected optical input channel(s) away from the Fourier lens (i.e., the dropped channels) to the other optical portion **412** and reflects the remaining optical input channel(s) (i.e., returned or express optical channels) back through the same optical path to the pigtail **404**. The returned optical input channel(s) propagates through the optical circulator **408** to provide an express output signal **438** from optical fiber **440**.

The dropped channel(s) passes through the other optical portion **412** of the ROADM **430**. Specifically, the dropped channel(s) passes through the bulk lens **428** (e.g., a Fourier lens), and then reflects off the mirror **426** onto a light diffraction element **424** (e.g., a diffraction grating). The diffraction grating **424** further disperses the dropped channel(s). A collimator **422** focuses the dispersed light **62** onto the second pigtail **406**, which is optically connected to the second 3-port circulator **410**. The dropped channel(s) propagates from the second pigtail **406** to the output optical fiber **442** to provide an optical drop signal **444**.

One or more optical channels **14** of an optical WDM add signal **432** may be added to the express/output signal **438** by providing to the optical fiber **446** the optical channels to be added. The added channel(s) **14** exits the pigtail **406** and passes through the collimator **422** to the diffraction grating **424**, which separates spectrally the add channels of the collimated add signals **450** by dispersing or diffracting from (or through) the diffraction grating **424**. The diffraction grating **424** directs the separated light **452** to the mirror **426** disposed in the second tier, similar to that described above in FIG. **2**. The mirror **426** reflects the separated light **452** to the Fourier lens **28**, which focuses the separated light **452** onto the spatial light modulator **30**. The spatial light modulator **30** reflects selected add channel(s) of the separated light **452** to the Fourier lens **428** and reflects the remaining add channel(s) away from the spatial light modulator **30**, as shown by arrows **454**.

The selected add channel(s) **19** passes through the Fourier lens **28**, which are then reflected off the mirror **26** onto the diffraction grating **24**. The diffraction grating **24** further disperses the selected add channel(s) onto the collimator **22** which focuses the selected add channels to the pigtail **404**. The selected add channel(s) propagates from the pigtail **404** to optical fiber **440**, to thereby add the selected added channel(s) to the express/output signal **438**. As will be described hereinafter, the selected add channels **19** and input channels **14** at the same wavelengths reflect off the same portion of spatial light modulator **30**, and therefore when an add channel **19** is added to the express signal **438**, the corresponding input channel **14** is dropped simultaneously.

In the operation of the ROADM **430**, portions of the micromirrors **84** are tilted to the second position, as indicated by the black squares, to add and/or drop optical channels at λ_2, λ_6, λ_7 and λ_{10}. Specifically, the micromirrors at **456** reflect the optical channels **14** of the input light **418** at λ_2, λ_6, λ_7 and λ_{10} away from the return path **433**, as indicated by arrows **458**, to the drop output **442**. Further, the micromirrors at **456** reflect the optical channels **14** of the add signal **432** at λ_2, λ_6, λ_7 and λ_{10} along the return path, as indicated by arrows **433**, to the express output **440**. When the micromirrors **84** are tilted to the first position, as indicated by the white squares, the optical channels **14** of the input signal **418** are returned to the express output **440**, while the optical channels of the add signal **432** reflect along the optical path indicated by arrows **454**.

In FIG. **14**, an embodiment of a multi-functional optical device **500** in accordance with the present invention is shown. The optical device **500** combines the function of a reconfigurable optical filter **502**, an optical channel monitor (OCM) **504** and a reconfigurable optical add/drop multiplexer (ROADM) **506** using one spatial modulator **30**. The optical filter portion **502** is substantially the same as the optical filter portion **302** of FIG. **10** as described hereinbefore. The OCM portion **504** is substantially the same as the OCM portion **302** of FIG. **10** as described hereinbefore. The ROADM portion **506** is substantially the same as the ROADM portion **430** of FIG. **12** as described hereinbefore.

Not only does each device **502**, **504**, **506** use a common spatial light modulator **30** in this embodiment, the devices use a common set of free-space optics, namely the collimator **22**, mirror **26**, diffraction grating **24** and Fourier lens **28**, similar to the device **400** of FIG. **12**. The ends of the pigtails **20**, **304**, **404** of each device **502**, **504**, **506**, respectively, are spaced in the spatial direction **88** so that the input light **12**, **314**, **418** of the devices **502**, **504**, **506** propagate along separate optical paths. Consequently, the diffracted light is spaced spatially on the micromirror device as illustrated in FIG. **15**. As shown, the diffracted light of the input light **12** of the optical filter **502** is spectrally spread over the upper portion of the micromirror device **82**, the diffracted light of the input light **418** and add light **432** of the ROADM **506** is spectrally spread over the intermediate portion of the micromirror device, and the diffracted light of the input light **314** of the OCM **504** is spectrally spread over the lower portion of the micromirror device. The operation of the devices **502**, **504**, **506** is the same as the optical filter **302** of FIGS. **10**, the OCM **312** of FIG. **10** and the ROADM portion **430** of FIG. **12**, as described hereinbefore.

In FIG. **16**, an embodiment of a multi-functional optical device **600** in accordance with the present invention is shown. The device **600** combines the functions of an interleaver/deinterleaver device **602**, a dual pass blocking filter **604** and a reconfigurable optical add/drop multiplexer (ROADM) **606** using one spatial modulator **30**. Similar to the embodiments described hereinbefore, the devices **602**, **604**, **606** also use a common set of free-space optics **414**, namely the collimator **22**, mirror **26**, diffraction grating **24** and Fourier lens **28**, similar to the device **400** of FIG. **12**. In addition, the interleaver/deinterleaver device **602** and the ROADM **606** also use a second set of common optics **412** that comprise the collimator **422**, mirror **426**, diffraction grating **424** and Fourier lens **428**, similar to the device **400** of FIG. **12**. The ROADM portion **606** is substantially the same as the ROADM portion **430** of FIG. **12**, as described hereinbefore.

The functionality of the interleaver/deinterleaver device **602** is added to the ROADM device **606** by adding an input pigtail **610**, a circulator **612**, and an output pigtail **614**. Not only does the interleaver/deinterleaver device **602** use a common spatial light modulator **30** in this embodiment, the interleaver/deinterleaver device uses common first and second set of free-space optics **412**, **414**, namely the collimators **22**, **422**, mirrors **26**, **426**, diffraction grating **24**, **424** and Fourier lens **28**, **428**. The interleaver/deinterleaver portion **602** of the optical device **600** is substantially the same as the interleaver/deinterleaver described in co-pending U.S. Patent Application Ser. No. 60/325,064, which is incorporated herein by reference in its entirety.

The functionality of the dual pass blocking filter **604** is added to the ROADM device **606** by adding a pair of three-port circulators **620**, **622** and a pair of input pigtails **624**, **626**. Not only does the blocking filter **604** use a common spatial light modulator **30** in this embodiment, the blocking filter uses common set of free-space optics **412**, namely the collimators **22**, mirrors **26**, diffraction grating **24**, and Fourier lens **28**. The blocking filter **604** of the optical device **600** is substantially the same as the blocking filter described in co-pending U.S. Patent Application Ser. No. 60/344,585, which is incorporated herein by reference in its entirety.

The ends of the input pigtails **610**, **622**, **624**, **404** of each device **602**, **604**, **606** are spaced in the spatial direction **88** so that the input light **630**, **632**, **418** of the devices **602**, **604**, **606** propagate along separate optical paths. Consequently, the diffracted light is spaced spatially on the micromirror device **82** as illustrated in FIG. **17**. As shown, the diffracted light of the input light **630** of the interleaver device **602** is spectrally spread over the upper portion of the micromirror device **82**, the diffracted light of the input light **632** of the blocking filter **604** is spectrally spread over the intermediate portion of the micromirror device, and the diffracted light of the input light **418** of the ROADM **606** is spectrally spread over the lower portion of the micromirror device. The operation of the ROADM **606** is the same as the ROADM portion **312** of FIG. **12**, as described hereinbefore.

The interleaver/deinterleaver device **602** may function as an interleaver device or a deinterleaver device. As an interleaver, the device combines at least two optical WDM input signals **630**, **634** into a single optical output signal **636**. In one embodiment, as shown, one input signal **630** includes the odd input channels **14** (e.g., λ_1, λ_3, λ_5), and the other input signal **634** includes the even input channels (e.g., λ_2, λ_4, λ_6). The combined input signals **630**, **634** provide a WDM output signal having each input channel **14**, **14'** (e.g., λ_1–λ_6). As a deinterleaver, the deinterleaver device separates an optical WDM input signal **642** into at least two optical output signals **638**, **640**. In one embodiment, as shown, the input signal **642** includes a WDM output signal having input channels at λ_1–λ_6. The input signal **642** is separated such that one output signal **638** includes the odd input-channels **14**,**14'** (i.e., λ_1, λ_3, λ_5), and the other output signal **640** includes the even input channel (i.e., λ_2, λ_4, λ_6). In FIG. **16**, the input signals **630**, **634** and output signal **636** of the interleaver device are shown as solid arrows, while the input signal **642** and the output signals **638**, **640** of the deinterleaver device are shown as dashed arrows. To simplify the description of the present invention, the interleaver/deinterleaver device is described as an interleaver, however, one should appreciate that the device may function as a deinterleaver by configuring one of the input ports to an output port, as illustrated by the dashed arrows **638**, **640**, **642**.

Accordingly, the interleaver device **602** comprises a pair of optical portions **412**, **414** that focuses and receives light to and from the spatial light modulator **30**. A three-port circulator **612** provides input signals **630** to and receives an output signal **636** (at optical fiber **644**) from the optical portion **414** via pigtail **610**. The pigtail **614** receives the other input signal **634** from the second optical portion **412**.

The first input signal **630** exits pigtail **610** (into free space) and passes through the first collimator **22**, which collimates the first input signal. The collimated input signal is incident on the light dispersion element **24** (e.g., a diffraction grating or a prism), which separates spatially the optical channels of the collimated input signal by diffracting or dispersing the light from (or through) the first light dispersion element. The diffraction grating **24** directs the separated light to the mirror **26**. The first mirror **26** reflects the separated light to the first bulk lens **28** (e.g., a Fourier lens), which focuses the separated light onto the spatial light modulator **30**, as shown in FIG. **17**.

In response to a switching algorithm and input command **46**, the spatial light modulator **30** reflects the optical input channel(s) **14** of first input signal back through the same optical path to the pigtail **610**. The returned optical input channel(s) propagates to the optical circulator **612** to provide an output signal **636** from optical fiber **642**.

The optical channels **14'** of the second input signal **634** are combined with or added to the output signal **636**. The channel **14'** of the second input signal **634** exit the second pigtail **614** and passes through the collimator **422** to the diffraction grating **424**, which separates spectrally the channels **14'** of the collimated second input signal **634** by dispersing or diffracting from (or through) the diffraction grating **424**. The diffraction grating **424** directs the separated light to the mirror **426** for the optical portion **412**. The mirror **426** reflects the separated light to the bulk lens **428**, which focuses the separated light onto the spatial light modulator **30**. As shown in FIG. **17**, the separated light of the first input signal **630** and the separate light of the second input signal **634** occupy different, alternating portion (or sections) of the spatial light modulator **30**. The spatial light modulator **30** reflects the channel **14'** of the separated light to the bulk lens **28**.

The channel **14'** of the second input signal **634** passes through the bulk lens **28**, which are then reflected off the mirror **26** onto the diffraction grating **24**. The diffraction grating **24** further disperses the channel **14'** onto the collimator **22** which focuses the channels **14'** to the pigtail **610**. The channels **14'** propagate from the pigtail **610** to optical fiber **642**, to thereby combine the channels **14'** to the output signal **636**.

FIG. **17** further illustrates the outline of the optical channels **14**, **14'** of the first and second input signals **630**, **634**, respectively, which are dispersed off respective diffraction gratings **24**, **424** and focused by bulk lens **28**, **428** respectively, onto the array of micro-mirrors **84** of the micro-mirror device **82**. Each channel **14**, **14'** is distinctly separated from other channels across the spectrum and have a generally circular cross-section, such that the optical channels do not substantially overlap spatially when focused onto the spatial light modulator **30**. The optical channels have a circular cross-section to project as much of the beam as possible over a multitude of micro-mirrors **84**, while keeping the optical channels separated by a predetermined spacing. One will appreciate though that the diffraction gratings **24**, **424** and bulk lens **28**, **428** may be designed to reflect and focus any optical channel or group of optical channels with any desired cross-sectional geometry, such as elliptical, rectangular, square, polygonal, etc. Regardless of the cross-sectional geometry selected, the cross-sectional area of the channels **14** should illuminate a plurality of micro-mirrors **84**, which effectively pixelates the optical channels.

FIG. **17** further illustrates the position of the micro-mirrors **84** of the micro-mirror device **82** for combining the optical channels **14**, **14'** of the input signals **630**, **634**. The outline of each channel **14**, **14'** is shown to provide a reference to visually locate the groups of tilted mirrors **650**. As shown, the groups of mirrors **650** associated with each respective optical channel **14'** at λ_2, λ_4, λ_6, λ_8, λ_{10}, λ_{12} of the second input signal **634** are tilted away from the return path to the second position, as indicated by the blackening of the micro-mirrors **84**. Each group of tilted mirrors **650** provides a generally rectangular shape, but one will appreciate that any pattern or shape may be tilted to redirect an optical channel. In an exemplary embodiment, each group of micro-mirrors **650** reflects substantially all the light of each respective optical channel **14'** and reflects substantially no light of any adjacent channels. The remaining micro-mirrors **84** reflects substantially all the light of each channel **14** at λ_1, λ_3, λ_5, λ_7, λ_9 are flat (i.e., first position), as indicated by the white micro-mirrors, to reflect the light back along the return path to the first pigtail **610**, as described hereinbefore.

Referring to FIGS. **16** and **17** in the operation of the blocking filter **604**, the input signal **632** is first dispersed by the diffraction grating **24** onto the micro-mirror device **82** of the spatial light modulator **30**. Each input channel **14** is spread along the spectral axis **86** as shown in FIG. **17**. The groups **452**, **453**, **454** of shaded micro-mirrors **84** delete the optical input channels at λ_2, λ_6, λ_7 and λ_{10} of the input signal **632**, and reflect the through input channels at λ_1, λ_3–λ_5, λ_8, λ_9 and λ_{11}–λ_N back to the first pigtail **622**. The through input channels at λ_1, λ_3–λ_5, λ_8, λ_9 and λ_{11}–λ_N then propagate to second pigtail **624** through the circulators **620**, **622** respectively. The end of the second pigtail **624** is displaced spatially such that the through input channels **14'** at λ_1, λ_3–λ_5, λ_8, λ_9 and λ_{11}–λ_N are dispersed onto the micro-mirror device **82** and spaced in the spatial axis **88** a predetermined distance from the input channels **14** at λ_1–λ_N, as shown in FIG. **17**. The micro-mirrors **84** are titled to reflect the selected input channel **14'** back to second pigtail **624**, while the micro-mirrors adjacent the input channels at λ_2, λ_6, λ_7 and λ_{10} are tilted to delete any remaining light. The through input channels **14'** then propagate through the second circulator **622** to the output fiber **656** to provide output signal **658**.

While the embodiments of the present invention described hereinbefore provide optical channels having a circular cross-section imaged on the micromirror device **82** of the spatial light modulator **30**, the present invention contemplates imaging optical channels onto the micromirror device having different cross-sectional geometry as shown in FIG. **18**. As shown, the cross-sectional geometry of one optical function is elliptical while the cross-sectional geometry of the second optical function is circular. To accomplish the different cross-sections using the same optical components (e.g., collimator **28**), an additional lens **700** (e.g., a cylindrical lens) is provided in the optical path of one of the collimated light beams as shown in FIG. **19**.

In the embodiments of the present invention described hereinbefore, the launch pigtails of the optical function are spaced in the spatial direction **88** that results in the channels of the corresponding input signals being similarly space in the spatial direction. The present invention, however, contemplates spacing the launch pigtail in the spectral direction **86**, such that the respective input channels **14** of each function are spaced sequentially in the spectral direction as shown in FIGS. **20** and **21***a*. FIG. **20** is also illustrative of the optical channels of each input signal having a different cross-sectional geometry, and the channels of the respective input channels have different spacing.

FIG. **21***a* illustrates an optical channel of the second function that is spread over a large number of micromirrors **84** similar to that used to provide an optical chromatic dispersion compensation device as described in U.S. Patent Application Ser. No. 60/332,318 which is incorporated herein by reference. FIG. **21***b* shows an embodiment wherein the optics (i.e., collimating lens **26**, bulk lens **34** and diffraction grating **24**) spread or disperse the input light onto the micromirror device such that the optical channels substantially overlap. The tilt of a micromirror will filter or attenuate the light of two or more adjacent channels. See patent application Ser. No. 10/115,647 for an example of this technology applied to a digital signal equalizers.

FIG. **22** shows an embodiment of a reconfigurable multifunctional optical device generally indicated as **1000** having optical portions **15**, **16** with one or more optical PDL devices **1002**, **1004**, **1006**, **1008** for minimizing polarization dependence loss (PDL). The one or more optical PDL devices **1002**, **1008** are arranged between the capillary tube **36** and the grating **24**, while the one or more optical PDL devices **1004**, **1006** are arranged between the grating **24** and the spatial light modulator **30**.

The optical PDL device **1002** may include a polarization splitter for splitting each channel into its pair of polarized light beams and a rotator for rotating one of the polarized light beams of each optical channel. The optical PDL device **1008** may include a rotator for rotating one of the previously rotated and polarized light beams of each optical channel and a polarization splitter for combining the pair of polarized light beams of each channel.

The one or more optical devices **1002**, **1004**, **1006**, **1008** may be incorporated in any of the embodiments shown and described above, including but not limited to the embodiments shown and described above.

In effect, as a person skilled in the art will appreciate, a diffraction grating such as the optical elements **42**, **54** has a predetermined polarization dependence loss (PDL) associated therewith. The PDL of the diffraction grating **24** is dependent on the geometry of the etched grooves **42** of the grating. Consequently, means to mitigate PDL may be desired. The λ/4 plate between the spatial light modulator **30** and the diffraction grating(s) **24**, **54** (before or after the bulk lens **28**, **52**) mitigates the PDL for any of the embodiments described hereinbefore. The fast axis of the λ/4 plate is aligned to be approximately 45 degrees to the direction or axis of the lines **42** of the diffraction grating **24**. The mirror is angled to reflect the separated channels back through the λ/4 plate to the diffraction grating. In the first pass through the λ/4 plate, the λ/4 plate circularly polarizes the separated light. When the light passes through the λ/4 plate again, the light is linearly polarized to effectively rotate the polarization of the separated channels by 90 degrees. Effectively, the λ/4 plate averages the polarization of the light to reduce or eliminate the PDL. One will appreciate that the λ/4 plate may not be necessary if the diffraction grating has low polarization dependencies, or other PDL compensating techniques are used that are known now or developed in the future.

As shown and described herein, the polarized light beams may have a generally circular cross-section and are imaged at separate and distinct locations on the spatial light modulator **30**, such that the polarized light beams of the optical channels do not substantially overlap spatially when focused onto the spatial light modulator, as shown, for example, in FIGS. **6**, **18**, **25**, **34** and **35**.

FIG. **23** shows a reconfigurable multifunctional optical device generally indicated as **1600** similar to that shown above, except that the micromirror device is oriented such that the tilt axis **85** is perpendicular to the spectral axis **86**. The reconfigurable multifunctional optical device **1600** has a chisel prism **1602** arranged in relation to the spatial light modulator **30**, a set of optical components **1604**, a retromirror **1605** and a complimentary set of optical components **1606**. The underlying configuration of the reconfigurable multifunctional optical device **1600** may be implemented in any of the embodiments show and described in relation to that shown and described above in which the pivot or tilt axis of the mirrors of the DVD device is perpendicular to the spectral axis of the channels projected on the DVD device.

The set of optical components **1604** and the complimentary set of optical components **1606** are similar to the optical portions **15**, **16** shown and described herein. For example, see FIG. **1**A. The spatial light modulator **30** is shown and described herein as the well known DMD device. The chisel prism **1602** has multiple faces, including a front face **1602***a*, first and second beveled front faces **1602***b*, **1602***c*, a rear face **1602***d* and a bottom face generally indicated by **1602***e*. (It is noted that in embodiments having no retroflector or third optical path only two front faces are used, and in embodiments having a retroflector all three front faces are used.) Light from the set of optical components **1604** and the complimentary set of optical components **1606** passes through the chisel prism **1602**, reflects off the spatial light modulator, and passes back through the chisel prism **1602**.

The chisel prism design described herein addresses a problem in the optical art when using micromirror devices. The problem is the ability to send a collimated beam out to a reflective object and return it in manner that is insensitive to the exact angular placement of the reflective object. Because a light beam is typically collimated and spread out over a relatively large number of micromirrors, any overall tilt of the array causes the returned beam to "miss" the optical component, such as a pigtail, intended to receive the same.

The present invention provides a way to reduce the tilt sensitivity by using a classical optical design that certain combinations of reflective surfaces stabilize the reflected beam angle with respect to angular placement of the reflector. Examples of the classical optical design include a corner-cube (which stabilize both pitch and yaw angular errors) or a dihedral prism (which stabilize only one angular axis.).

One advantage of the configuration of the present invention is that it removes the tilt sensitivity of the optical system (which may comprise many elements besides a simple collimating lens such as element **26** shown and described above) leading up to the retro-reflective spatial light modulator **30**. This configuration allows large beam sizes on the spatial light modulator without the severe angular alignment sensitivities that would normally be seen.

Patent application Ser. No. 10/115,647, which is hereby incorporated by reference, shows and describes the basic principal of these highly stable reflective elements in which all the surfaces of the objects being stable relative to one another, while the overall assembly of the surfaces may be tilted without causing a deviation in reflected angle of the beam that is large compared to the divergence angle of the input beam.

FIG. **24** illustrates a schematic diagram of reconfigurable multifunctional optical device generally indicated as **1700** that provides improved sensitivity to tilt, alignment, shock, temperature variations and packaging profile, which incorporates such a tilt insensitive reflective assembly. The scope of the invention is intended to include using the chisum prism technology described herein in any one or more of the embodiments described herein.

Similar to the embodiments described hereinbefore, and by way of example, the reconfigurable multifunctional optical device **1700** includes a first set of optical components having a dual fiber pigtail **1702** (circulator free operation), the collimating lens **26**, a bulk diffraction grating **42**, a Fourier lens **34**, a 1/4λ plate **35**, a reflector **26** and a spatial light modulator **1730** (similar to that shown above). The dual fiber pigtail **1702** includes a transmit fiber **1702*a*** and a receive fiber **1702*b***. The first set of optical components typically provide a first optical input signal having one or more optical bands or channels on the receive fiber **1702*b***, as well as providing an optical output signal on the transmit fiber **1702*b***.

Similar to the embodiments described hereinbefore, the reconfigurable multifunctional optical device **1700** also includes a complimentary set of optical components **1703** for providing a second optical input signal, which is typically an optical signal to be added to the first optical input signal.

The reconfigurable multifunctional optical device **1700** also includes a chisel prism **1704** having multiple internally reflective surfaces, including a top surface, a back surface, as well as transmissive surfaces including two front surfaces and a bottom surface, similar to that shown in FIG. **23**. The micro-mirror device **1730** is placed normal to the bottom surface, as shown. In operation, the chisel prism **1704** reflects the first optical input signal from the first set of optical components and the second optical input signal from the complimentary set of optical components **1703** both to the spatial light modulator **1730**, and reflects the optical output signal back to the first set of optical components.

The chisel prism **1704** decreases the sensitivity of the optical filter to angular tilts of the optics. The insensitivity to tilt provides a more rugged and robust device to shock vibration and temperature changes. Further, the chisel prism **1704** provides greater tolerance in the alignment and assembly of the optical filter **1700**, as well as reduces the packaging profile of the filter. To compensate for phase delay associated with each of the total internal reflection of the reflective surfaces of the prism (which will be described in greater detail hereinafter), a λ/9 wave plate **1708** is optically disposed between the prism **1704** and the λ/4 wave plate **35**. An optical wedge or lens **1710** is optically disposed between the λ/4 wave plate **35** and the diffraction grating **30** for directing the output beam from the micro-mirror device **1730** to the receive pigtail **1702*a*** of the dual fiber pigtail **1702*b***. The optical wedge or lens **1710** compensates for pigtail and prism tolerances. The scope of the invention is intended to cover embodiments in which the optical wedge **1710** is arranged parallel or oblique to the front surface of the wedge **1704**. Moreover, as shown, these components are only arranged in relation to one front surface; however, as a person skilled in the art would appreciate, these optical components would typically be arranged in relation to any one or more front surfaces shown in FIG. **24**, as well as the front surfaces in the other chisel prism embodiments shown ad described herein.

The optical device **1700** further includes a telescope **1712** having a pair of cylindrical lens that are spaced a desired focal length. The telescope **1712** functions as a spatial beam expander that expands the input beam (approximately two times) in the spectral plane to spread the collimated beam onto a greater number of lines of the diffraction grating. The telescope **1712** may be calibrated to provide the desired degree of beam expansion. The telescope advantageously provides the proper optical resolution, permits the package thickness to be relatively small, and adds design flexibility.

A folding mirror **1714** is disposed optically between the Fourier lens **34** and the λ/4 wave plate **35** to reduce the packaging size of the optical filter **1700**.

FIG. **25** shows a practical embodiment of a tilt-insensitive reflective assembly **1800** comprising a specially shaped prism **1804** (referred as the "chisel prism") arranged in relation to the micro-mirror device **1830**, a set of optical components as shown, a compliment set of optical components generally indicated as **1805**, as well as a retroreflector **1803** consistent with that discussed above.

Unlike an ordinary 45 degree total internal reflection (TIR) prism, in this embodiment the back surface **1821** of the prism **1804** is cut at approximately a 48 degree angle indicated as **1804*a*** relative to the bottom surface **1820** of the prism **1804**. The top surface **1822** of the prism **1804** is cut at a 4 degree angle indicated as **1804*b*** relative to the bottom surface **1820** to cause the light to reflect off the top surface **1822** via total internal reflection. The front surface **1823** of the prism **1804** is cut at a 90 degree angle relative to the bottom surface **1820**. The prism **1804** therefore provides a total of 4 surface reflections in the optical assembly (two TIRs off the back surface **1821**, one TIR off the micromirror device **1830**, and one TIR off the top surface **1822**.)

In order to remove the manufacturing tolerances of the prism angles, a second smaller compensating prism or wedge **1810** (or wedge), having a front surface cut at a shallow angle (e.g., as 10 degrees) with respect to a back surface, may also be used. Slight tilting or pivoting about a pivot point of the compensation wedge **1810** causes the light beam to be pointed in the correct direction for focusing on the receive pigtail **1802**.

The combination of the chisel prism **1804** and the compensation wedge **1810** allows for practical fabrication of optical devices that spread a beam out over a significant area and therefore onto a plurality of micromirrors, while keeping the optical system robust to tilt errors introduced by vibration or thermal variations.

In FIG. **26**, the input light rays **1826*a*** first pass through the λ/4 wave plate **35** and the λ/9 wave plate **1840**. The input rays **1826*a*** reflect off the back surface **1821** of the prism **1804** the micro-mirror device **1830**. The rays **1826*b*** then reflect off the micromirror device **1830** back to the back surface **1821** of the prism **1804**. The rays **1826*b*** then reflect off the top surface **1822** for a total of 4 surfaces (an even number) and passes through the front surface **1823** of the prism **1804**. The rays **1826*b*** then pass back through the λ/4 wave plate **35** and the λ/9 wave plate **1840** to the wedge **1810**. The wedge **1810** redirects the output rays **1826*c*** to the receive pigtail **1802** (FIG. **24** of the dual fiber pigtails **1802**. As shown by arrows, the wedge **1810** may be pivoted about its long axis **1850** during assembly to slightly steer the output beam **1826*c*** to the receive pigtail **1802** with minimal optical loss by removing manufacturing tolerances of the chisel prism.

In FIG. **25**, the prism **1804** (with wave plates **35**, **1840** mounted thereto) and the micro-mirror device **1830** are mounted or secured in fixed relations to each other. The prism **1804** and micro-mirror device **1830** are tilted a predetermined angle off the axis of the input beam **614** (e.g., approximately 9.2 degrees) to properly direct the input beam onto the micromirrors of the micromirror device, as described hereinbefore. The wedge **1810** however is perpendicular to the axis of the input beam **1826*a***. Consequently, the receive pigtail of the dual fiber pigtail **1802** is rotated a predetermined angle (approximately 3 degrees) from a vertically aligned position with the transmit pigtail. Alternatively, the wedge **1810** may be rotated by the same predetermined angle as the prism and the micromirror device (e.g., approximately 9.2 degrees) from the axis of the input beam. As a result, the receive pigtail of the dual pigtail assembly **1802** may remain vertically aligned with transmit pigtail.

FIGS. **27***a* and **27***b* illustrate a technique to compensate for this diffraction effect introduced by the micromirror array **100**, described hereinbefore. As shown, each optical channel **14** is dispersed onto the micro-mirrors array **100** along the spectral axis or direction **86** such that each optical channel or group of optical channels are spread over a plurality of micro-mirrors.

FIG. **27***a* illustrates the case where a grating order causes the shorter wavelength light to hit a part of the micro-mirror array **100** that is closer than the section illuminated by the longer wavelengths. In this case the Fourier or bulk lens **28** is placed at a distance "d" from the grating **30** that is shorter than focal length "f" of the Fourier lens **28**. For example, the distance "d" may be approximately 71 mm and the focal length may be approximately 82 mm. It may be advantageous to use this configuration if package size is limited, as this configuration minimizes the overall length of the optical train.

FIG. **27***b* illustrates the case where the grating order causes the longer wavelengths to hit a part of the micromirror array **100** that is closer than the section illuminated by the shorter wavelengths. In this case the Fourier lens **28** is placed a distance "d" from the grating **30** that is longer than focal length "f" of the Fourier lens **28**. This configuration may be advantageous to minimize the overall area illuminated by the dispersed spectrum on the micromirror array.

The Scope of the Invention

While the micro-mirrors **84** may switch discretely from the first position to the second position,. as described hereinabove, the micro-mirrors may move continuously (in an "analog" mode) or in discrete steps between the first position and second position. In the "analog" mode of operation the micro-mirrors can be can be tilted in a continuous range of angles. The ability to control the angle of each individual mirror has the added benefit of much more attenuation resolution than in the digital control case. In the "digital" mode, the number of micro-mirrors **84** illuminated by each channel determines the attenuation step resolution. In the "analog" mode, each mirror can be tilted slightly allowing fully continuous attenuation of the return beam. Alternatively, some combination of micro-mirrors may be switched at a predetermined or selected pulse width modulation to attenuate the optical channel or band.

One will appreciate though that the diffraction grating **24** and bulk lens **28** may be designed to reflect and focus any input channel or group of input channels with any desired cross-sectional geometry, such as elliptical, rectangular, square, polygonal, etc.

The embodiments of the present invention described hereinbefore include a common spatial light modulator **30** and other optical components, namely a collimating lens **22**, a mirror **26**, a diffraction grating **24** and a bulk lens **28**. The present invention, however, contemplates having separate and distinct components that image onto a common spatial light modulator. One should therefore appreciate that any of the optical devices referenced herein may be combined with any other optical devices referenced herein, including any alternative embodiments, using a common spatial light modulator and/or other common optical components.

While the embodiments of the present invention described hereinbefore describe multi-functional devices wherein the functions of each device operate independent of the others, one will appreciate that the present invention contemplates interconnecting the inputs and outputs of the separate devices to provide another level of functionality, similar to that described for FIG. **10**.

One should also appreciate that the only limit on the number of multifunctional device utilizing a single spatial light modulator is the number of pixels per channel that provide the required per channel attenuation or switching variation or the required channel plan independence.

Although the invention has been described as using an array of digital micro-mirrors to implement the pixelating device in the embodiments shown herein, it should be understood by those skilled in the art that any pixelating device that provides pixelated optical signal processing may be used, as described further below. Further, instead of using micro-mirrors with two reflective states or angles of reflection (e.g., +/−10 deg) as a pixel that reflects a portion of the light beam, the pixels may have one reflective state and the other state may be absorptive or transmissive. Alternatively, instead of the pixel having at least one state being reflective (which may provide other design advantages), the pixel may have one state being transmissive and the other state being absorptive. Alternatively, the pixel may have two transmissive or partially transmissive states that refract the incoming light out at two different angles. For each of various pixelating devices, the optics surrounding the pixelating device would be changed as needed to provide the same functions as that described for each of the embodiments herein for the different type of pixelated optical signal processing used.

Also, instead of the pixels having a square, diamond or rectangular shape, the pixels may have any other two or three-dimensional shapes, i.e., circle, oval, sphere, cube, triangle, parallelogram, rhombus, trapezoid.

The spatial light modulator is shown and described herein as a DMD device; however, the scope of the invention is intended to include other types of light modulator devices. For example, the spatial light modulator may also include a pixelating device, based on, for example, liquid crystal technology, such as a liquid crystal display (LCD). An LCD may provide a device having either one absorptive state and one reflective state, or one absorptive state and one transmissive state. The underlying principle of an LCD is the manipulation of polarized light (i.e., an optical channel). For example, the polarized light may be rotated by 90 degrees in one state of the liquid crystal and not rotated in another state. To provide an LCD having one absorptive state and one transmissive state, a polarizer is provided at each side of the liquid crystal, such that the polarization angles of the polarizers are offset by 90 degrees. A mirror can be added at one end to provide an LCD having one absorptive state and one reflective state.

One example of having a reflective state and a transmissive state is a variation on existing bubble jet technology currently produced by Agilent and Hewlett-Packard Co., and described in U.S. Pat. Nos. 6,160,928 and 5,699,462, respectively. In that case, when the bubble is in one state, it has total internal reflection; and when in the other state, it is totally transmissive. Also in that case, the pixels may not be square but circular or oval.

One example of having a transmissive state and an absorptive state is Heterojunction Acoustic Charge Transport (HACT) Spatial Light Modulator (SLM) technology, such as that described in U.S. Pat. Nos. 5,166,766, entitled "Thick Transparent Semiconductor Substrate, Heterojunction Acoustic Charge Transport Multiple Quantum Well Spatial Light Modulator", Grudkowski et al and 5,158,420, entitled "Dual Medium Heterojunction Acoustic Charge Transport Multiple Quantum Well Spatial Light Modulator" to Grudkowski et al, provided the material used for the HACT SLM will operate at the desired operational wavelength. In that case, the pixels may be controlled by charge packets that travel along a surface acoustic wave that propagates along the device, where the size of the charge controls the optical absorption.

The dimensions and geometries for any of the embodiments described herein are merely for illustrative purposes and, as much, any other dimensions may be used if desired, depending on the application, size, performance, manufacturing requirements, or other factors, in view of the teachings herein.

It should be understood that, unless stated otherwise herein, any of the features, characteristics, alternatives or modifications described regarding a particular embodiment herein may also be applied, used, or incorporated with any other embodiment described herein. Also, the drawings herein are not drawn to scale.

Although the invention has been described and illustrated with respect to exemplary embodiments thereof, the foregoing and various other additions and omissions may be made therein without departing from the spirit and scope of the present invention.

We claim:

1. A reconfigurable multifunctional optical device comprising:

an optical arrangement for receiving a first optical input signal and a second optical input signal, each of the first and second optical input signals having optical bands or channels, the optical arrangement having a free optics configuration with a light dispersion element for spreading each of the first and second optical input signals into respective optical bands or channels on separate portions of a spatial light modulator having an array of micromirrors and being programmable to perform separate optical functions on each of the first and second optical signals;

the spatial light modulator having a first set of micromirrors programmed to perform a first overall optical function on the first optical input signal, and having a second set of micromirrors programmed to perform a second overall optical function on the second optical input signal, wherein the first overall optical function and second overall optical function are different.

2. A reconfigurable multifunctional optical device according to claim **1**, wherein the separate optical functions include reflecting the first and second optical input signals off separate non-overlapping areas on the spatial light modulator.

3. A reconfigurable multifunctional optical device according to claim **1**, wherein the separate optical functions include optical switching, conditioning or monitoring functions such as either an optical add/drop multiplexer function, an optical channel monitor function, an optical cross-connect function, an optical interleaver/deinterleaver, an optical filtering function, or any some combination thereof.

4. A reconfigurable multifunctional optical device according to claim **1**, wherein the light dispersion elements include either a diffraction grating, an optical splitter, a holographic device, a prism, or a combination thereof.

5. A reconfigurable multifunctional optical device according to claim **4**, wherein the diffraction grating is a blank of polished fused silica or glass with a reflective coating having a plurality of grooves either etched, ruled or suitably formed thereon.

6. A reconfigurable multifunctional optical device according to claim **1**, wherein the light dispersion element is oriented to spread the at least two optical input signals along a spectral axis, wherein the spectral axis is parallel to the tilt axis of the micromirrors of the spatial light modulator.

7. A reconfigurable multifunctional optical device according to claim **6**, wherein the switching algorithm is based on the wavelength of the at least two optical input signals.

8. A reconfigurable multifunctional optical device according to claim **7**, wherein the one or more optical portions provide one optical input signal, the other optical input signal, or a combination thereof as different channels having different wavelengths on the spatial light modulator.

9. A reconfigurable multifunctional optical device according to claim **8**, wherein the different channels have a desired cross-sectional geometry, including elliptical, rectangular, square or polygonal.

10. A reconfigurable multifunctional optical device according to claim **8**, wherein the spatial light modulator is configured so one group of channels is spaced at 100 GHz and another group of channels is spaced at 50 GHz.

11. A reconfigurable multifunctional optical device according to claim **6**, wherein the light dispersion element is oriented to spread the optical signal along a spectral axis, wherein the spectral axis is perpendicular to the tilt axis of the micromirrors of the spatial light modulator.

12. A reconfigurable multifunctional optical device according to claim **1**, wherein the spatial light modulator includes an array of micro-mirrors having a multiplicity of micro-mirrors that are separately controllable for tilting on an axis depending on a control signal in accordance with a switching algorithm.

13. A reconfigurable multifunctional optical device according to claim **1**, wherein the at least two optical input signals include a wavelength division multiplexed (WDM) optical input signal having a plurality of wavelengths and a corresponding plurality of optical bands or channels, each optical band or channel reflecting off a respective group of micro-mirrors of the micro-mirror device.

14. A reconfigurable multifunctional optical device according to claim **13**, wherein the respective group of micro-mirrors are collectively tilted to reflect channels in the at least two optical input signals.

15. A reconfigurable multifunctional optical device according to claim **1**, wherein the different optical characteristics includes different channel spacing, the shape of the light beam, the center wavelength of the light beam of the at least one optical signal, or some combination thereon.

16. A reconfigurable multifunctional optical device according to claim **1**, wherein each micro-mirror is tiltable in either a first position or a second position along an axis either substantially parallel to the spectral axis of the at least two optical input signals, parallel to the spatial axis of the at least two optical input signals, or at an angle of 45 degrees in relation to the spatial axis.

17. A reconfigurable multifunctional optical device according to claim **1**, wherein the optical arrangement includes one or more optical portions that provide the at least two optical input signals to the spatial light modulator, and also provide reflected optical signals depending on the first optical function and the second optical function.

18. A reconfigurable multifunctional optical device according to claim **17**, wherein the one or more optical portions include either one or more circulators, one or more waveguides, or a combination thereof.

19. A reconfigurable multifunctional optical device according to claim 18, wherein the one or more circulators includes a pair of circulators.

20. A reconfigurable multifunctional optical device according to claim 18, wherein the one or more waveguides includes a pair of capillary tubes.

21. A reconfigurable multifunctional optical device according to claim 18, wherein the one or more circulators includes a three port circulator.

22. A reconfigurable multifunctional optical device according to claim 17, wherein the one or more optical portions include a pair of optical portions, including one optical portion for providing one optical input signal to the spatial light modulator, and another optical portion for providing another optical input signal to the spatial light modulator.

23. A reconfigurable multifunctional optical device according to claim 17, wherein the one or more optical portions include a collimator, a reflective surface, the dispersion element, a bulk lens, or a combination thereof.

24. A reconfigurable multifunctional optical device according to claim 23, wherein the collimator includes either an aspherical lens, an achromatic lens, a doublet, a GRIN lens, a laser diode doublet, or a combination thereof.

25. A reconfigurable multifunctionall optical device according to claim 23, wherein the reflective surface includes a mirror.

26. A reconfigurable multifunctional optical device according to claim 23, wherein the bulk lens includes a Fourier lens.

27. A reconfigurable multifunctional optical device according to claim 23, wherein the lens distance between the spatial light modulator and the bulk lens is greater than the focal length of the bulk lens.

28. A reconfigurable multifunctional optical device according to claim 23, wherein the lens distance between the spatial light modulator and the bulk lens is less than the focal length of the bulk lens.

29. A reconfigurable multifunctional optical device according to claim 17, wherein the one or more optical portions include one or more optical PDL mitigating devices for minimizing polarization dependence loss (PDL).

30. A reconfigurable multifunctional optical device according to claim 29, wherein one optical PDL mitigating device is arranged between a waveguide and a grating in the optical arrangement, and another optical PDL mitigating device is arranged between a grating and the spatial light modulator.

31. A reconfigurable multifunctional optical device according to claim 29, wherein the one or more optical PDL mitigating devices include a pair of optical PDL mitigating devices.

32. A reconfigurable multifunctional optical device according to claim 29, wherein the one or more optical PDL mitigating devices includes one optical PDL mitigating device having a polarization splitter for splitting each channel into a pair of polarized light beams and a rotator for rotating one of the polarized light beams of each optical channel.

33. A reconfigurable multifunctional optical device according to claim 32, wherein the one or more optical PDL mitigating devices includes another optical PDL mitigating device having a rotator for rotating one of the previously rotated and polarized light beams of each optical channel and a polarization splitter for combining the pair of polarized light beams of each channel.

34. A reconfigurable multifunctional optical device according to claim 29, wherein the one or more optical PDL mitigating devices includes a $\lambda/4$ plate.

35. A reconfigurable multifunctional optical device according to claim 17, wherein the optical arrangement includes a chisel prism having multiple faces for modifying the direction of the at least one optical signal.

36. A reconfigurable multifunctional optical device according to claim 35, wherein the multiple faces include at least a front face, first and second beveled front faces, a rear face, a top face and a bottom face.

37. A reconfigurable multifunctional optical device according to claim 35, wherein optical light from first or second optical portions passes through one or more faces of the chisel prism, reflects off one or more internal surfaces of the chisel prism, reflects off the spatial light modulator, again reflects off the one or more internal surfaces of the chisel prism, and passes back to the first or second optical portions.

38. A reconfigurable multifunctional optical device according to claim 1, wherein the diffraction grating has a low PDL.

39. A reconfigurable multifunctional optical device according to claim 1, wherein

the reconfigurable multifunctional optical device includes an optical add/drop multiplexer configuration; and

the dispersion element spreads at least one optical signal and an optical add signal so that each optical band or channel is reflected by one respective plurality of micro-mirrors of the spatial light modulator to selectively add or drop the one or more optical bands or channels to and/or from the at least one optical signal.

40. A reconfigurable multifunctional optical device according to claim 1, wherein

the reconfigurable multifunctional optical device includes an optical cross-connect configuration; and

the light dispersion element spreads two or more optical input signals so that each optical band or channel is reflected by one respective plurality of micro-mirrors of the spatial light modulator to selectively switch the one or more optical bands or channels between the two or more optical input signals.

41. A reconfigurable multifunctional optical device according to claim 1, wherein the reconfigurable multifunctional optical device includes an optical channel monitor configuration having a light detector, the light dispersion element directing one or more reflected optical bands or channels reflected by one respective plurality of micro-mirrors of the spatial light modulator to provide an optical output signal, and the light detector detecting the one or more reflected optical bands or channels in the optical output signal.

42. A reconfigurable multifunctional optical device according to claim 1, wherein

the reconfigurable muitifunctional optical device includes an interleaver/deinterleaver configuration; and

the light dispersion element spreads two or more optical input signals so that each optical band or channel is reflected by one respective plurality of micro-mirrors of the spatial light modulator to selectively either combine two respective sets of at least one optical band or channel into one optical output signal, or de-combine one set of the at least one optical band or channel into two optical output signals each having a different set of the at least one optical band or channel.

43. A reconfigurable multifunctional optical device according to claim 1, wherein

the reconfigurable multifunctional optical device includes a chromatic dispersion compensation configuration for receiving an optical signal having one or more optical channels; and

the spatial light modulator selectively reflects a respective spectral portion of a plurality of spectral bands or sections of the one or more channels from one respective plurality of micro-mirrors of the spatial light modulator to compensate each channel for chromatic dispersion.

44. A reconfigurable multifunctional optical device according to claim **1**, wherein

the reconfigurable multifunctional optical device includes an optical blocking filter for receiving an optical input signal having one or more optical bands or channels; and

the spatial light modulator selectively deflects the one or more optical bands or channels from one respective plurality of micro-mirrors of the spatial light modulator to eliminate a selected band or channel or a specified selection of bands or channels from the optical signal provided along an optical return path.

45. A reconfigurable multifunctional optical device according to claim **1**, wherein one optical function is performed on one optical input signal for providing an optical output signal, and wherein a second optical function is performed on the optical output signal.

46. A reconfigurable multifunctional optical device according to claim **1**, wherein the free optics configuration includes a common set of optical components for performing the separate optical functions on each optical signal.

47. A reconfigurable multifunctional optical device according to claim **1**, wherein the optical arrangement disperses optical channels so they are substantially separated.

48. A reconfigurable multifunctional optical device according to claim **1**, wherein the optical arrangement disperses optical channels so they are substantially overlapping.

49. A reconfigurable multifunctional optical device according to claim **1**, wherein the light dispersion element provides two or more optical return signals, each having modified optical bands or channels depending on the separate optical functions performed on each optical input signal.

50. A reconfigurable multifunctional optical device according to claim **1**, wherein said spatial light modulator is reconfigurable by modifying a switching algorithm that drives the array of micro-mirrors to change the first overall optical function to a different overall optical function, and/or the second overall optical function to a different overall optical function.

51. A reconfigurable multifunctional optical device according to claim **1**, wherein the spatial light modulator is selectively reconfigurable by statically or dynamically modifying a switching algorithm to accommodate different optical characteristics of the first and/or second optical input signals.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 7,126,740 B2
APPLICATION NO. : 10/353772
DATED : October 24, 2006
INVENTOR(S) : Szczepanek et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 1, line 41 change “2002now” to -- 2002, now --
Column 1, line 44 change “2002now” to -- 2002, now --
Column 1, line 48 change “2002now” to -- 2002, now --
Column 1, line 52 change “2002now” to -- 2002, now --
Column 10, line 50 “60/281,019” should be -- 60/281,079 --
Column 19, line 54 “ad” should be -- as --
Column 20, line 47 change “(FIG. 24” to -- (FIG. 24) --
Column 21, line 34 “.” should be deleted
Column 21, line 38 second occurrence of “can be” should be deleted

Signed and Sealed this

Sixteenth Day of March, 2010

David J. Kappos

David J. Kappos
Director of the United States Patent and Trademark Office

EXHIBIT D

US006430328B1

(12) **United States Patent**
Culver et al.

(10) **Patent No.: US 6,430,328 B1**
(45) **Date of Patent: Aug. 6, 2002**

(54) **OPTICAL SWITCH**

(76) Inventors: **William H. Culver**, 4253 Fordham Rd., Washington, DC (US) 20016; **Donald Cronin Schmadel, Jr.**, 7201 Princeton Ave., Apt., 10, College Park, MD (US) 20740

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/689,694**

(22) Filed: **Oct. 13, 2000**

(51) **Int. Cl.**[7] **G02B 6/26**
(52) **U.S. Cl.** **385/16**; 385/18
(58) **Field of Search** 385/16–24

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Primary Examiner—Phan T. H. Palmer
(74) *Attorney, Agent, or Firm*—Staas & Halsey LLP

(57) **ABSTRACT**

The present invention is a system that includes phase spatial light modulators as optical switching elements in an optical switching system. One or more input light beams are deflected by one or more input optical deflectors to a mirror and then to one or more output optical deflectors. Each deflector is a phase spatial modulator which changes the direction of the light beam by changing the phase of the beam wave front. The wave front is two dimensionally subdivided into pixels and pixel reflectors are used displace portions of the wave front in a direction generally perpendicular to the beam axis and relative to each other. Beam splitters, lenses, decoders and controllers provide the ability to cross connect or reroute beams and route packets.

40 Claims, 17 Drawing Sheets

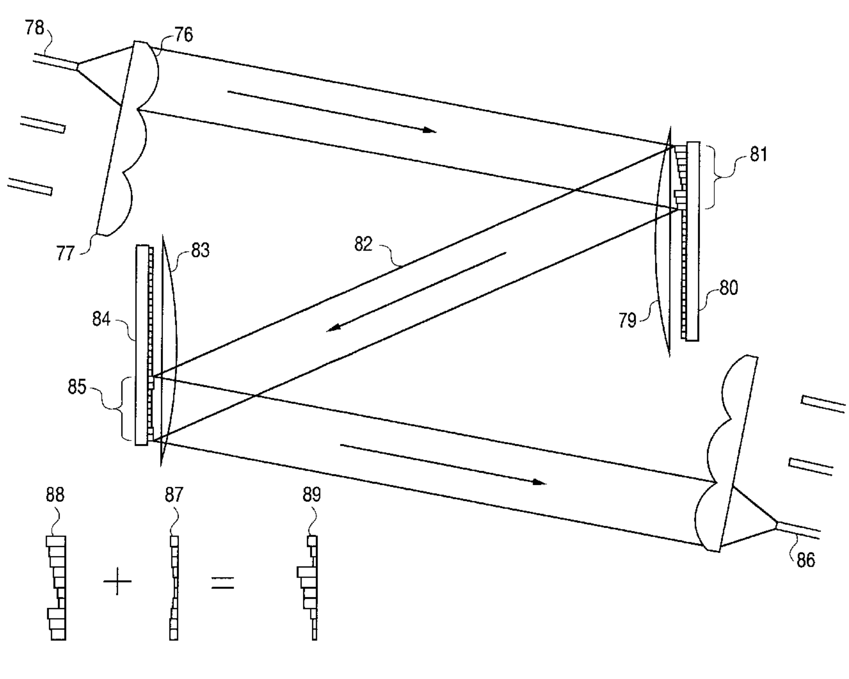
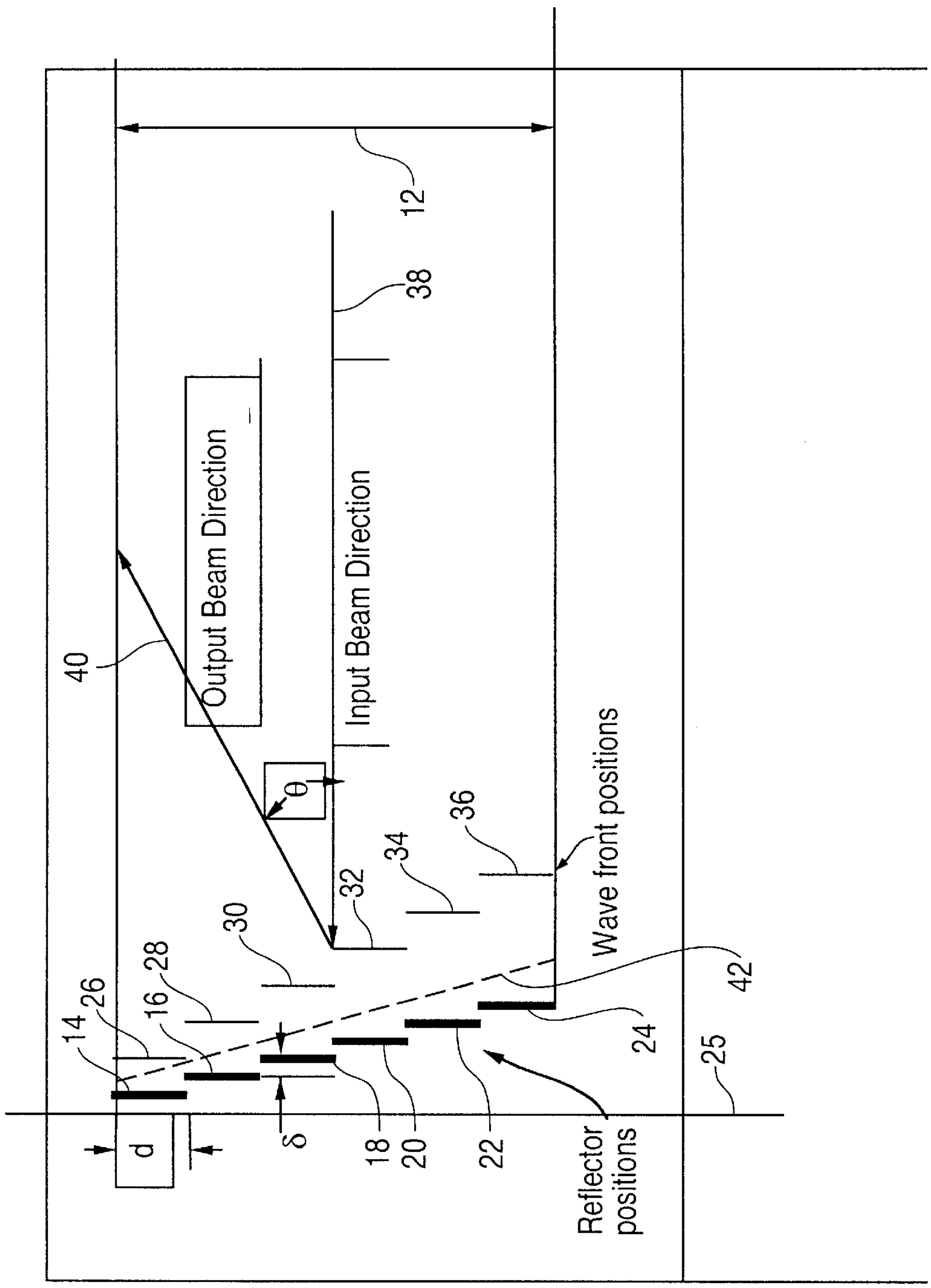


FIG. 1


12
38
Output Beam Direction
Input Beam Direction
40
θ
36
34
32
30
28
26
14
16
Wave front positions
42
24
25
22
20
18
δ
d
Reflector positions

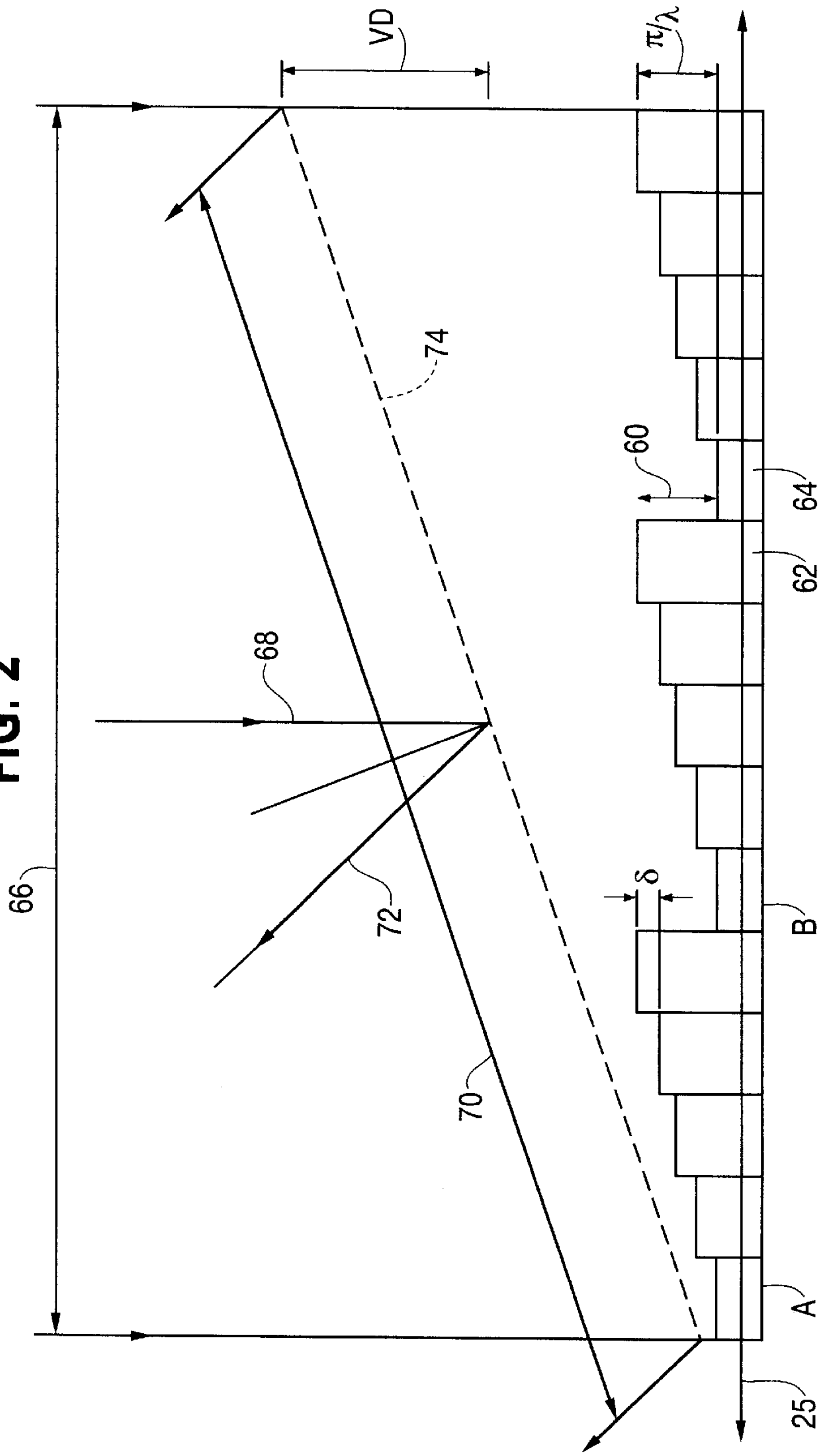


FIG. 2

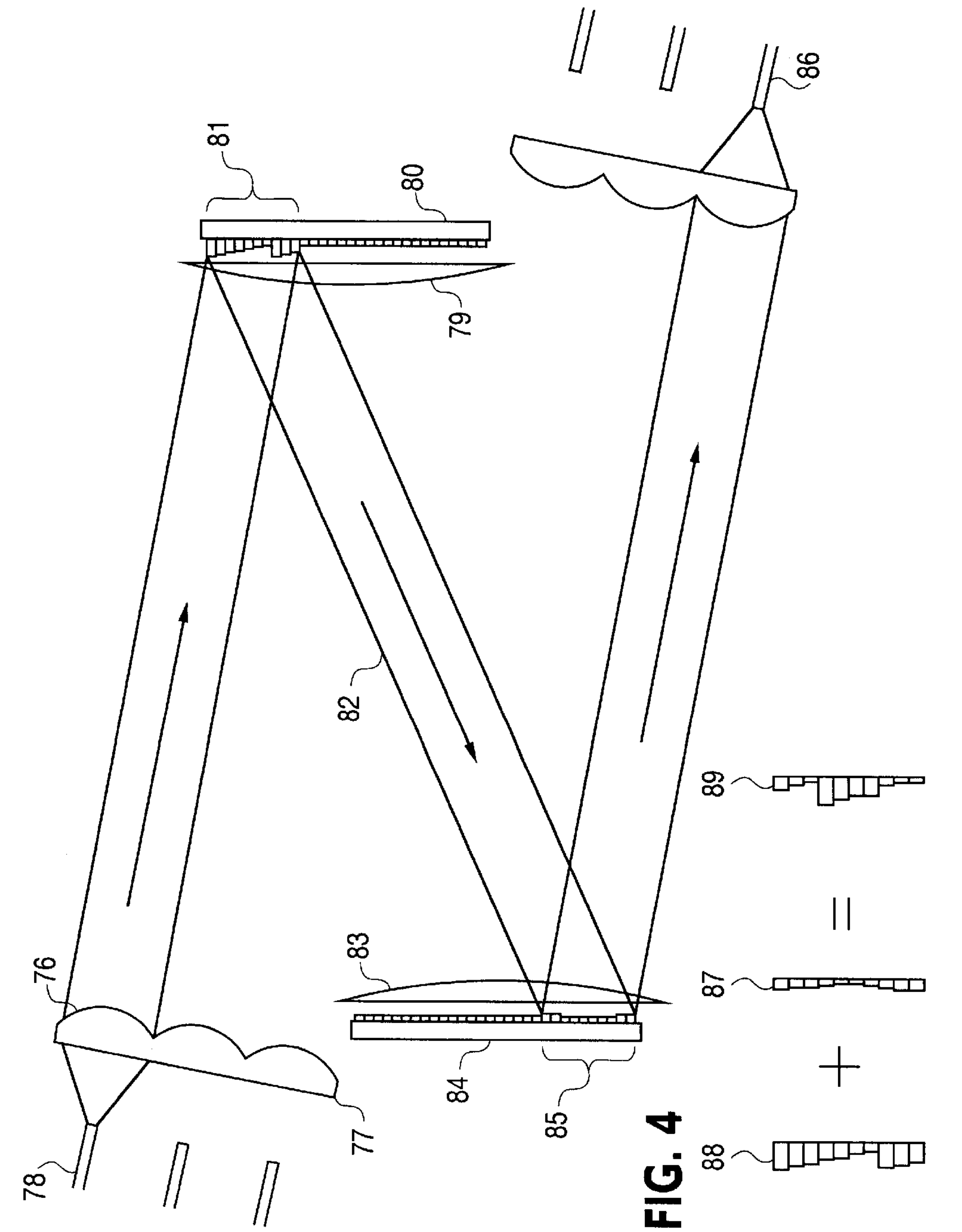


FIG. 3

FIG. 4

FIG. 5A

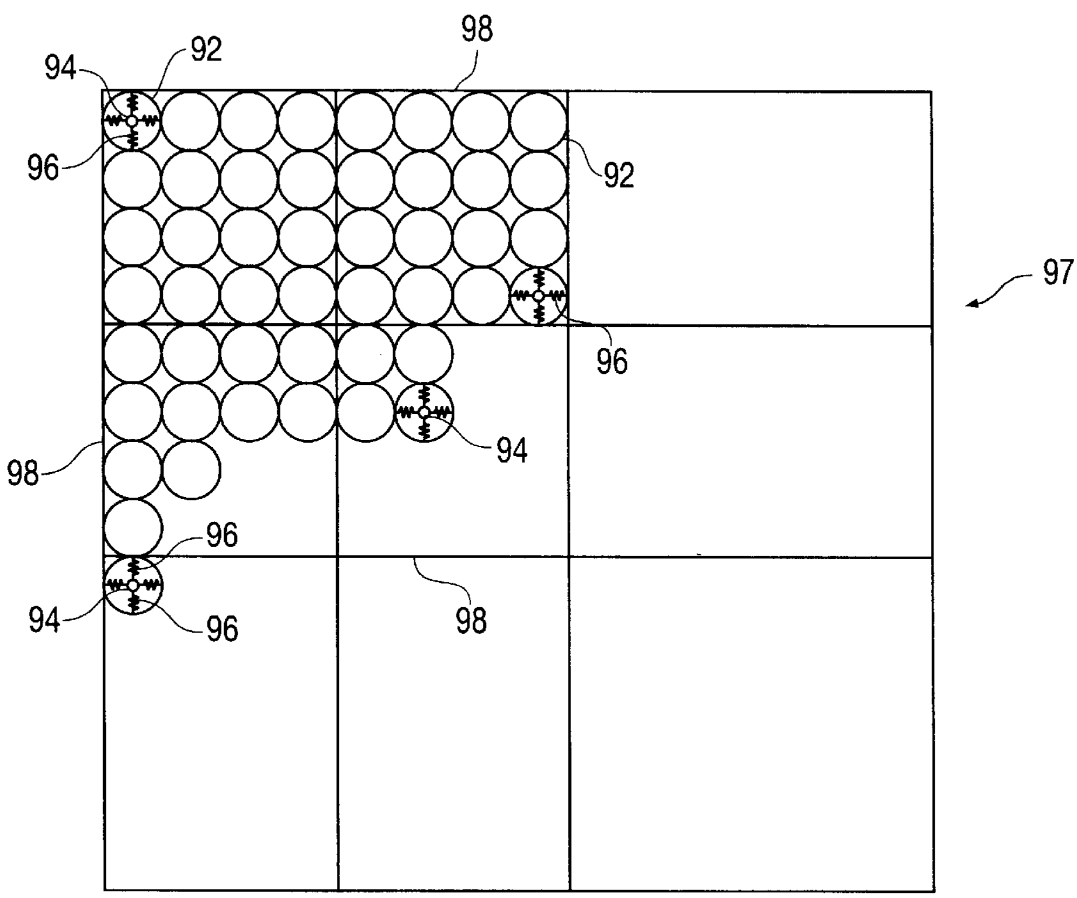


FIG. 5B

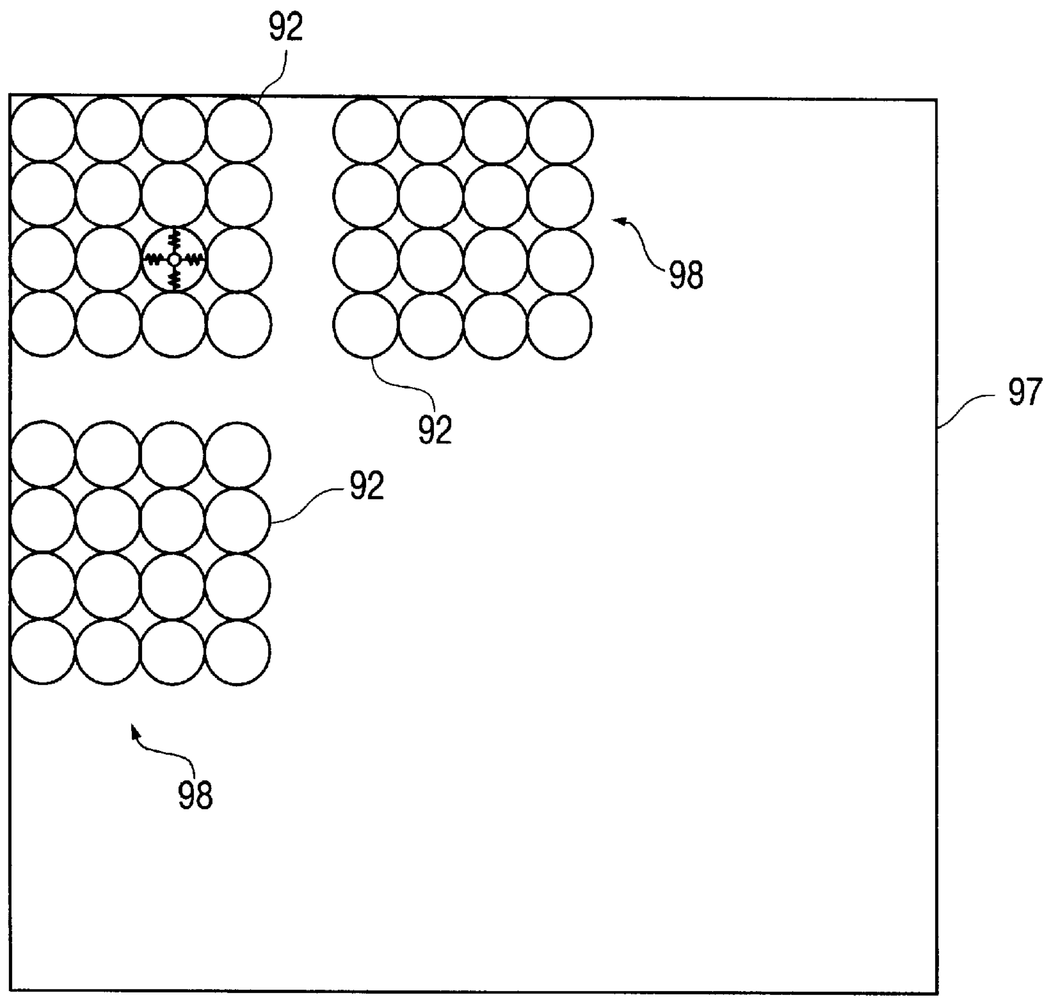


FIG. 6A

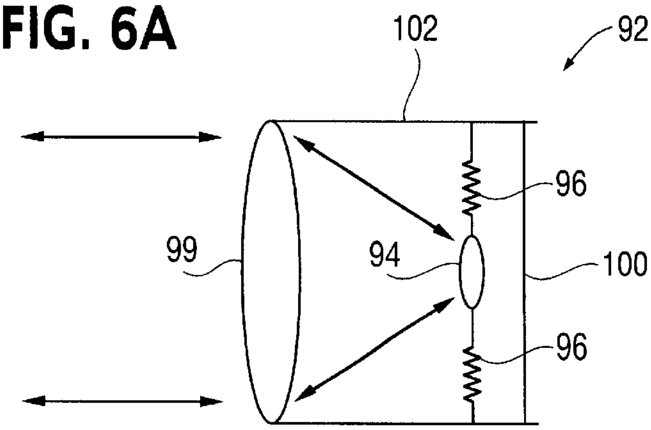


FIG. 6B

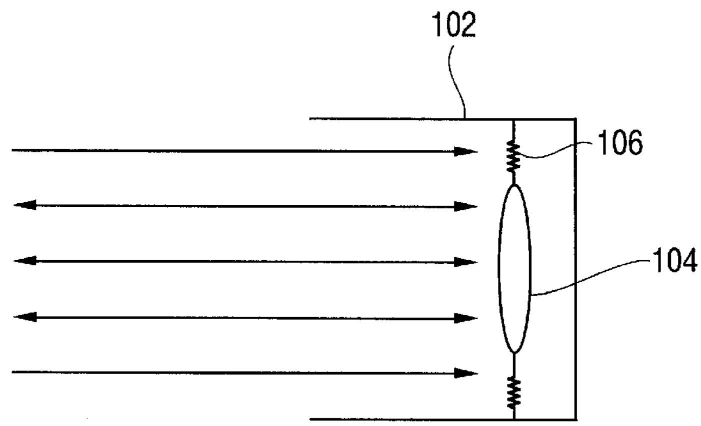


FIG. 7

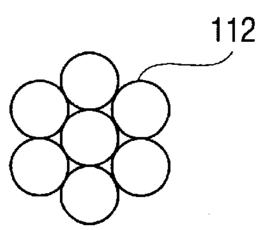


FIG. 8

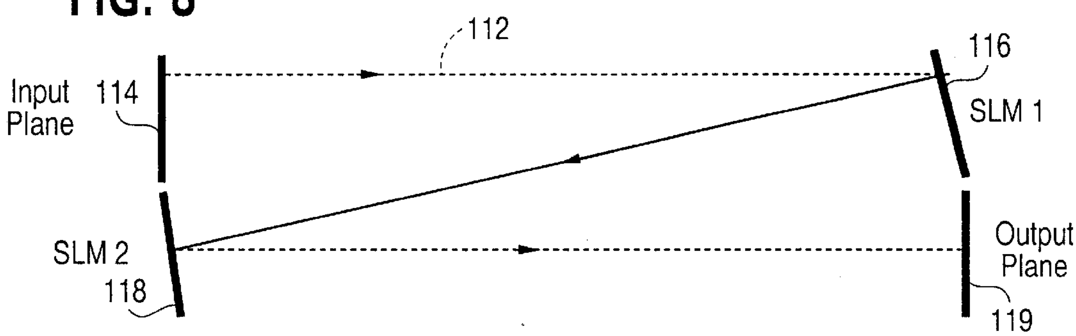


FIG. 9

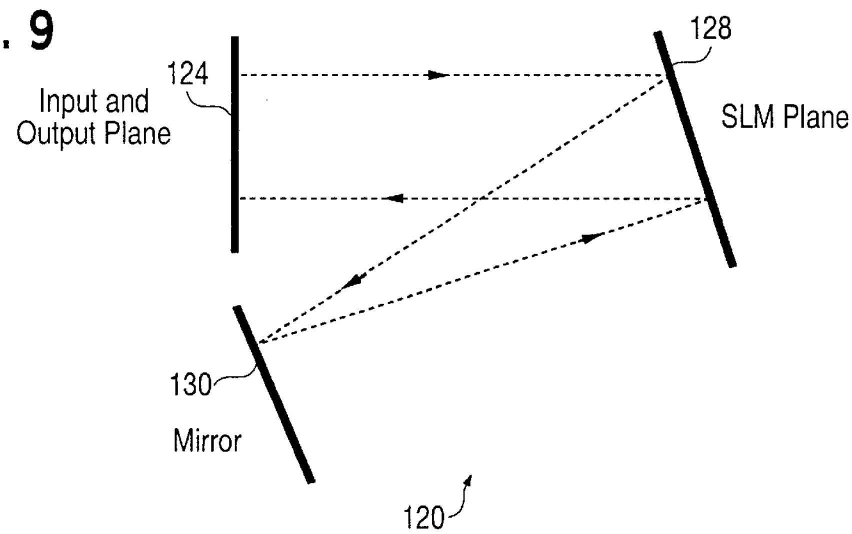


FIG. 10

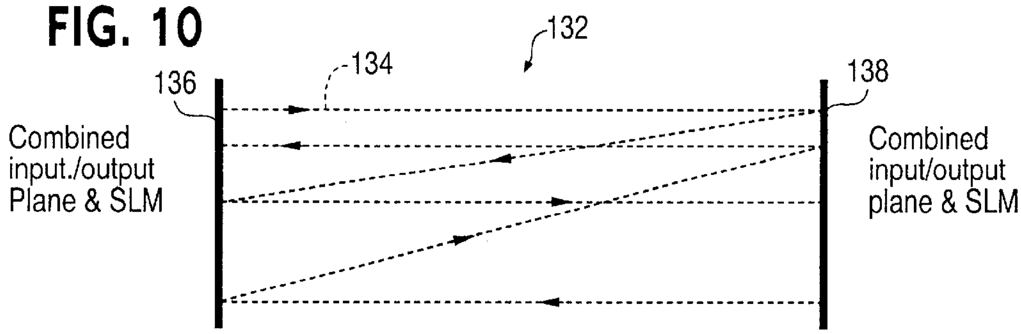
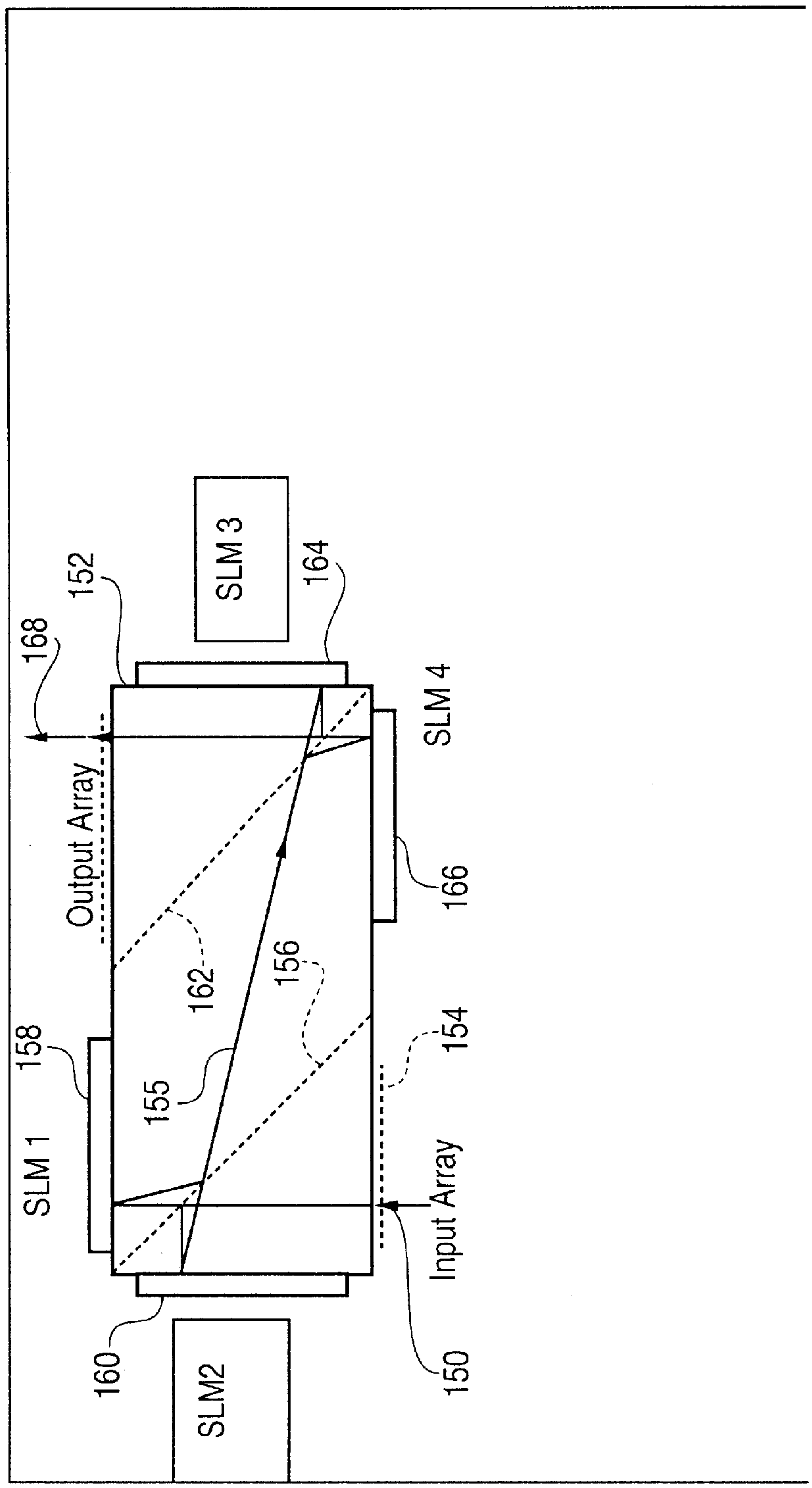


FIG. 11



SLM 3
152
164
168
SLM 4
Output Array
166
162
156
158
155
154
SLM 1
Input Array
160
150
SLM2

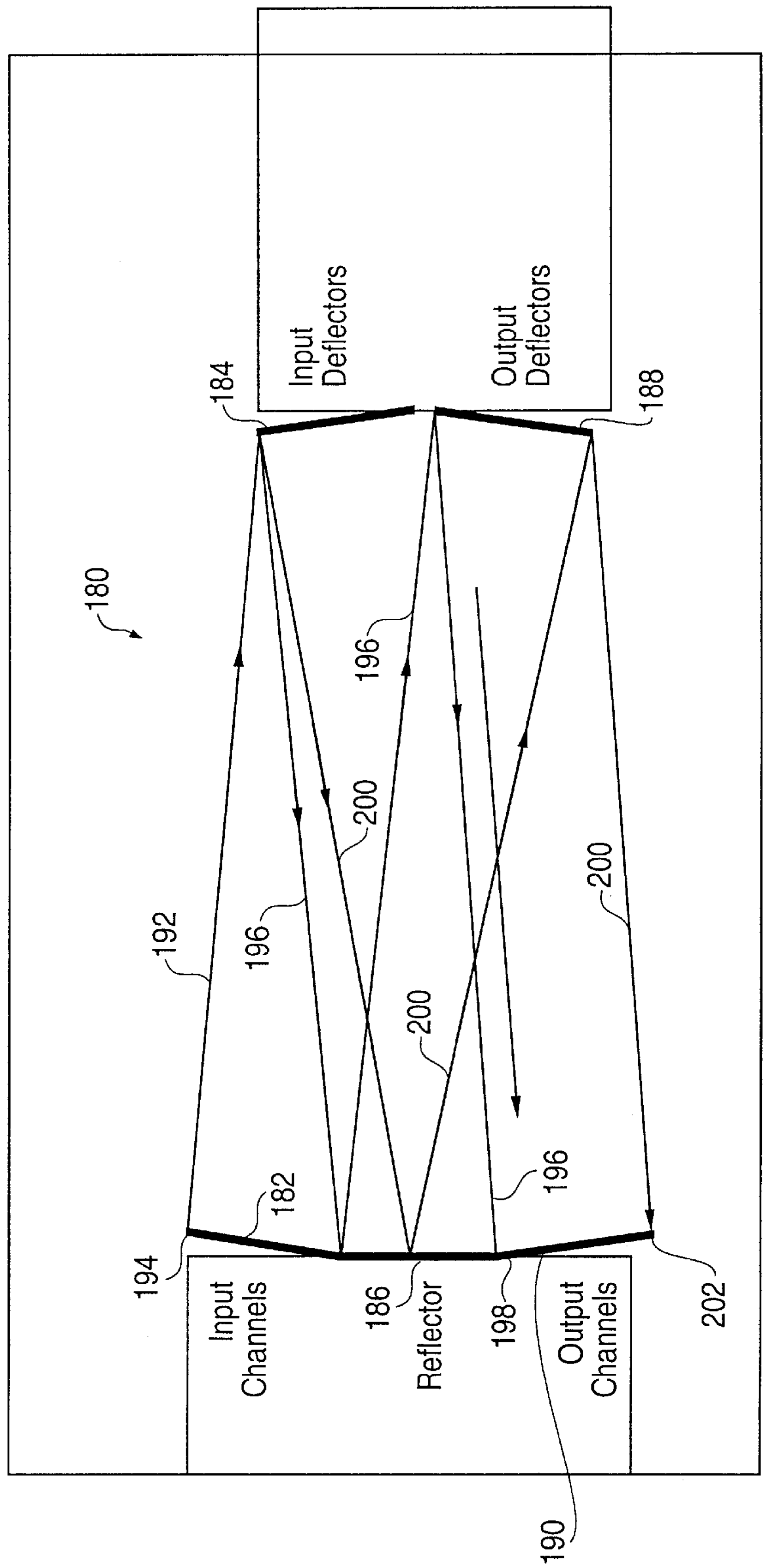

Input Deflectors
Output Deflectors
184
188
180
192
196
200
182
194
186
198
202
190
Input Channels
Reflector
Output Channels

FIG. 12

FIG. 13

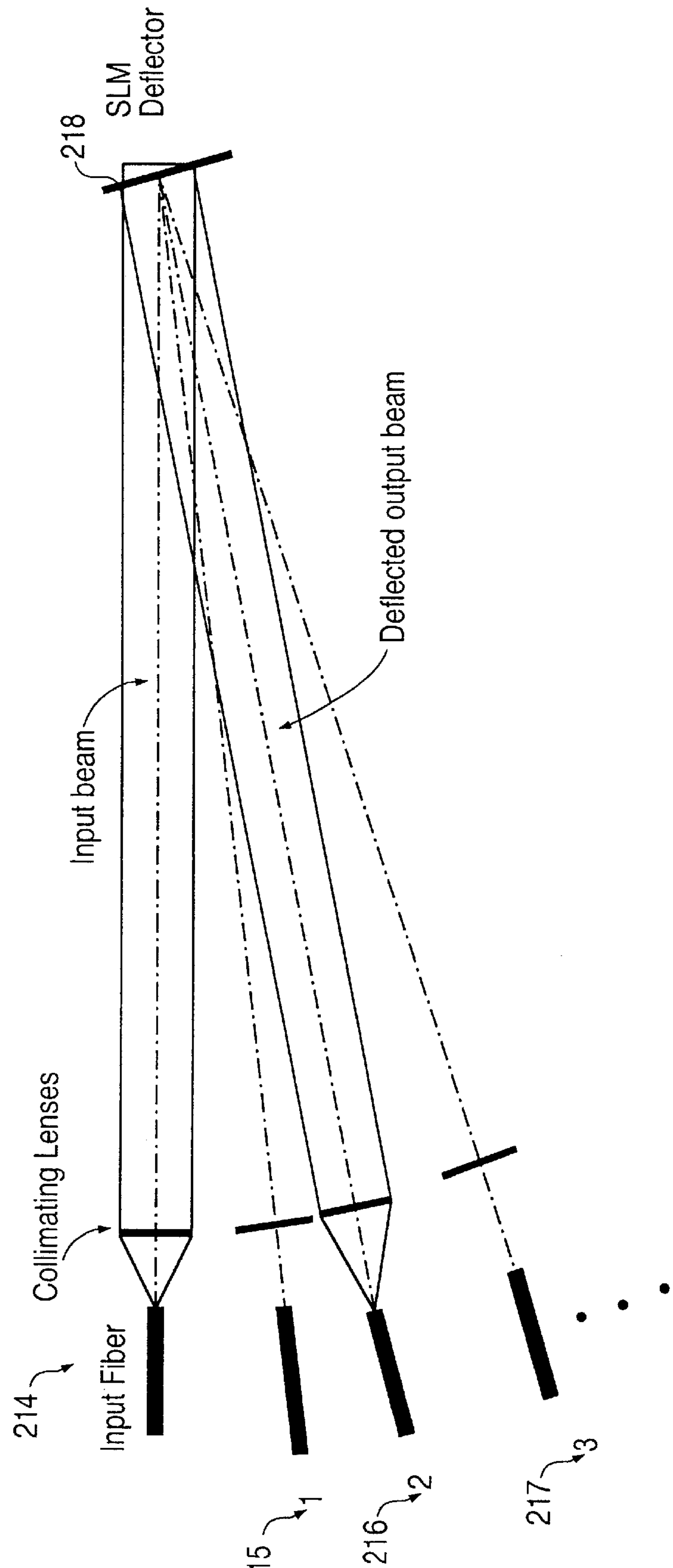

SLM
Deflector
218
Deflected output beam
Input beam
Collimating Lenses
Input Fiber
214
215
1
216
2
217
3

FIG. 14

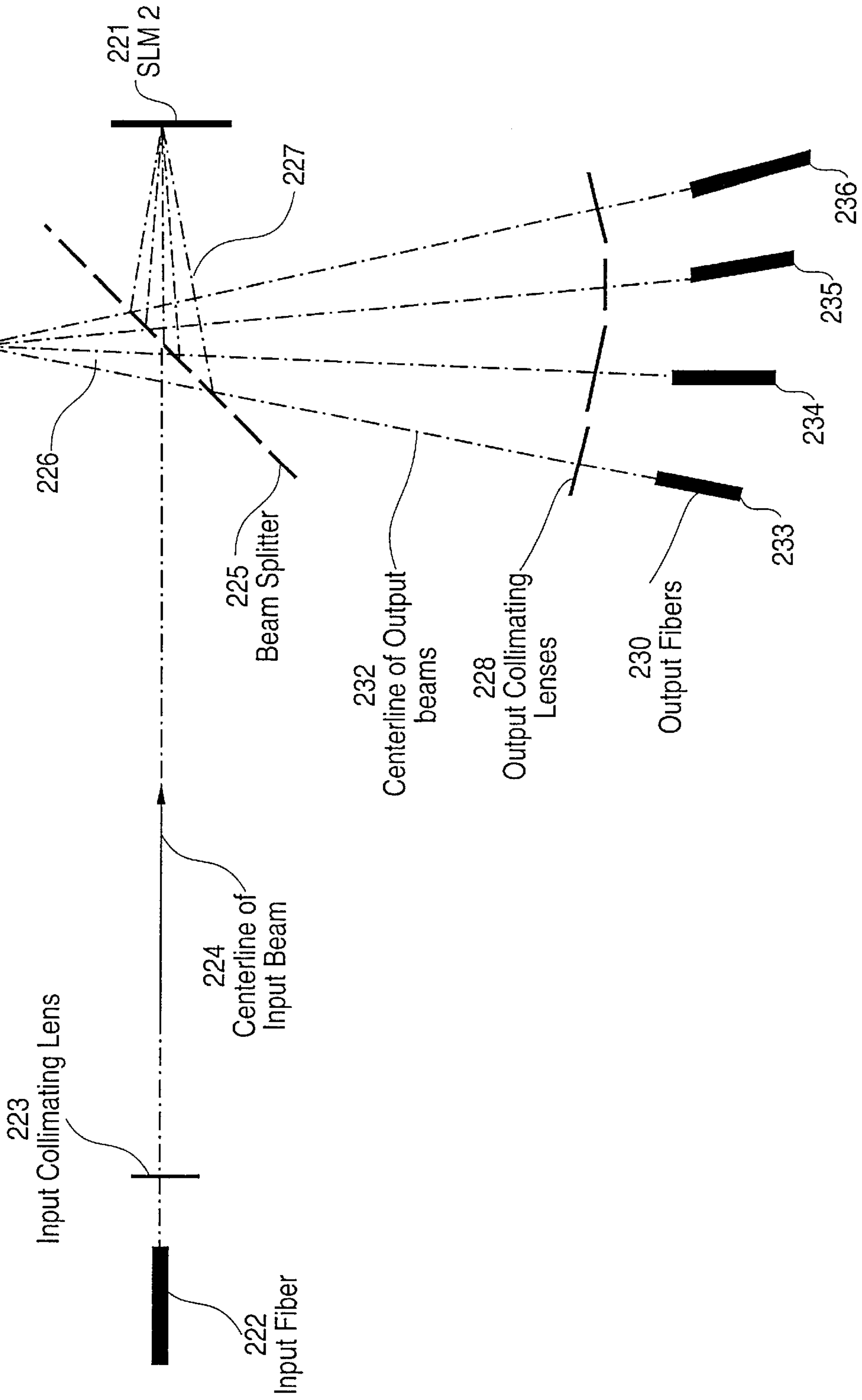

220
SLM 1
221
SLM 2
227
236
235
234
233
226
225
Beam Splitter
232
Centerline of Output beams
228
Output Collimating Lenses
230
Output Fibers
224
Centerline of Input Beam
223
Input Collimating Lens
222
Input Fiber

FIG. 15

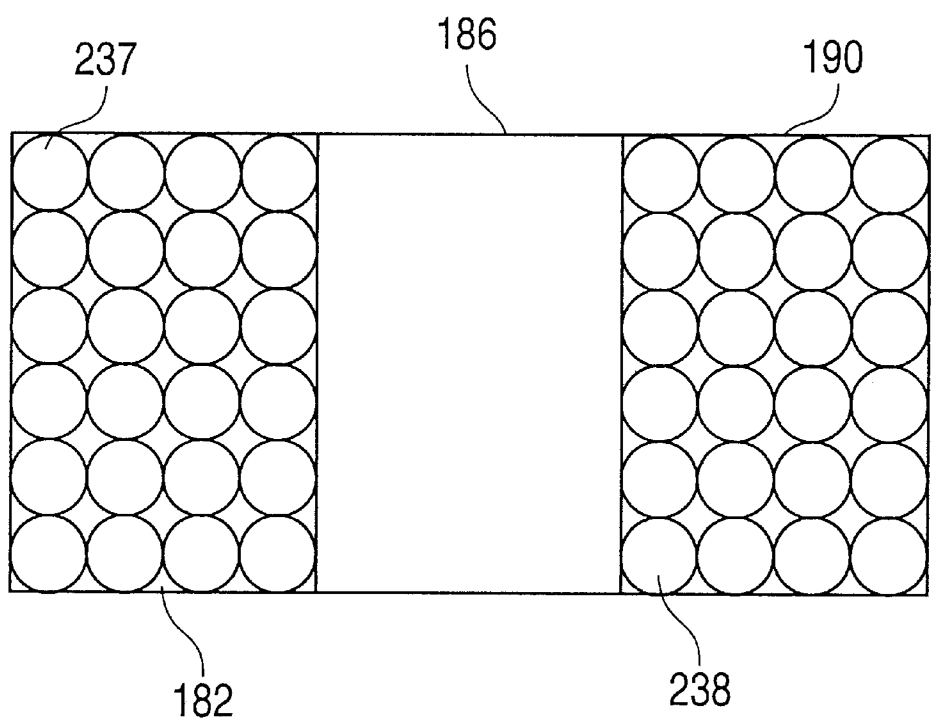
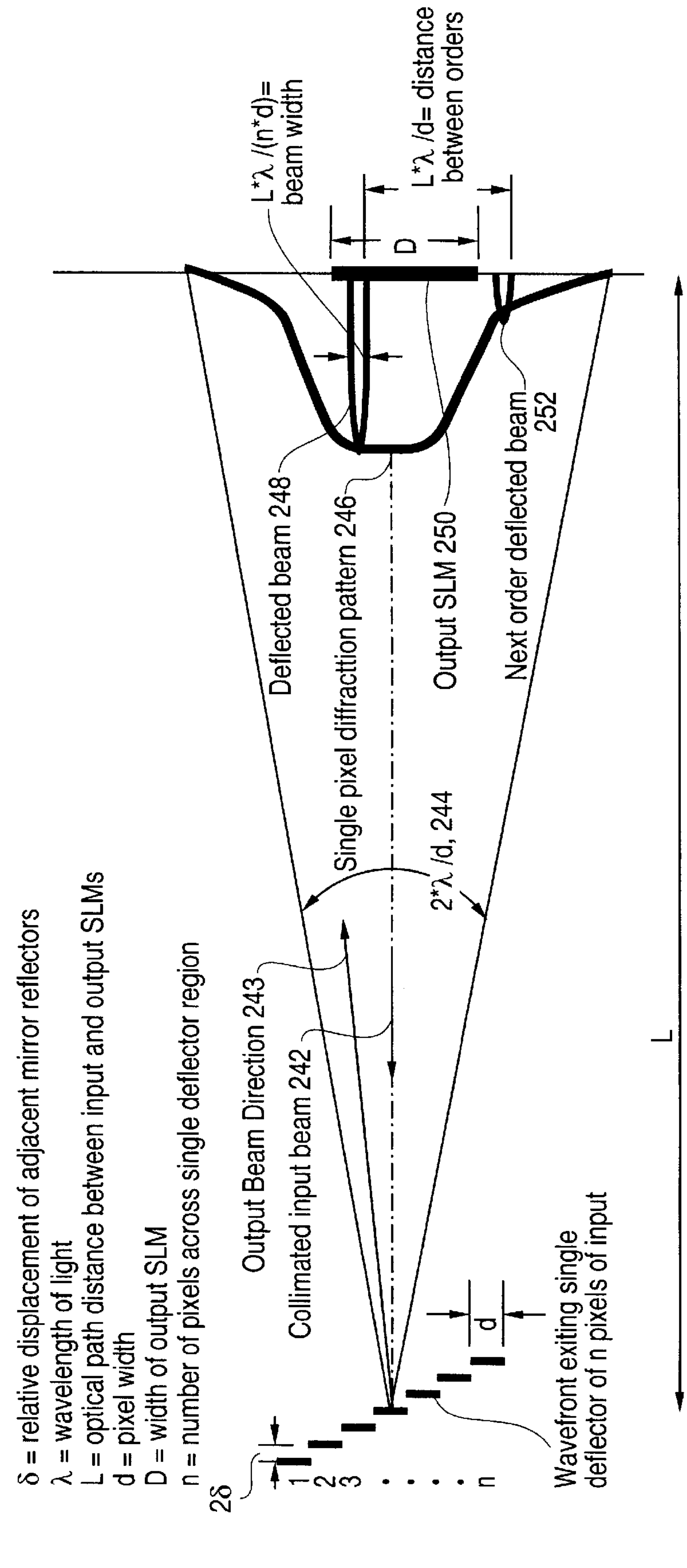


FIG. 16


δ = relative displacement of adjacent mirror reflectors
λ = wavelength of light
L = optical path distance between input and output SLMs
d = pixel width
D = width of output SLM
n = number of pixels across single deflector region
2δ
1
2
3
n
d
Wavefront exiting single deflector of n pixels of input
Output Beam Direction 243
Collimated input beam 242
L
2*λ /d, 244
Single pixel diffraction pattern 246
Deflected beam 248
Output SLM 250
Next order deflected beam 252
D
L*λ /(n*d)= beam width
L*λ /d= distance between orders

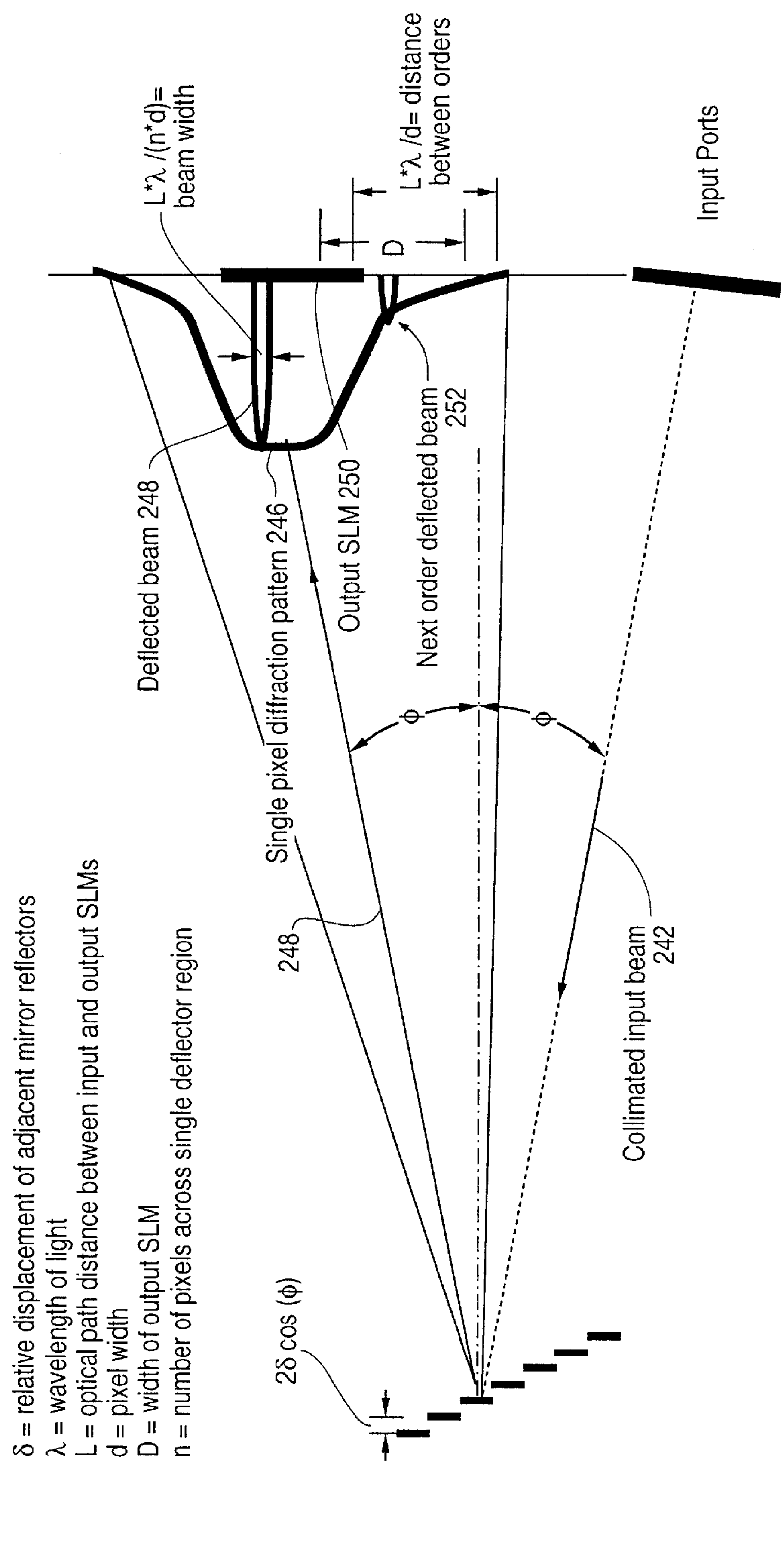

δ = relative displacement of adjacent mirror reflectors
λ = wavelength of light
L = optical path distance between input and output SLMs
d = pixel width
D = width of output SLM
n = number of pixels across single deflector region
L*λ /(n*d)= beam width
L*λ /d= distance between orders
D
Input Ports
Deflected beam 248
Single pixel diffraction pattern 246
Output SLM 250
Next order deflected beam 252
φ
φ
248
Collimated input beam 242
2δ cos (φ)

FIG. 17

FIG. 18

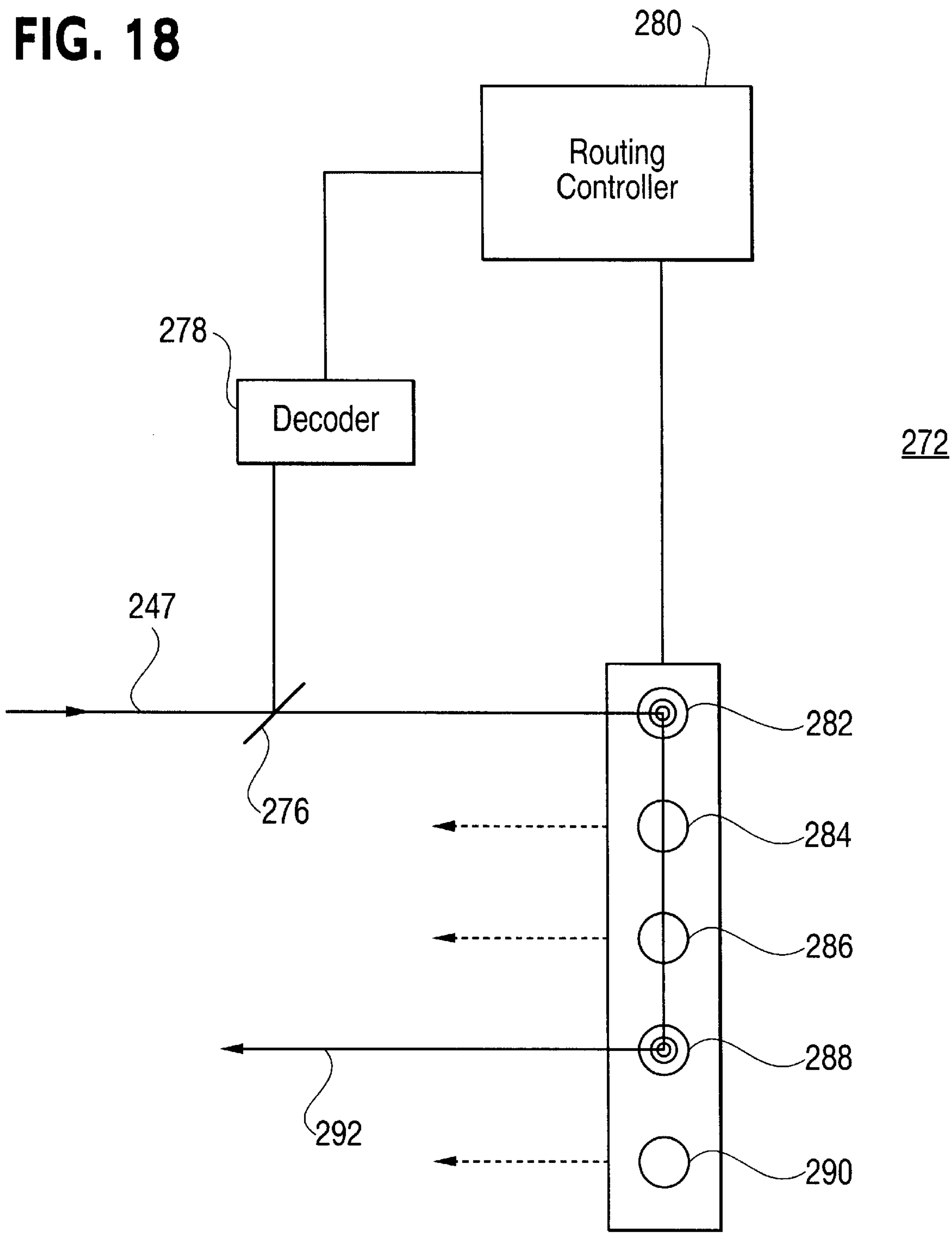
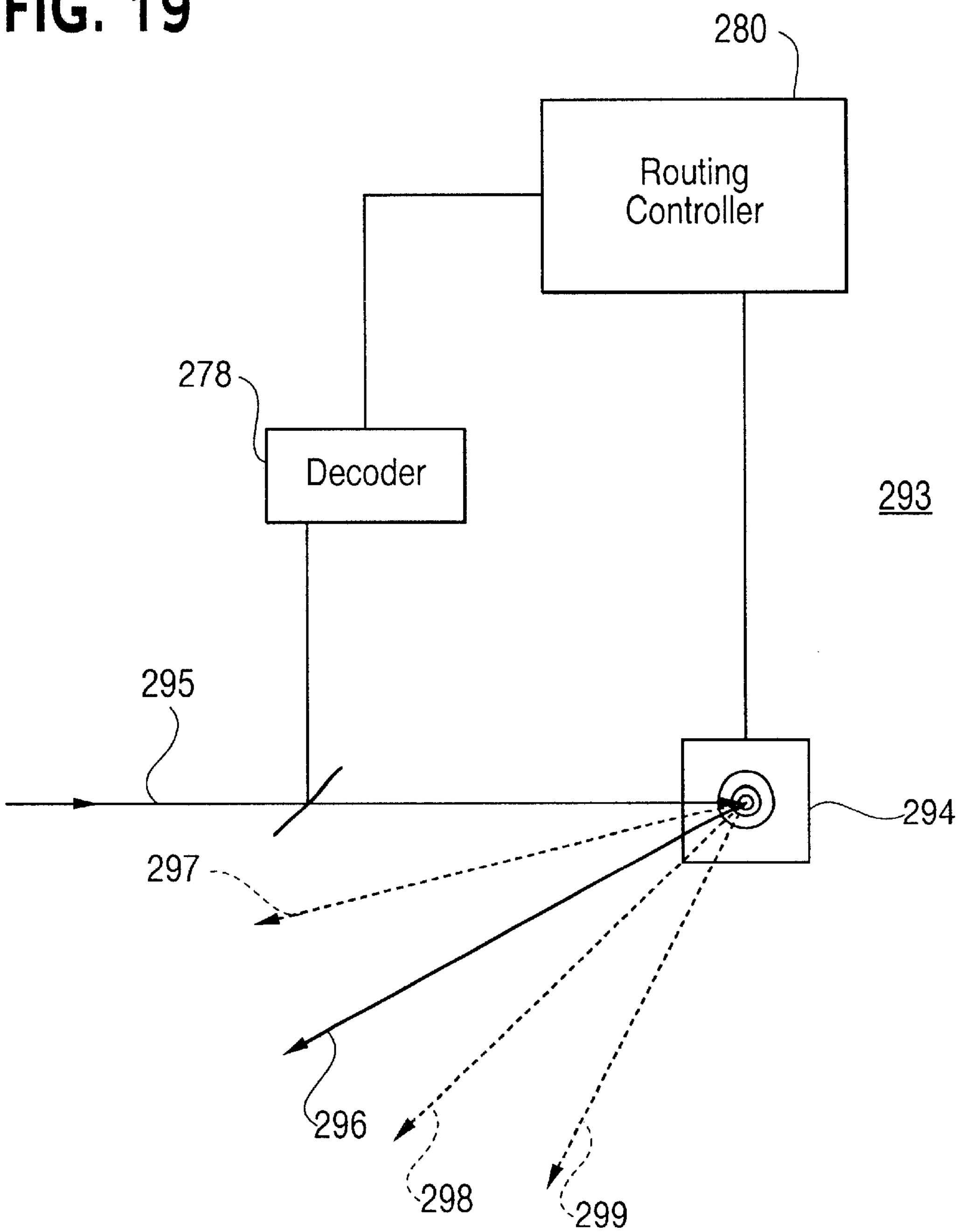
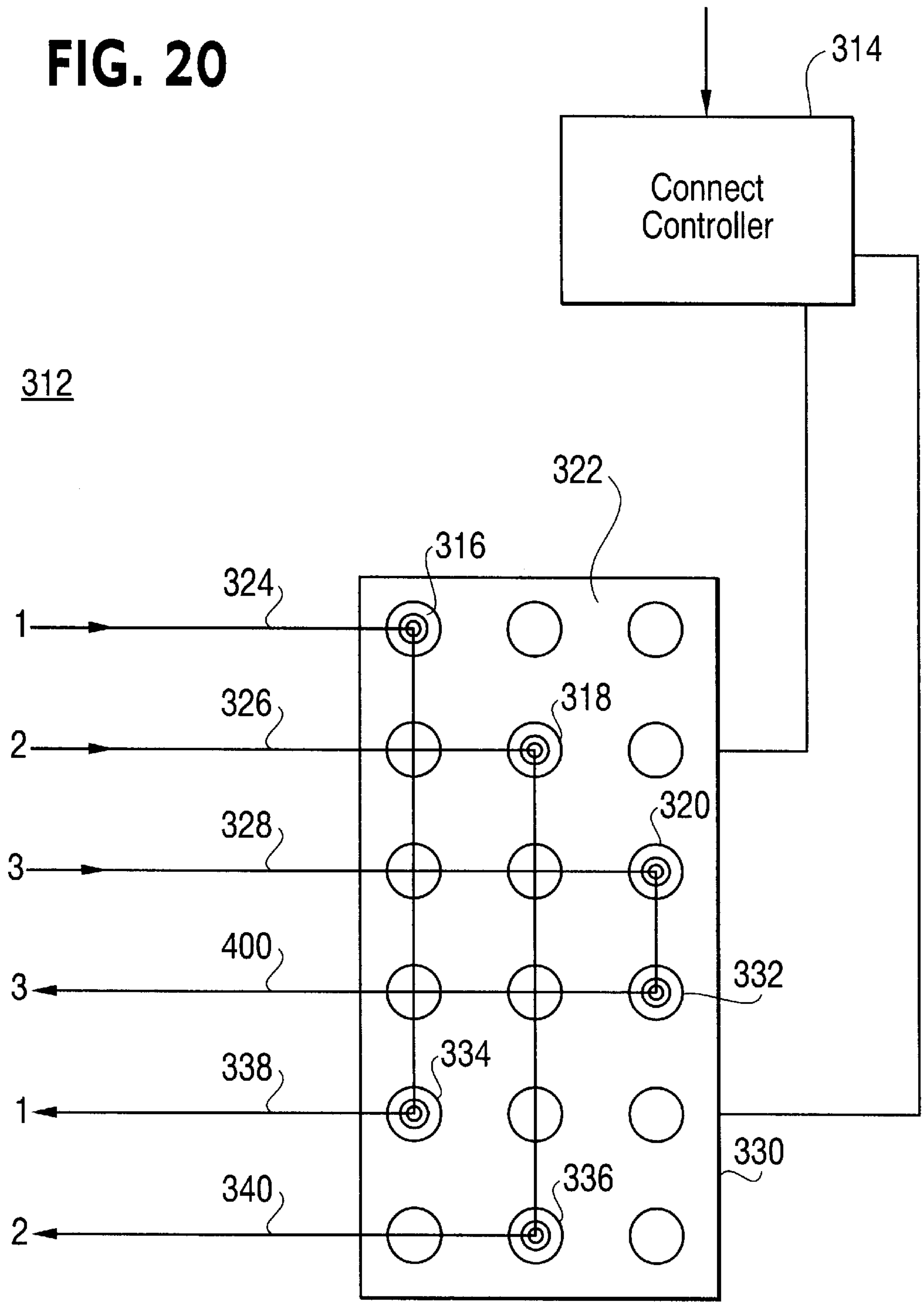

280
Routing
Controller
278
Decoder
272
247
276
282
284
286
288
292
290

FIG. 19



280
Routing Controller
278
Decoder
293
295
294
297
296
298
299

FIG. 20



314
Connect Controller
312
322
316
324
1
326
2
318
328
3
320
400
3
332
338
1
334
340
2
336
330

OPTICAL SWITCH

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is directed to an optical switch and, more particularly, to a switch that switches an optical beam from an input port to an output port without converting the signal to electrical form by the use of one or more optical phase changing spatial light modulators (SLMs).

2. Description of the Related Art

Today's packet switched communication networks, such as the Internet, are implemented using fiber optic technology where a modulated laser beam is transmitted down an optical fiber or glass wave guide. Switching between fibers within the network is typically performed by converting the light signal into an electrical signal, performing the switching function on the electrical signal and then converting the electrical signal into a light signal. These conversion operations are slow and expensive.

What is needed is a switch that switches the light beam between input and output fibers optically directly without converting the signal into electrical form.

A direction of a laser beam can be changed via a number of different techniques, including reflecting the beam from a mirror that can be rotated. However, rotating a mirror is slow slower than desired for many switching operations.

What is needed is an optical switch that will switch beam directions faster.

SUMMARY OF THE INVENTION

It is an object of the present invention to perform optical switching for an optical network by changing the relative-phase of individual portions of the cross section of a wave front of a beam.

It is another object of the present invention to use one or more phase spatial light modulators (SLMs) to perform optical switching.

It is another object of the present invention to use phase spatial light modulators that include an array of phase shifting elements in such a manner that each of the phase shifting elements moves a maximum distance of about one half of the wavelength of light.

It is an additional object of the present invention to use phase spatial light modulators that include an array of phase shifting elements in such a manner that the area of the phase shifting mirror or element is smaller than the cross section of the portion of the beam of light the element is modulating.

It is also an object of the present invention to provide optical routers and cross connect switches which perform switching of one or more optical beams between optical fibers using phase spatial light modulation.

The above objects can be attained by a system that includes one or more phase spatial light modulators as optical switching elements in an optical switching system. One or more input light beams are deflected by one or more input optical deflectors. The beam can be further deflected by one or more output optical deflectors. Each deflector changes the direction of the light beam by changing the phase of the beam wave front by displacing pixel reflectors in a direction essentially perpendicular to the beam axis and relative to each other.

These together with other objects and advantages which will be subsequently apparent, reside in the details of construction and operation as more fully hereinafter described and claimed, reference being had to the accompanying drawings forming a part hereof, wherein like numerals refer to like parts throughout.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** depicts the operations of an SLM according to the present invention.

FIG. **2** depicts the changing of the direction of a beam using SLM pixels.

FIGS. **3** and **4** show how a beam is defected between SLMs and corrected for divergence.

FIGS. **5**A and **5**B shows pixel reflectors of an SLM.

FIGS. **6**A and **6**B show embodiment of a pixel.

FIG. **7** shows an arrangement of pixels of a deflector.

FIGS. **8**–**14** depict beam reflecting embodiments.

FIG. **15** depicts input and output deflector arrays.

FIGS. **16** and **17** depict a relationship between beam characteristics and pixels.

FIGS. **18** and **19** depict a packet router.

FIG. **20** depicts a beam cross connect.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention optically switches a signal carrying light beam, such as a laser beam, between input and outputs, such as input and output optical fibers, by changing the direction of an optical beam, such as a data carrying laser beam, by independently changing a phase of individual sections of the beam wave front using a phase spatial light modulator (SLM). This change in direction can be accomplished by a transmissive SLM, such as those available from Kopin Corporation of Taunton, Mass. or Coretech of Burlington, Mass. or, more preferably by a reflective SLM., such as those available from MEMS Optical, Inc. of Huntsville, Ala. or Boulder Nonlinear of Boulder, Colo. The direction of each light beam is altered by varying the relative phase shift imparted to successive adjoining pixels within the beam. The angular deviation of each light beam is equal to the relative optical phase shift imparted to adjacent pixels divided by the pitch of the pixel array measured in wavelengths of the light. The advantage of using an array of small phase shifting pixels is that the pixels can be brought to the correct position for the desired deflection angle much more rapidly than other types of devices and that no pixel of the SLM needs to advance the phase of the wave front by more than one wavelength of the light.

A portion of a reflective SLM, as depicted in cross section in FIG. **1**, changes the phase of a beam **12** wave front by changing the positions of small plate shaped reflectors **14**–**24** in the path of the beam **12**. The beam **12** is "divided" into or by a series of pixels that correspond to these reflectors. Each pixel or pixel reflector has width d and is positioned a varying distance from a reference position **25**. Each pixel reflector is moved in a direction that is generally perpendicular the reflective surface of the element. When successive pixel reflectors are advanced δ relative to the previous pixel reflector, such as depicted for the pixel reflectors **16** and **18**, successive wave front elements (portions of the incoming beam) **26**–**36** will be relatively advanced or displaced by 2δ. As a result, the advancement of the wave front **36** for the last pixel **24** is $n*2\delta$, where n is the number of pixels. This results in a beam deflection angle of $\theta=\arctan(2\delta/d)$, such that the incoming beam direction **38** is reflected in an outgoing direction **40** at an angle of θ. The phase change can be made to increase linearly across the beam, thus causing a deflection as shown in FIG. **1**. The effect of the wave front displacements caused by moving the reflectors is the creation of a virtual mirror **42** depicted by the dashed line in FIG. **1**.

When the reflector displacement **60** of successive pixels, for example pixels **62** (see FIG. **2**) cumulatively exceeds λ/2, where λ is the wavelength of the light, the displacement for the nth element, such as pixel **64**, is reduced by λ/2, that is to nδ modulo(λ/2). nδ modulo(λ/2) is the remainder when nδ is divided by λ/2, thus no mirror displacement need be greater than λ/2. Since the light beam is from a laser it is essentially monochromatic and has a phase angle which is periodic in distance λ, the relative phase angle of the reflected light between pixel **62** and pixel **64** is equivalent to δ. In this figure the incoming beam **66** arrives via direction **68** and results in an outgoing beam **70** being reflected in an exit direction **72** and again creating a virtual mirror **74** depicted by the dashed line in FIG. **2**. That is, with this approach a pixel reflector must be moved at most the λ/2 distance which is a fraction of the distance or virtual displacement VD that an edge of a rotating mirror is moved to produce the same angle of reflection. VD indicates the displacement of a mirror that rotates or pivots around it's axial center which is the place where the beam line **68** hits the virtual mirror **74** and reflects as beam line **72**. If the virtual mirror **74** pivots around an end, rather than around the center, the displacement will be 2*VD. As a result, the angle of the beam can be changed much faster using an SLM than when using a rotating mirror. Additionally, the reflector elements of an SLM are very small requiring that a very small mass be moved. The mass of the reflectors may be much smaller than that of a stiff relatively massive rotating mirror and for this additional reason, the switching of the beam is faster.

The virtual mirror **74** has the same resolving power as a real plane mirror of the same diameter. A separate resolvable direction requires a motion of one side of the mirror with respect to the other side of λ/2. Thus for a deflector that is n pixels wide, δ should be chosen to be approximately λ/(2*n) depending on the application.

Note that FIG. **2** is somewhat of a simplification of the actual relationship between successive pixels as the relative movement of a pixel crosses the λ/2 reset threshold. FIG. **2** could be seen to imply that when the modulo(λ/2) shift is performed that a successive pixel position always returns to the same base level set above the reference level **25**. In fact that could be the case, but most of the time it will not return to the base level. The reflector position will return to the base level only when δ is a sub-multiple of λ/2. In practice pixels A, B and **64** do not typically return to the same level. For instance pixel B might return to half the level of pixel A and pixel **64** might return to the base level. However, all increments between successive pixels do remain the same.

Although it is not necessary to advance any pixel mirror more that a distance of λ/2 the deflector will deflect the beam equally well if full advantage is not taken of this principle. For instance successive mirrors might be advanced by 0.0, 0.2, 0.4, 0.6, 0.8, 0.5, 0.7, etc. wavelengths. In this case the mirror was moved a distance equal to 0.8 wavelengths. The mirrors can also be allowed to advance more than λ/2, generally in integral multiples. The advantage of moving the mirror no more than λ/2 is that it will allow higher speed switching but not taking full advantage of the feature does not violate the spirit of this invention. Any decrease of motion or wave front phase modulation allowed by dividing up the deflector into separate pixels is within the spirit of this invention.

The pixel reflector displacement structure depicted in FIGS. **1** and **2** is repeated in the dimension perpendicular to the diagrams allowing the beam to be steered in two dimensions.

A transmissive SLM changes a direction of the beam by changing the phase of the wave front of the beam passing through the pixels of the SLM by retarding the wave front elements by a displacement equivalent to that of the advancement displacement of the wave front elements caused by the reflective SLM. This advancement need not be greater than λ.

FIG. **3** is a 2 dimensional depiction of another configuration of the invention. This particular illustrative example switches a 3 by 3, 2 dimensional array of optical fibers. Referring to FIG. **3**, lens **76** of lens array **77** collimates the light from fiber **78**. This light then passes through an optional field lens **79** and strikes a reflective SLM **80** in the region of n×n pixel elements **81** corresponding to fiber channel **78**. An SLM control adjusts and maintains the relative phase modulo λ (as discussed earlier) of n×n elements **81** to direct the resulting reflected collimated beam **82** back through field lens **79**, through another optional field lens **83** and onto reflective SLM **84** in the region of any of the other 9 groups of n×n elements corresponding, such as group **85** forming an output deflector, to one of 9 output fiber channels. In FIG. **3** SLM **84** then directs the beam **82** back through field lens **83** to fiber channel **86** which corresponds to SLM region **85**.

The optional field lenses **79** and **83** serve to aim the diffraction pattern of each SLM element towards the center of the other SLM so as to reduce power loss particularly from channels near the periphery of the input and output arrays. As such the lenses **79** and **83** should have a focal length of twice the separation between SLM **79** and **83**. For transmissive SLM configurations the focal length should equal the separation between SLMs since the beams pass through each lens only once.

From a consideration of the light propagation modes for square arrays, n squared equals the total number of channels and the total number of SLM elements equals n squared times the total number of channels. These exact relations are not required. The invention only requires enough elements to sufficiently confine and deflect each beam into the intended channel so that any portion of the beam which strikes any other elements results in radiant energy in other channels which produces no more than acceptable crosstalk.

The invention also provides additional phase adjustments to be added by the SLM elements to further confine the beams and reduce diffraction effects. Consider, for example, that even after collimation each beam may continue to diverge due to diffraction. For example, the beam will continue to diverge as it is reflected by regions **81** and **85**. The invention further adjusts and maintains each of the n×n elements to provide a focusing effect at SLM **80**. FIG. **4** shows this additional set of phase corrections **87** which when added to the original phases **88** used for deflection produce the result **89** which is reduced to modulo(λ/2) as discussed earlier. This focusing correction can be applied to all deflecting regions on SLMs **80** and **84**. Further, the invention provides that additional phases can be added or subtracted by the SLMs to correct for other errors such as in the lens arrays, such discussed below.

The pixel reflectors can be manufactured in a planar array of mirror elements **92** as depicted in FIG. **5**A where each element **92** or pixel reflector includes a mirror **94** and springs **96**. FIG. **5**A shows a close packed array of pixels **92** of an

SLM **97** divided into individual beam deflection regions **98**. FIG. **5**B shows the pixels **92** separated into regions **98** on an SLM **97**.

Each element **92** may also include a lens **99** that covers the surface of the element and focuses light onto the mirror **94** where it reflected back through the lens **99**, as shown in FIG. **6**A. The position or displacement of each mirror **94** above the back plate or base **100** of the cavity **102** is controlled by a voltage applied between the reflector **94** and the base plate **100**. Lenses **99** of contiguous pixels can form a continuous array/plane (see FIGS. **5**A and **5**B) thus collecting more of the incident light which is focused on to the mirror which has a smaller area. The small size of the mirror allows it to be moved more rapidly than a larger mirror.

In another embodiment as shown in FIG. **6**B, the reflector **104** is made larger that the reflector **94** allowing the lens **99** to be eliminated and increasing the useful solid angle into which the beam can be deflected compared to the pixel with the lens.

The use of a lens array with the pixels allows the use of smaller mirrors, which allows faster switching operation than the use of bare mirrors that have the same light collection efficiency. The smaller mirrors can be made less massive than larger mirrors by a proportion greater than their ratio of the areas because the smaller mirrors also require less material strength to maintain flatness.

If the position of the mirrors (**94**/**104**) is controlled to 8 bits the reflected wave front will be flat to approximately one part in 64, sufficient to maintain and precisely direct a diffraction limited beam for a 4000 port crossbar or cross connect type switch.

In the above discussion the input, output and deflector arrays have been described as contiguous close packed rectangular arrays of pixels, however, other arrangements can be used such as the hexagon depicted in FIG. **7**. The pixels may, of course, be arranged in a rectangular grid as previously discussed or in another convenient pattern.

FIG. **8** depicts a folded path cavity embodiment in which input an beam(s) **112** from an input plane **114** is deflected by a first SLM **116** to a second SLM **118** which deflects the beam to an output channel on the output plane **119**. A cross connect cavity design capable of switching 900 channels (a 30×30 array) using 30 micron pixels results in a cavity 4 cm high, 12 cm wide and 24 cm long. A similar switch using 20 micron pixels would be only 2.5 cm high, 7.5 cm wide and 11 cm long.

FIG. **9** depicts a folded light path cavity **120** in which an input beam from an input fiber of an array **124** of fiber input channels passes through an input lens of a lens array and is incident on an SLM input beam deflector within an array **128** of input beam deflectors. The beam is directed to a mirror **130** where it is reflected onto an output deflector of the array **128**. The output beam is deflected to an output lens of the array **124** where it is focused into an output fiber of the array **124**.

FIG. **10** depicts another embodiment in which each end of the cavity **132** includes a plane that functions as an input plane, an SLM deflector and an output plane such that a beam **134** entering on the left via plane **136** is deflected by a deflector on plane **138** back to a deflector on plane **136** and then back to plane **138** where it is output. This configuration allows the inputs to be on the opposite side of the cavity **132** from the outputs.

FIG. **11** shows another configuration in which 4 SLMs are used. SLM **1** (**158**) and SLM **2** (**160**) are configured in a Michelson interferometer as are SLM **3** (**164**) and SLM **4** (**166**). An input beam **150**, from an input array **154**, is split into two equal intensity beams by beam splitter **156**. Each of these beams is incident on beam deflectors on the SLMs **1** and **2**. The beam incident on SLM **2** is deflected in direction **155**. The beam incident on SLM **1** is deflected so that it is incident on beam splitter **156** coincident with the beam from SLM **2**. By proper adjustment of the phases of the individual pixels, which is within the ordinary skill in the art of Michelson of interferometers, the relative phase of these two beams is controlled so that when they interfere on beam splitter **156** all of the beam intensity is directed in the direction of beam **155** where it is split into two equal intensity beams by beam splitter **162**. When these two equal intensity beams are incident on the same region of beam splitter **156** from opposite sides, one direction being a mirror image of the other, their electric vectors will add vectorially according to their relative optical phases. They may proceed in their original direction as two beams, dividing up the energy such that the intensity of one beam is proportional to the square of the sine of their relative phases and the other beam is proportional to the square of the cosine of their relative phases. Thus, adjustment of the relative phase can allow all of the light to proceed along direction **155**. The relative phase of the two beams can be adjusted by setting the displacement of the pixels mirrors of one of the SLMs.

The two equal intensity beams are directed on to beam deflectors on SLMs **3** and **4** where they are deflected onto coincident regions of beam splitter **162**. As discussed above, the relative phase of the beams is controlled so when they interfere on **162** all of the light is directed to outport **168**. This configuration allows the use of lensed pixels without having output ports and input ports occupy the same areas.

A cross connect configuration and a configuration which can function as a multiple channel router includes a cavity **180** depicted in cross section in FIG. **12**. The cavity **180** includes a two dimensional array **182** of input channels or beams which are deflected by a two dimensional input deflector array **184** (SLM) onto a mirror **186**. Each of the input beams is preferably collimated so that it can traverse the whole path through the switch maintaining essentially the same diameter. Each beam is directed onto a different pre-assigned deflection region on the "input deflector" plane. The mirror **186** reflects the beams onto an output deflector **188** (SLM) where the beams are deflected onto an output channel array **190**. This figure also depicts the steering of an input beam **192** from an input fiber location **194** over a path **196** to a first output fiber position **198** and the steering of the beam **192** over a different path **200** to a second output fiber position **202**. Within each deflection area (pixel array) on the input SLM **184** (or SLMs as needed) the pixel phase delays are adjusted to impart the phase delay appropriate to direct the incident beam to a desired deflection area on the output deflector plane including the output SLM **188** (or SLMs as needed), which is populated by a similar array of pixels divided into beam deflecting areas. In addition to deflecting the beam the deflecting region will refocus the beam by appropriate phase adjustment of the pixel mirrors.

FIG. **13** depicts an embodiment which is particularly suitable for a router. This embodiment includes an input port **214** and multiple output ports **215**, **216** and **217**. This switch also has single deflector **218** which can be on the axes of both the input port and all of the output ports. One input port and three output ports are shown, however, additional output ports are possible as discussed below. The deflector **218** is, like other embodiments, a phase SLM array of pixels which can include a micro lens array, having one lens per pixel as in FIG. 6A or be without the lenses as in FIG. 6B. Only one deflecting region is necessary. The array of output ports can be duplicated in the dimension perpendicular to the drawing allowing a greater number of output ports. Alternatively the view shown can be duplicated in n parallel planes allowing for n input ports. Other applications of the same device are possible such as any of the n ports can be used as inputs that can be sequentially switched to any other port.

FIG. 14 shows the optical configuration for a router that uses two SLMs 220 and 221 in a Michelson interferometer configuration. It combines features of FIG. 11 and FIG. 13. Light from input fiber 222 is collimated by lens 223 to form an input beam 224 which is input to a Michelson Interferometer formed from beam splitter 225, SLM 1 (220) and SLM 2 (221). The input beam 224 is split into two equal intensity beams by beam splitter 225 incident on SLM 1 and SLM 2, respectively. These SLMs are phase SLMs as previously described except they are made up of an n×n array of pixels, comprising a single deflector. The pixels may have bare reflectors or be lensed pixels, as previously described.

The light beams incident on deflector SLMs 1 (220) and 2 (221) are deflected respectively into directions 226 and 227, where they interfere on beam splitter 225 and are directed through one of the output collimating lenses 228 to the output optical fibers 230 as output beams 232. The relative phases of pixels of the output beams can be adjusted by the phase shifting mirrors of the SLMs so that all of the light of the output beam is directed to, for example, output fiber 233. Changing the deflection angles while maintaining the same relative phases between the beams will allow the output to be directed to outputs fibers 234, 236 or 236. The light beam can also be deflected into a dimension perpendicular to the plane of the figure. The order of n×m output ports can be addressed using an array of n×m pixels having reflectors n×m wavelengths in size.

Because of the limited ability of the beam deflectors (pixel deflection areas or pixel arrays) to steer each beam, the configuration of the input, output and deflector arrays can have rectangular type shape as shown in FIG. 15 for embodiments such as that of FIG. 12. In such a situation the path with the greatest deflection is between input fiber 237 and output fiber 238. The arrangement of the input and output channels in a two dimensional array is advantageous in that in such arrays the deflectors move into position to connect each input channel individually to any output channel The two dimensional input and output configuration of the present invention can also be more compact for a large number of channels that other devices. The packing of the pixels on an array can be hexagonal.

In the configurations shown in FIGS. 8–12, any input channel of the switch may also be an output channel.

The multi-channel inputs and outputs are arranged in essentially two-dimensional planar arrays as indicated in FIG. 12. The input deflector plane 184 and output deflector plane 188 are SLMs. If the input and output each have N channels, each SLM is divided into N contiguous close packed arrays of pixels 112, called beam deflectors, such as the hexagon depicted in FIG. 7. The pixels may, of course, be arranged in a rectangular grid or other convenient pattern. For convenience, we will consider a square rectangular grid. Note that a rectangular array of pixels of an SLM as depicted in FIGS. 5A and 5B would be grouped into deflector areas or regions and the pixels within such designated areas are deflection adjusted together and will together deflect the beam from a single channel.

Each input beam requires a deflector, which is located on the axis of the input beam. Similarly each output beam is reflected from a deflector that is on the axis of the output beam. Since we are using diffraction limited beams and single mode fibers this alignment needs to be accurate. Thus, there is a symmetry between input and output optics as shown in several of the figures where each input deflector deflects its beam to the output deflector assigned to the desired output channel. That output deflector deflects the beam to its assigned output position. Note that stray light from areas other than the assigned output deflector will not be able to enter the single mode fiber core. Thus, the effects of stray light are diminished.

Note that because of symmetry between the input optics and the output optics any single channel can be used either as an input or an output. The number of input channels need not be the same as the number of output channels. Further discussion here will assume an equal number of input channels and output channels.

For an n*m two dimensional array of input beams there will be an n*m two dimensional array of input deflectors and an n*m array of output deflectors. In order to maintain the diffraction limited beam diameter and be able to not have cross talk between beams, it is preferred that each deflector include approximately n*m pixels. Thus, there should be approximately $(n{*}m)^2$ pixels in each SLM.

The size or dimension, number of reflectors, etc. for each deflector needs to be determined. General design considerations that apply to a two dimensional SLM array optical switch design include the following considerations as discussed below.

The number of pixels per dimension ("n" above) preferably equals or exceeds the number of beams in that same dimension ("m" above). This is preferred so that side lobes from one beam do not interfere with adjacent beams. A matching array of micro lenses, such as previously discussed, placed over the SLM, one per pixel, can increase the throughput efficiency and decrease stray light. The range of the wave front phase shift need only be a total of λ. Thus, the total motion required for the pixel mirrors is only λ/2, which for 1.55 micron light used in long distance fiber optic communication, is about 0.76 microns.

Pixel size has large impact on the design. The length of the switch and the SLM area both increased as the pixel width is squared. In the case of the SLM developed by MEMS Optical, Inc. the small reflector (or membrane) is displaced by varying an electric field between the reflector and the back plate. The speed of response can be less than 10^{-5} seconds for pixels of 20 microns diameter or smaller. The speed decreases for larger pixels.

Design of the electronic backplane imposes tradeoffs in optical design. The voltages or charge appropriate for each deflection can be stored in memory and accessed as needed. As is known in the operation of MEMS devices, controlling the voltage to cause deflection of a pixel mirror introduces instability in the mirror positioning. This is because, as the mirror moves closer to the back electrode in response to the electric force, the capacitance increases causing more charge to collect on the electrodes thus, further increasing the pulling force. To eliminate this instability the invention provides that charge may be placed onto the pixel electrodes by connecting them to a constant current source for a controlled time. The appropriate times to achieve the various useful deflections can be stored in memory. Symmetry characteristics of the array significantly reduce the number of individual deflection patterns that need be stored.

For a cross connect type switch only a few beams are typically switched during any switching period. Switching all channels of a very large array at the same time may put high data rate demands on an electronic backplane. The number of channels to be switched essentially simultaneously effects the number of input and output channels that a switch can handle.

FIG. **16** is a cross section schematic diagram, in which the direction of the collimated input beam is perpendicular to the deflector elements, i.e. parallel to the optic axis. The main features of the region of the switch between the input and the output SLMs are shown. The diagram is not to scale, however, it is useful in describing the geometric design parameters of the switch. The bare pixels are illuminated by a collimated beam of light **242** aimed essentially perpendicular to their surfaces. **243** is the direction of a wave front reflected by a group of n pixels comprising one deflector (region) for a single beam **248** (or **243**). Light from an individual pixel spreads out by diffraction into angle $2*\lambda/d$, **244**, giving rise to single pixel diffraction pattern **246**. The interference of the coherent light from the n individual pixels gives rise to a deflected beam **248** of angular spread $\lambda/(n*d)$ that is incident on a single deflector region of the output SLM **250**. The displacement of the deflected beam from the axis of the optical system is $2*\delta*L/d$. At a distance $L*\lambda/d$ from the main beam there is side lobe beam **252** caused by another order of interference. The number of pixels per deflector is preferred to be approximately as great as the number of beams in each of the two dimensions of the beam array so that adjacent beams do not interfere with each other.

FIG. **17** shows an input beam incident on the bare pixel mirrors from an angle θ from below the perpendicular to the pixel mirror. The center of the single pixel diffraction pattern shifts to an angle θ above the axis as shown in the figure. Thus, the input array can be displaced from the region of the deflected beams. However, if individual lenses are used on each pixel as in FIG. **6**A, the single pixel diffraction pattern may overlap the region of the input ports as in FIG. **16**, decreasing the optical channel capacity of the switch. The use of a lens array with the pixels allows the use of smaller mirrors resulting in a faster switching operation than the use of bare mirrors with the same effective optical collection area.

Thus, lensed pixels offer an advantage for routers, in which very high switching speed is appropriate and in which the demand for total number of channels is less.

The Appendix contains a table of approximate switch dimensions for different pixel sizes, number of beams and number of pixels per beam for one dimension of the input array. The values given in the table are approximate, based on a simplified analysis. The actual practical values will be determined by more detailed optical design, as is practiced by persons knowledgeable in the art of optical system design, and by component cost. Similar calculations can be made for a two-dimensional array suitable for an optical router, switch or preferably an optical cross connect switch.

As previously noted the present invention is suitable for use as an optical router switch (see the block diagrams of FIGS. **18** and **19**) and as an optical cross connect switch (see block diagram of FIG. **20**).

A router switch **272** (see FIG. **18**) includes an input beam **274** from an input optical fiber which is split by an optical beam splitter **276** and decoded by a routing address decoder **278**. An address produced by the decoder **278** is supplied to a routing controller **280**. The controller **280** produces pixel displacement values for the pixels of an input deflector region **282** which can be produced via table look-up or via hardwired encoding logic. The circular pattern of the deflector **282** is designed to indicate that the "shape" of the virtual reflecting surface of the deflector has been changed. The controller also selects an output channel or deflector region **288** from among plural output channels or deflector regions **284**, **286**, **288** and **290** to activate and the produces pixel displacement values for each of the pixels of the selected deflector **288**. Because the beam from deflector **282** reaches only one of the deflectors **284**–**288** (in this example deflector **288**), the output deflection values can be applied to all of the output deflectors since only the one that receives the beam will displace it further. This can also be determined by table look-up or hardwired logic. The output deflector **288** receives the input beam from the input deflector **282** via a mirror (not shown) and produces an output beam **292** transmitted by an outgoing optical fiber.

A router switch **293** (see FIG. **19**) can also have a configuration which essentially uses a single deflector **294** (such as in FIGS. **13** and **14**) to deflect an input beam **295** to one of several output positions such as an output beam **296** among output beam positions **296**, **297**, **298** and **299**.

A cross connect switch **312** (see FIG. **20**) receives a switching configuration signal from a configuration controller (not shown) which determines a switch configuration responsive to network conditions such as fiber availability/failure. A connection controller **314**, responsive to the configuration signal, selects appropriate deflectors **316**, **318** and **320** of an input array **322** to activate and produces deflection values for the pixels of the selected deflectors **316**, **318** and **320**. The deflectors receive input beams **324**, **326** and **328** and deflect the beam via a mirror (not shown) to an output deflector array **330**. At the same time, the controller **314** also selects deflectors **332**, **334** and **336** of the output array **330** and produces deflection values for the pixels of the selected deflectors **332**, **334** and **336** of the array **330**. The beams from the input array **322** are deflected as corresponding output beams **338**, **340** and **400**. The switch configuration of FIG. **13** can also be used as an optical router.

The many features and advantages of the invention are apparent from the detailed specification and, thus, it is intended by the appended claims to cover all such features and advantages of the invention which fall within the true spirit and scope of the invention. Further, since numerous modifications and changes will readily occur to those skilled in the art, it is not desired to limit the invention to the exact construction and operation illustrated and described, and accordingly all suitable modifications and equivalents may be resorted to, falling within the scope of the invention.

APPENDIX

Switch examples: calculations for one dimension input arrays
Calculation for optical path between input port plane and output port plane
Input data entries underlined. Wavelength assumed to be 1.55 um

pixel size d	diffraction half angle of pixel	Pixel/beam	No of beams	input array width (cm)	apodized beam width	diff angle of beam	beam Fresnel length (cm)	unfolded length in in Fresnel lengths	distance between orders (cm)	diffraction spot size must < H	1-D deflection needed	(Want < 1) max adjacent phase shift range including +&- wavelengths)	pixels per dim	# of channels in 2-D array
5	0.300	25	20	0.25	125	0.0120	1.04	1.0	0.313	125	0.240	0.800	500	400
5	0.300	25	25	0.31	125	0.0120	1.04	1.0	0.313	125	0.300	1.000	625	625
5	0.300	40	30	0.60	200	0.0075	2.67	1.0	0.800	200	0.225	0.750	1200	900
5	0.300	40	40	0.80	200	0.0075	2.67	1.0	0.800	200	0.300	1.000	1600	1600
5	0.300	60	60	1.80	300	0.0050	6.00	1.0	1.800	300	0.300	1.000	3600	3600
10	0.150	25	20	0.50	250	0.0060	4.17	1.0	0.625	250	0.120	0.800	500	400
10	0.150	25	25	0.63	250	0.0060	4.17	1.0	0.625	250	0.150	1.000	625	625
10	0.150	40	30	1.20	400	0.0038	10.67	1.0	1.600	400	0.113	0.750	1200	900
10	0.150	40	40	1.60	400	0.0038	10.67	1.0	1.600	400	0.150	1.000	1600	1600
10	0.150	60	50	3.00	600	0.0025	24.00	1.0	3.600	600	0.125	0.833	3000	2500
10	0.150	80	70	5.60	800	0.0019	42.67	1.0	6.400	800	0.131	0.875	5600	4900
15	0.100	80	70	8.40	1200	0.0013	96.00	1.0	9.600	1200	0.088	0.875	5600	4900
20	0.075	25	20	1.00	500	0.0030	16.67	1.0	1.250	500	0.060	0.800	500	400
20	0.075	25	25	1.25	500	0.0030	16.67	1.0	1.250	500	0.075	1.000	625	625
20	0.075	40	30	2.40	800	0.0019	42.67	1.0	3.200	800	0.056	0.750	1200	900
20	0.075	40	40	3.20	800	0.0019	42.67	1.0	3.200	800	0.075	1.000	1600	1600
20	0.075	80	75	12.00	1600	0.0009	170.67	1.0	12.800	1600	0.070	0.938	6000	5625
30	0.050	25	20	1.50	750	0.0020	37.50	1.0	1.875	750	0.040	0.800	500	400
30	0.050	25	25	1.88	750	0.0020	37.50	1.0	1.875	750	0.050	1.000	625	625
30	0.050	40	30	3.60	1200	0.0013	96.00	1.0	4.800	1200	0.038	0.750	1200	900
30	0.050	40	40	4.80	1200	0.0013	96.00	1.0	4.800	1200	0.050	1.000	1600	1600
5	0.300	60	40	1.20	300	0.0050	6.00	1.0	1.800	300	0.200	0.667	2400	1600
30	0.050	80	60	14.40	2400	0.0006	384.00	1.0	19.200	2400	0.038	0.750	4800	3600
40	0.038	80	60	19.20	3200	0.0005	682.67	0.6	25.600	1920	0.047	1.250	4800	3600

What is claimed is:

1. An apparatus, comprising:

an optical switch changing a direction of a light beam by changing a phase of an optical wave front of the beam.

2. An apparatus, as recited in claim 1, wherein said switch comprises a spatial light modulator changing the direction of the beam.

3. An apparatus as recited in claim 2, wherein said modulator comprises a reflective phase spatial modulator having pixels grouped as a deflector region.

4. An apparatus as recited in claim 3, wherein each pixel comprises a spring held mirror having a position adjusted by a voltage.

5. An apparatus as recited in claim 4, wherein each pixel comprises a focusing lens.

6. An apparatus as recited in claim 5, wherein the mirror has an area substantially smaller than a size of the pixel.

7. An apparatus as recited in claim 4, wherein the mirror has an area substantially a size of the pixel.

8. An apparatus as recited in claim 3, wherein pixels are grouped into plural deflector regions.

9. An apparatus as recited in claim 8, wherein the deflector regions are contiguous.

10. An apparatus as recited in claim 8, wherein the deflector regions are separate.

11. An apparatus as recited in claim 3, wherein the beam is incident at an angle with respect to an axis of the deflector.

12. An apparatus as recited in claim 3, wherein the pixels are adjusted to form a virtual mirror.

13. An apparatus as recited in claim 1, wherein the phase of the wave front is changed in segments.

14. An apparatus as recited in claim 13, wherein the phase for each segment is modulo $\pi/2$.

15. An apparatus as recited in claim 1, wherein the beam is divided into pixels and each pixel comprises a spring held mirror having a position adjusted by a depositing a known charge upon mirror electrodes.

16. An apparatus as recited in claim 1, wherein the phase is additionally adjusted for divergence due to diffraction.

17. An optical switch, comprising:

an array of displaceable reflectors, each reflector displacing a portion of a wave front of an optical beam.

18. An optical switch as recited in claim 17, wherein the reflectors reflect the beam from an input port to one of plural output ports.

19. An optical switch as recited in claim 18, wherein the displaceable reflector are displaced relative to the adjoining deflector by a distance modulo($\lambda/2$).

20. An optical switch, comprising:

an input spatial light modulator deflecting an input beam producing an intermediate beam; and

an output spatial light modulator reflecting the intermediate beam as an output beam to one of two or more output ports.

21. An optical switch as recited in claim 20, further comprising a mirror in the optical path between the input spatial modulator and the output spatial modulator.

22. An optical switch, comprising:

an input optical deflector deflecting an input optical beam producing an intermediate optical beam; and

an output array of optical deflectors with one of the deflectors of the output array deflecting the intermediate beam producing an output beam with each of the optical deflectors comprising a spatial light modulator.

23. An optical switch as recited in claim 22, wherein the optical deflectors are phase SLMs comprising an array of reflecting mirrors inducing phase changes in the light beam by amounts of modulo($\lambda/2$).

24. An optical switch as recited in claim 22, further comprising a mirror reflecting the intermediate beam from the input deflector to the output deflector array.

25. An optical switch as recited in claim 22, further comprising:

a beam decoder decoding a routing address of an input beam; and

a routing controller controlling selection and deflection of the optical deflectors.

26. An optical switch, comprising:

an input array of optical deflectors deflecting the input optical beams producing intermediate optical beams; and

an output array of optical deflectors with the deflectors of the output array deflecting the intermediate beams producing output beams with each of the optical deflectors comprising a spatial light modulator.

27. An optical switch as recited in claim 26, wherein the optical deflectors are phase SLMs comprising an array of reflecting mirrors inducing phase changes in the light beam by amounts of modulo($\lambda/2$).

28. An optical switch as recited in claim 27, further comprising a connect controller controlling selection and deflection of the optical deflectors.

29. An optical switch as recited in claim 28, wherein the deflection includes a phase adjustment for divergence due to diffraction.

30. An optical switch as recited in claim 27, further comprising a mirror reflecting the intermediate beam from the input deflector to the output deflector array.

31. An optical switch as recited in claim 26, further comprising:

a first field lens focusing the input optical beams; and

a second field lens focusing the intermediate optical beams.

32. An apparatus, comprising:

an optical switch changing a direction of a light beam by changing a phase of an optical wave front of the beam using a phase spatial light modulator where the beam is divided into pixels and each pixel of the modulator comprises a focusing lense and spring held mirror having a position adjusted by a depositing a known charge upon the mirror, the phase of the wave front is changed in segments where the phase for each segment is responsive to an integral number of light beam wavelengths and additionally adjusted for beam divergence; and

a controller controlling the direction responsive to a routing address.

33. A method, comprising:

optically switching a light beam by changing a phase of a wave front of the beam using a spatial light modulator.

34. A method as recited in claim 33, wherein the switching switches multiple input light beams to multiple output ports by switching the light beams using pixelated spatial light modulators in which the phase of no part of the wave is changed more than one wavelength of light.

35. A method as recited in claim 33, wherein the phase of no part of the wave is changed more than three wavelengths of light.

36. An optical switch receiving a single input beam and producing of output beams and comprising two spatial light modulators configured in a Michelson interferometer to receive the single input beam and produce of output beams.

37. An optical switch receiving input beams and producing output beams and comprising four phase optical light modulators configured in pairs into two Michelson Interferometers receiving the input beams and producing the output beams.

38. An optical switch, comprising:

a optical beam splitter having an input side and splinting an input optical beam into two equal intensity beams; and

a pair of spatial light modulators deflecting the equal intensity beams back to a same area of the beam splitter with relative phase such that all of the light intensity exits from an output side opposite the side of the beam splitter from the input side where the modulators deflect the input optical beam into one of plural output beam positions.

39. An optical switch, comprising:

a Michelson interferometer having a pair of spatial light modulators deflecting an input optical beam to one of plural output beam positions.

40. An optical switch, comprising:

a pair of Michelson interferometers, each interferometer having a pair of spatial light modulators deflecting an input optical beam to one of plural output beam positions.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,430,328 B1
DATED : August 6, 2002
INVENTOR(S) : William H. Culver et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 11,
Lines 40-42, delete entire claim **1**.

Column 12,
Line 43, delete “15.” and insert -- 1. --.
Line 43, after “apparatus” delete “as recited in claim 1” and insert -- comprising: an optical switch changing a direction of a light beam by changing a phase of an optical wave front of the beam, --.
Line 45, after “by” delete “a”.
Line 47, delete “16” and insert -- 15 --.
Line 57, after “displaceable” delete “reflector” and insert -- reflectors --.
Line 58, delete “deflector” and insert -- reflector --.
Line 60, after “modulator” delete “deflecting” and insert -- reflecting --.

Column 14,
Line 47, delete “40” and insert -- 16 --.

Signed and Sealed this

Twenty-fifth Day of February, 2003

JAMES E. ROGAN
Director of the United States Patent and Trademark Office

EXHIBIT E

US007092599B2

(12) **United States Patent**
Frisken

(10) **Patent No.: US 7,092,599 B2**
(45) **Date of Patent: Aug. 15, 2006**

(54) **WAVELENGTH MANIPULATION SYSTEM AND METHOD**

(75) Inventor: **Steven James Frisken**, Vaucluse (AU)

(73) Assignee: **Engana PTY LTD**, Sydney (AU)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 183 days.

(21) Appl. No.: **10/706,901**

(22) Filed: **Nov. 12, 2003**

(65) **Prior Publication Data**

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(51) **Int. Cl.**
G02B 6/34 (2006.01)
G02B 6/293 (2006.01)

(52) **U.S. Cl.** **385/37**; 385/24

(58) **Field of Classification Search** 385/24, 385/33, 37; 398/84

See application file for complete search history.

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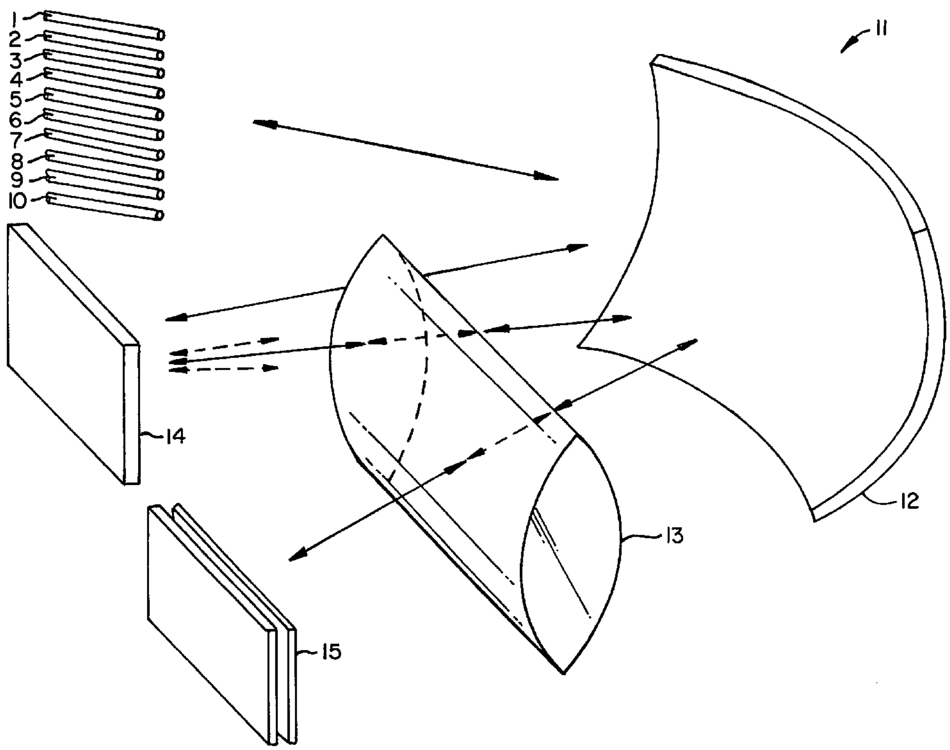
Primary Examiner—John D. Lee
(74) *Attorney, Agent, or Firm*—Townsend and Townsend and Crew LLP

(57) **ABSTRACT**

A wavelength selective manipulation device and method including: at least a first optical input port for inputting an optical signal including a plurality of wavelength channels; a first wavelength dispersing element for angularly dispersing the wavelength channels of the optical signal into angularly dispersed wavelength signals; an optical power element for focussing in the angularly dispersed dimension the angularly dispersed wavelength signals into a series of elongated spatially separated wavelengths bands; a spatial manipulation element for selectively manipulating the spatial characteristics of the spatially separated wavelength bands to produce spatially manipulated wavelength bands.

25 Claims, 10 Drawing Sheets



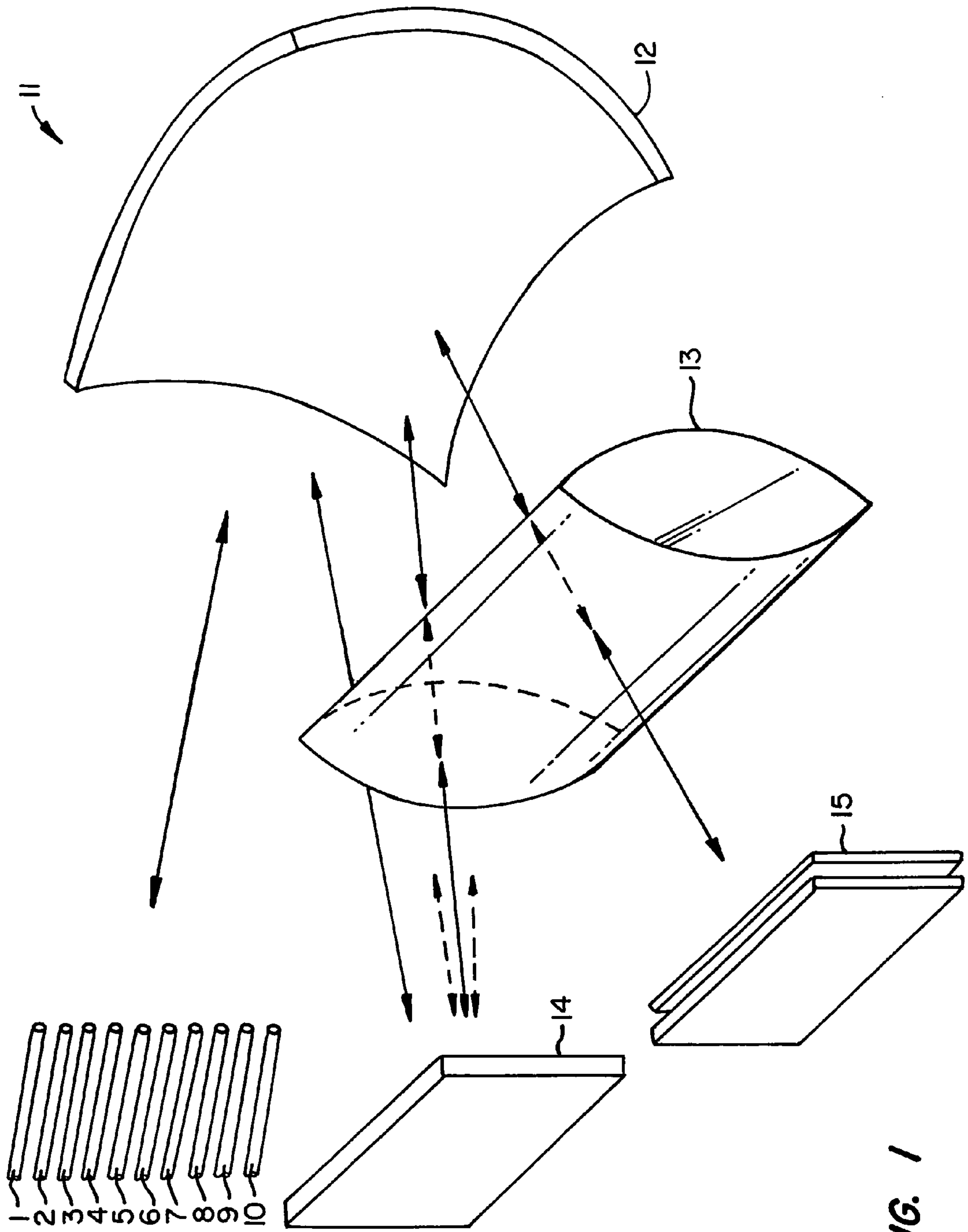


FIG. 1

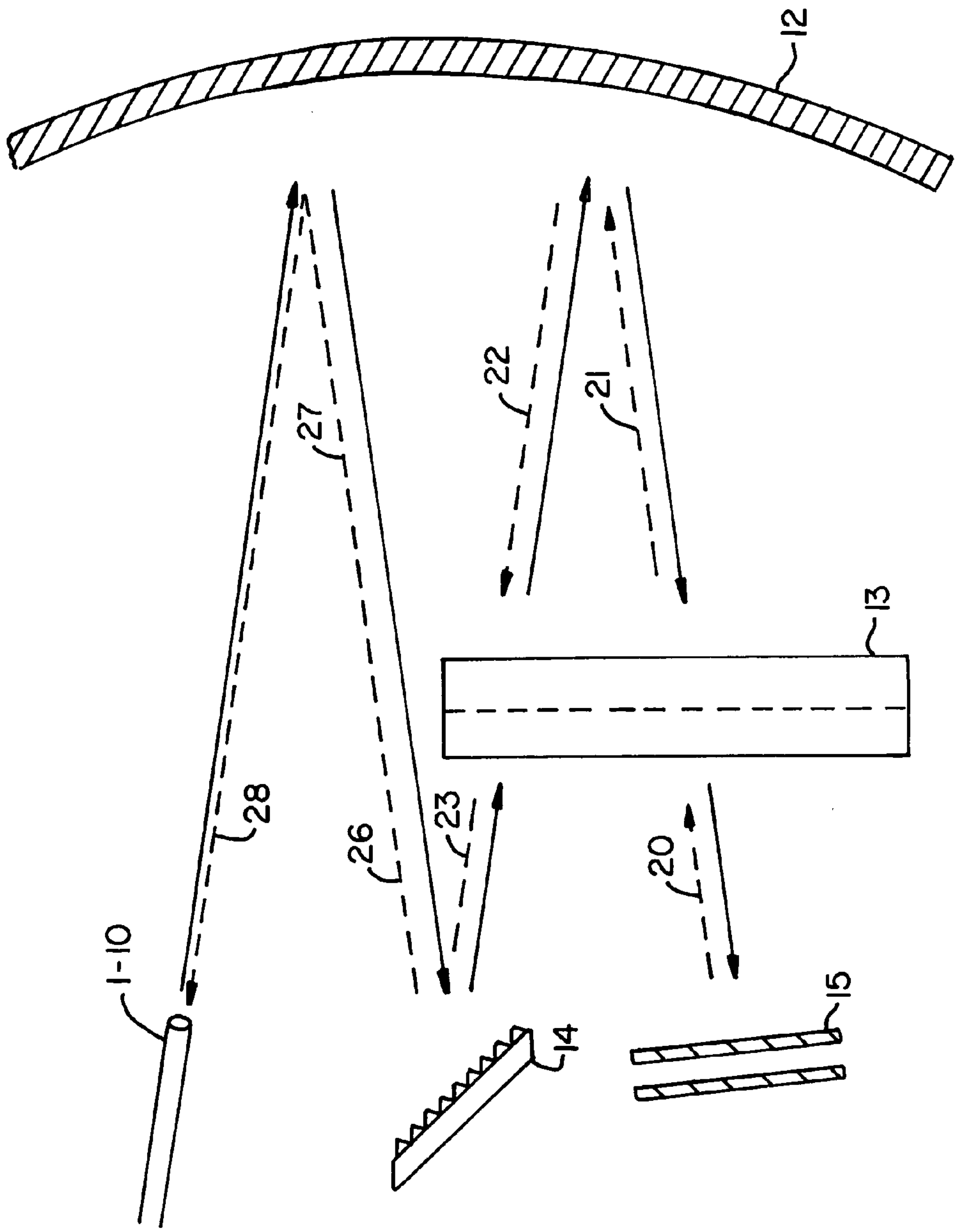


FIG. 2

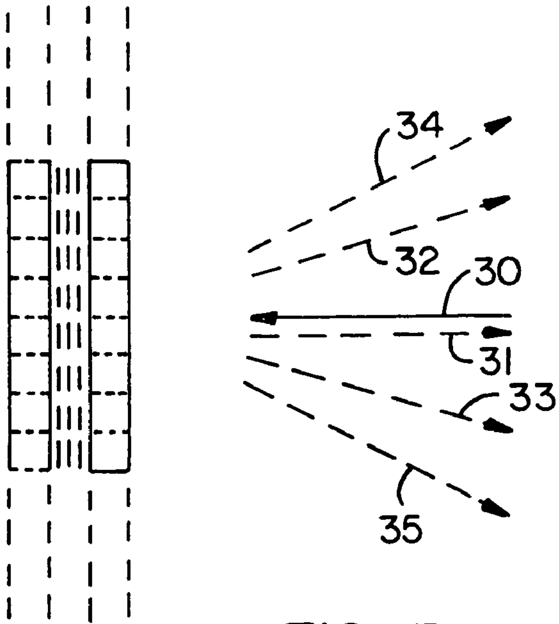


FIG. 3

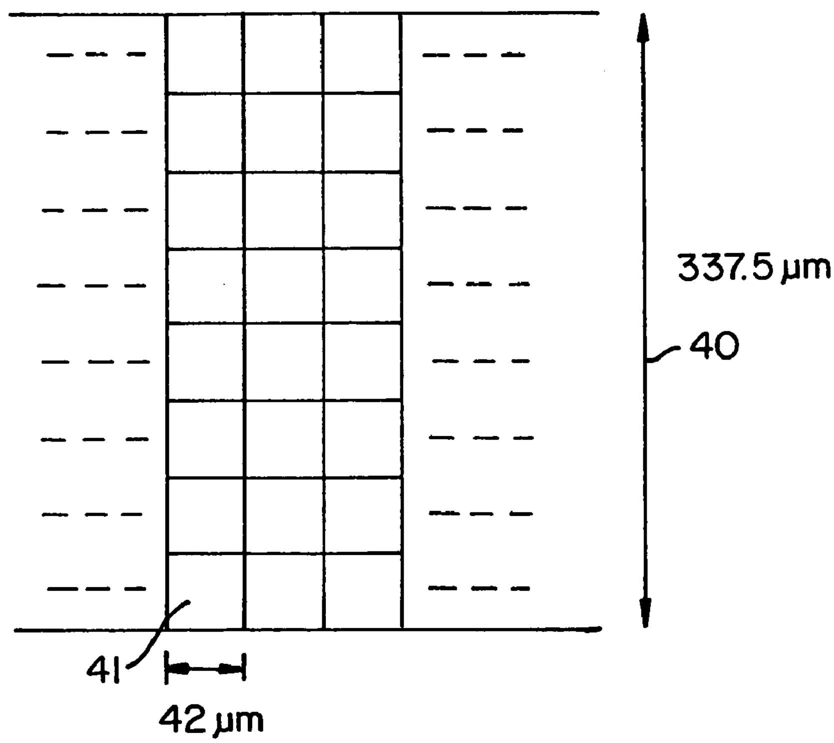


FIG. 4

FIG. 5

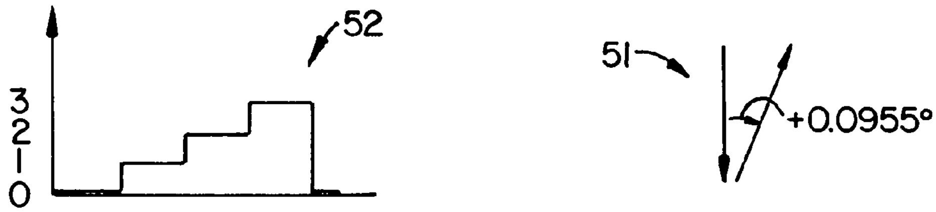


FIG. 6

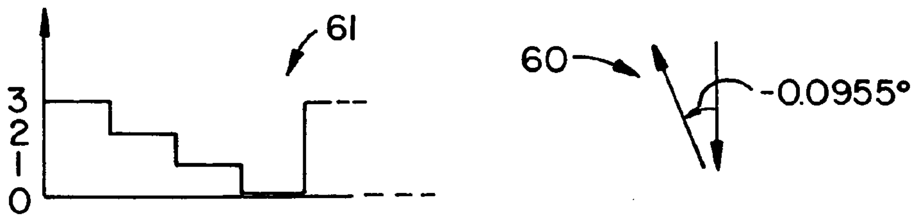


FIG. 7

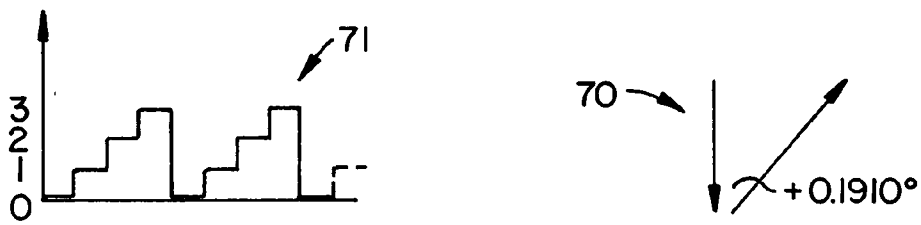


FIG. 8

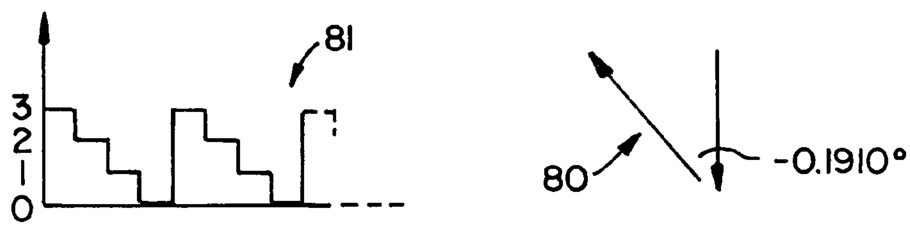
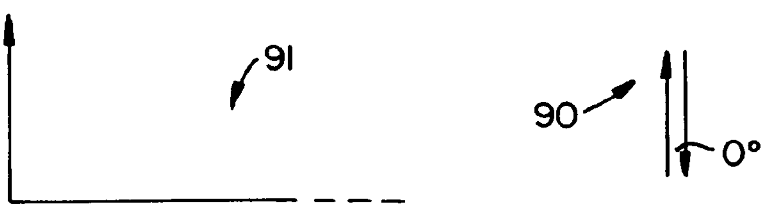


FIG. 9



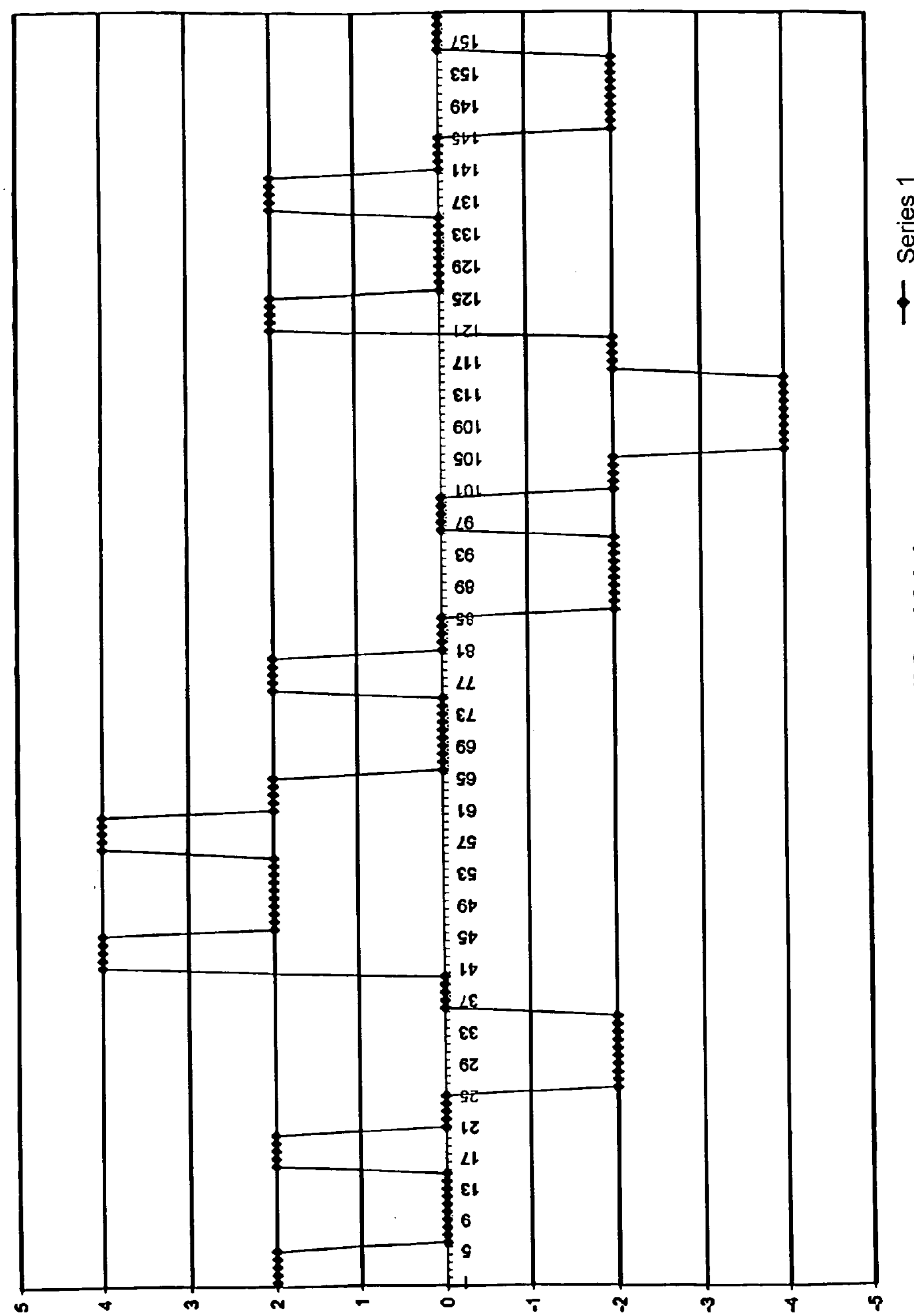

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FIG. 10(a)

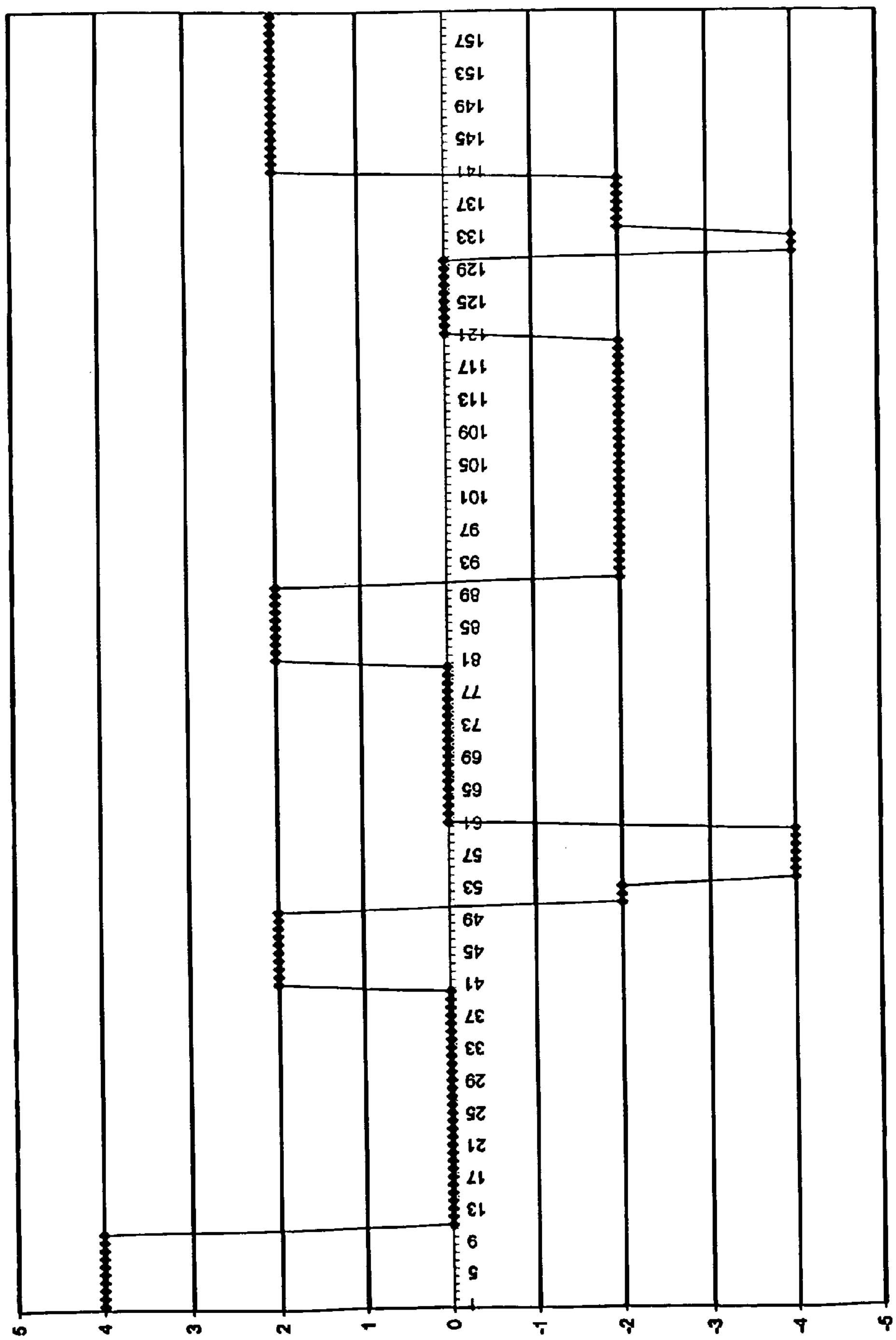


FIG. 10(b)

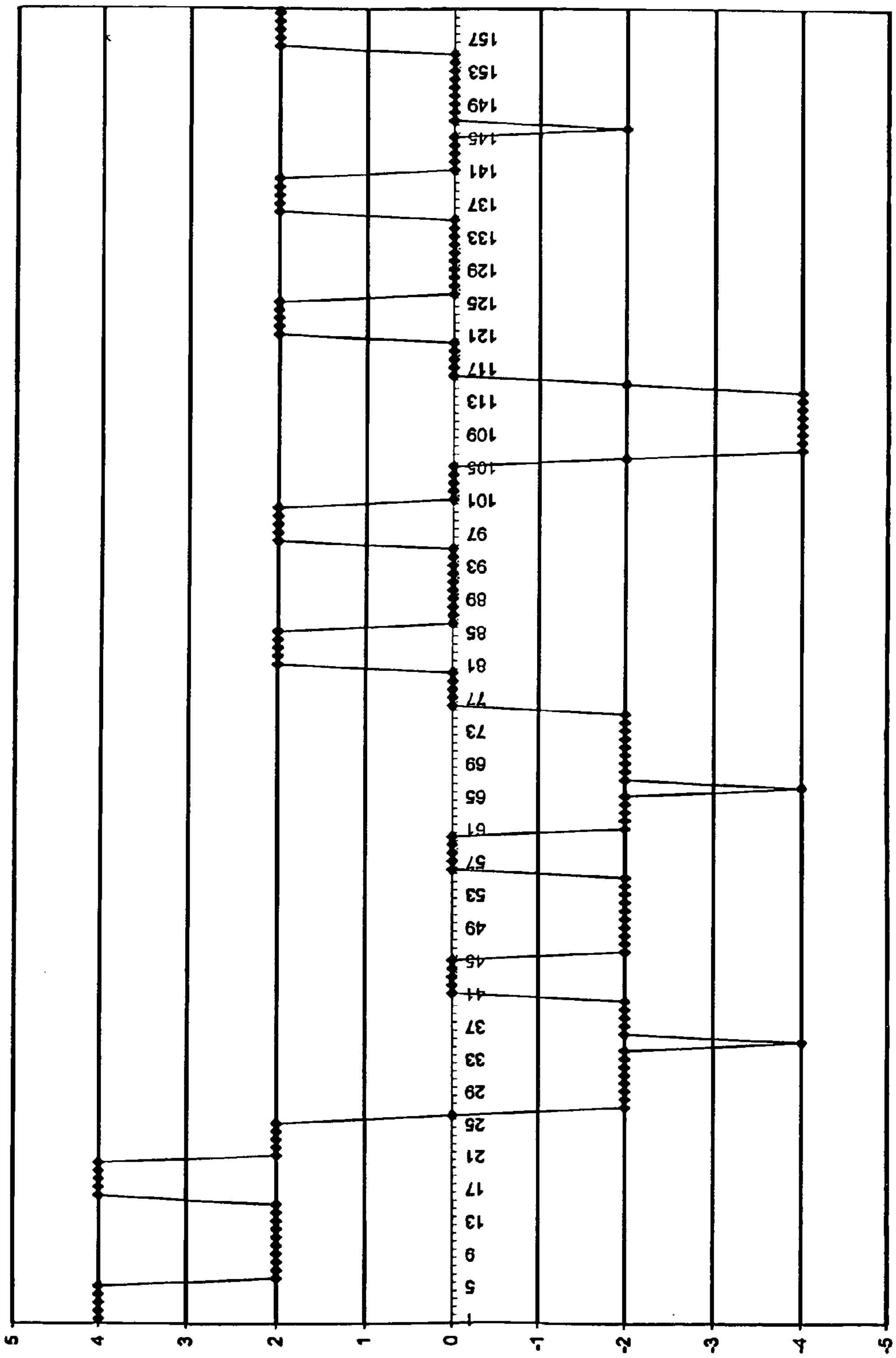


FIG. 10(c)

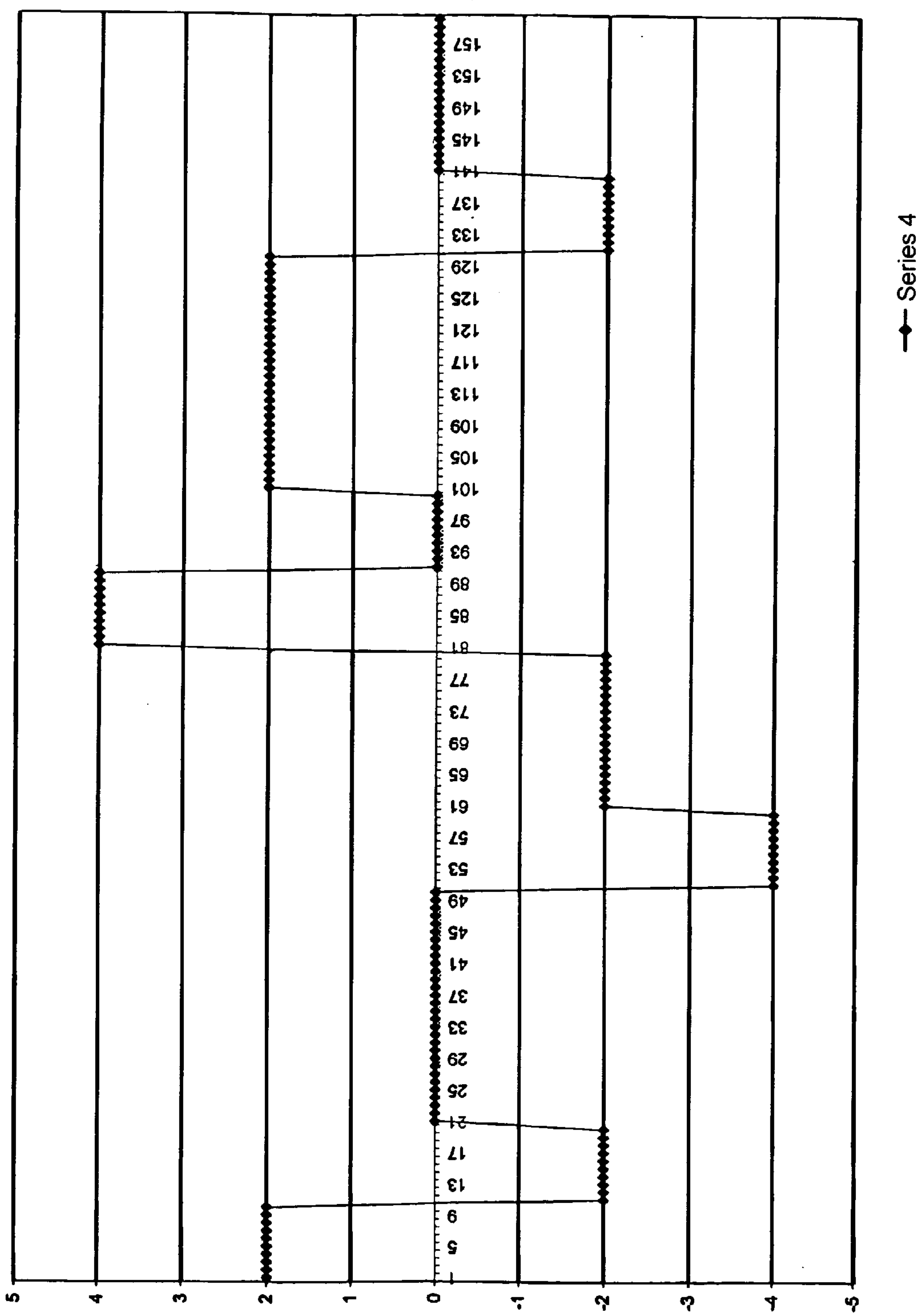


FIG. 10(d)

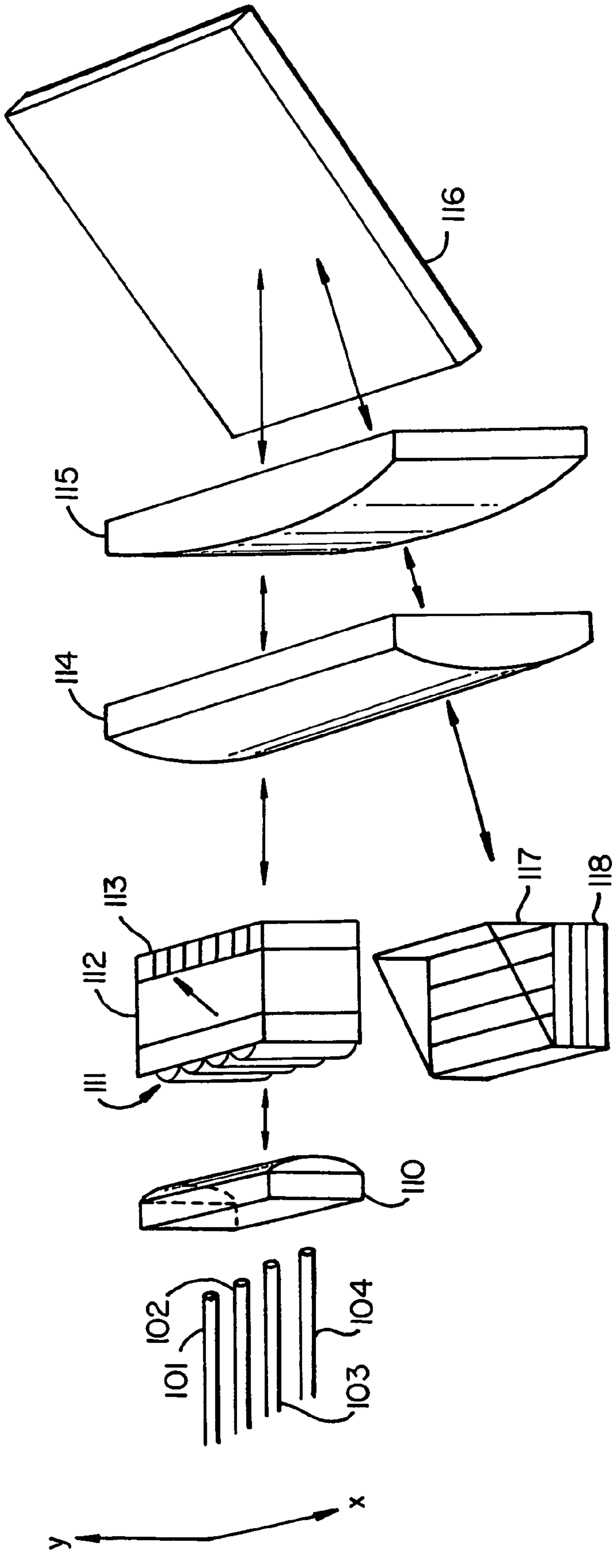


FIG. 11

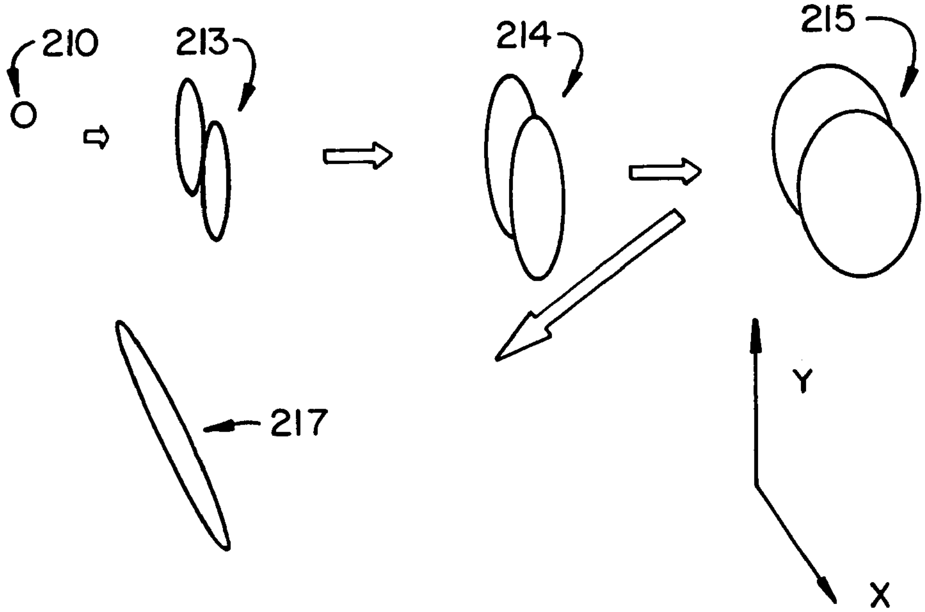


FIG. 12

WAVELENGTH MANIPULATION SYSTEM AND METHOD

FIELD OF THE INVENTION

The present invention relates to an optical switching systems and, in particular, discloses a wavelength selective switch having possible attenuation control characteristics.

BACKGROUND OF THE INVENTION

In optical communications systems, the use of wavelength selective switching for applications of optical cross-connects has attracted much interest because of the goal of fully flexible, networks where the paths of each wavelength can be reconfigured to allow arbitrary connection between nodes with the capacity appropriate for that link at a particular point in time. Although this goal is still valid, it is clear that optical networks will evolve to this level of sophistication in a number of stages—and the first stage of the evolution is likely to be that of a reconfigurable add/drop node where a number of channels can be dropped and added from the main path, whose number and wavelength can be varied over time—either as the network evolves or dynamically as the traffic demands vary.

This present invention is directed to applications such as reconfigurable optical add/drop multiplexer (ROADM) networks and is scalable to the application of wavelength reconfigurable cross-connects referred to generically as Wavelength Selective Switches (WSS).

The characteristics of a wavelength selective element which is ideal for the applications of Optical Add/drop and Wavelength selective switching can be summarized follows:

i) scalable to multiple fibre ports
ii) one channel per port or multiple channels per port operation
iii) reconfiguration of wavelength selectivity to different grids eg/50 GHz or 100 GHz or a combination of both
iv) low optical impairment of the express path
v) low losses on the drop and express paths
vi) ability to add and drop wavelengths simultaneously
vii) ability to reconfigure between any ports or between any wavelengths without causing transient impairments to the other ports
viii) equalisation of optical power levels on express path (OADM) or all paths (WSS)
ix) provision of shared optical power between ports for a given wavelength (broadcast mode)
x) flat optical passband to prevent spectral narrowing
xi) power off configurations that leave the express path of an OADM undisturbed
xii) small power and voltage and size requirements.

In reviewing the many technologies that have been applied it is necessary to generalize somewhat, but the following observations can be made.

Two basic approaches have been made for the OADM and WSS applications.

i) The first has been based on wavelength blocking elements combined with a broadcast and select architecture. This is an optical power intensive architecture, which can provide for channel equalization and reconfiguration of wavelength selectivity, but is not scalable to multiple ports, has very high loss and because of the many auxiliary components such as wavelength tuneable filters has a large power and footprint requirement.
ii) Wavelength switches have been proposed for OADMs, but do not naturally provide for channel equalization, the channel by channel switching in general leads to dispersion and loss narrowing of optical channels, and in the case of multiple port switches it is generally not possible to switch between ports without causing impairment (a hit) on intermediate ports. In addition the channel spacing cannot be dynamically reconfigured. Tuneable 3-port filters have also been proposed having a lack of impairment to the express paths but do not scale easily to multiple ports and may suffer from transient wavelength hits during tuning. Tuneable components are usually locked to a particular bandwidth which cannot be varied. In addition poor isolation of tuneable 3 ports means they are less applicable to many add/drop applications which demand high through path isolation.

One technology that has been applied to optical cross connects has become known as 3-D MEMs utilises small mirror structures which act on a beam of light to direct it from one port to another. Examples of this art are provided in U.S. Pat. Nos. 5,960,133 and 6,501,877. The ports are usually arranged in a 2 dimensional matrix and a corresponding element of the 2 dimensional array of mirrors can tilt in two axis to couple between any one of the ports. Usually two arrays of these mirrors are required to couple the light efficiently and because of the high degree of analogue control required structures based on this technology have proved to be extremely difficult to realize in practice and there are few examples of commercially successful offerings. In this type of structure, a separate component is required to separate each wavelength division multiplexed (WDM) input fibre to corresponding single channel/single fibre inputs.

One of the most promising platforms for wavelength routing application relies on the principle of dispersing the channels spatially and operating on the different wavelengths, either with a switching element or attenuation element. These technologies are advantageous in that the switching element is integrated with the wavelength dispersive element—greatly simplifying the implementation. The trade-off is that in general the switching is more limited, with most implementation demonstrated to date being limited to small port counts—and the routing between ports is not arbitrary. In general a diffraction grating is used for micro-optic implementations or an Array waveguide grating for waveguide applications. Most of the switching applications have been based on MEMS micro mirrors fabricated in silicon and based on a tilt actuation in one dimension. The difficulty with this approach has been that to achieve the wavelength resolution required when the angular dispersion is mapped to a displacement. In such cases, an image of the fibre (with or without magnification) is mapped onto the tilt mirror array. In order to couple the light into a second port, additional optical elements are required that convert the angle into a displacement. Different approaches to this have included retroreflection cubes wedges (U.S. Pat. No. 6,097,519) which provide discrete displacements or Angle to Displacement elements (U.S. Pat. No. 6,560,000) which can provide continuous mapping using optical power provisioned at the Rayleigh length of the image. In all of these cases, in order to switch between ports, the tilt mirror needs to pass through the angles corresponding to intermediate ports. In addition, the number of ports is limited in each of these cases by the numerical aperture of the fiber as each of the different switch positions are discriminated by angles. For a fibre with a numerical aperture of 0.1, a switch which can tilt by +−12 degrees could not distinguish 8 different switch positions. One approach that can be used is to decrease the numerical aperture through the use of thermally expanded cores or micro lenses—but this is done at the expense of wavelength resolution.

An alternative has been to use polarization to switch between ports. Obviously this is most appropriate to switching between 2 ports corresponding to the 2 polarisation states—so is not readily scalable, though more complicated schemes can be envisaged to allow for switching between multiple ports. With polarization switching, the dynamic equalization of channels can be done at the expense of the rejected light being channelled into the second fibre—so it is not applicable to equalization of the express path whilst dropping a number of wavelengths.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide for an improved form of optical switching system.

In accordance with a first aspect of the present invention, there is provided a wavelength selective manipulation device comprising: at least a first optical input port for inputting an optical signal including a plurality of wavelength channels; a first wavelength dispersing element for angularly dispersing the wavelength channels of the optical signal into angularly dispersed wavelength signals; an optical power element for focussing in the angularly dispersed dimension the angularly dispersed wavelength signals into a series of elongated spatially separated wavelengths bands; a spatial manipulation element for selectively manipulating the spatial characteristics of the spatially separated wavelength bands to produce spatially manipulated wavelength bands.

Preferably, the device also includes a first wavelength combining element for selectively combining the spatially manipulated wavelength bands together to produce a first output signal. The first wavelength dispersing element preferably can include a diffraction grating. The optical power element preferably can include a cylindrical lens and the spatial manipulation element can comprise a liquid crystal display device or splatial light modulator (SLM) acing on the phase of the light.

The SLM device can be divided into a series elongated cell regions substantially matching the elongated spatially separated wavelength bands. The cell regions each can include a plurality of drivable cells and wherein, in use, the cells are preferably driven so as to provide a selective driving structure which projects a corresponding optical signal falling on the cell region substantially into one of a series of output order modes. The optical power element also preferably can include a spherical or cylindrical mirror. The diffraction grating can be utilised substantially at the Littrow condition.

In one mode of operation, when the spatial manipulation element is in a first state, first predetermined wavelengths input at the first optical input port are preferably output at a first output port; and when the spatial manipulation element is in a second state, second predetermined wavelengths input at the first optical input port are preferably output at a second output port. Further, when the spatial manipulation element is in the first state, first predetermined wavelengths input at a third optical input port are preferably output at a fourth output port; and when the spatial manipulation element is in a second state, first predetermined wavelengths input at the third optical input port are preferably output at the first output port.

In accordance with a further aspect of the present invention, there is provided a wavelength selective manipulation device comprising: a series of optical input and output ports including a first optical input port inputting an optical signal including a plurality of wavelength channels; a first wavelength separation element for angularly dispersing the wavelength channels of the optical signal into angularly dispersed wavelength signals; a focussing element for focussing in the angularly dispersed dimension the angularly dispersed wavelength signals into a series of elongated spatially separated wavelengths bands; a spatial manipulation element for selectively manipulating the spatial characteristics of the spatially separated wavelength bands to produce spatially manipulated wavelength bands; the spatially manipulated wavelength bands being subsequently focused by the optical power element and combined in a spatially selective manner by the first wavelength separation element for output at the output ports in a spatially selective manner.

In accordance with a further aspect of the present invention, there is provided a method of providing wavelength selective separation capabilities for an optical input signal having multiple wavelength components, the method comprising the steps of: (a) projecting the optical input signal against a grating structure so as to angularly separate the wavelength components; (b) focussing each of the wavelength components in the wavelength dispersed dimension (vertical) into an elongated wavelength component element; (c) independently manipulating the elongated wavelength component element; (d) combining predetermined ones of the manipulated elongated wavelength components.

The focussing step preferably can include utilising a cylindrical lens and spherical mirror to focus the wavelength components. The step (c) preferably can include utilising a liquid crystal display device to separately manipulate each of the wavelength components. The liquid crystal display device can be divided into a series elongated cell regions substantially matching the elongated wavelength components. The cell regions each can include a plurality of drivable cells and wherein, in use, the cells are preferably driven so as to provide a selective driving structure which projects a corresponding optical signal falling on the cell region substantially into one of a series of output order modes.

In accordance with a further aspect of the present invention there is provided a wavelength selective manipulation device comprising: at least a first optical input port for inputting an optical signal including a plurality of wavelength channels; polarisation alignment element for aligning the polarisation state of the optical signal; a wavelength dispersion element for angularly dispersing the wavelength channels of the optical signal into angularly dispersed wavelength signals; an optical power element for focussing in the angularly dispersed wavelength signals into a series of elongated spatially separated wavelengths bands; a spatial manipulation element for selectively spatially manipulating the characteristics of the spatially separated wavelength bands to produce spatially manipulated wavelength bands.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred forms of the present invention will now be described by way of example only with reference to the accompanying drawings in which:

FIG. **1** illustrates schematically a side perspective view of the preferred embodiment;

FIG. **2** is a schematic top plan view of the arrangement of the preferred embodiment;

FIG. 3 illustrates schematically the operation of reflective modes;

FIG. 4 illustrates schematically the arrangement of cells on a Liquid Crystal Display device;

FIG. 5–FIG. 9 illustrate various driving arrangements for producing different diffractive orders;

FIG. 10(*a*) to FIG. 10(*d*) illustrates the driving arrangement for an AC driving of a Liquid Crystal type display;

FIG. 11 illustrates schematically a further alternative embodiment of the present invention; and

FIG. 12 illustrates the optical beam profile along the optical arrangement of FIG. 11

DESCRIPTION OF PREFERRED AND OTHER EMBODIMENTS

In the preferred embodiment, an arrangement is provided for each wavelength of light to be dispersed and focused in one axis and collimated in the orthogonal axis such that a mode selecting liquid crystal array or spatial light modulator can be utilised to select between the various orders of the reflective or transmissive diffraction grating as established by the liquid crystal operating on one polarisation state of light. As is well known, for a collimated beam an angular deflection of the beam such as that obtained by changing the order of a reflective diffraction grating will have the effect of translating the focus of the beam. If the optical train is established to be telecentric then this translation is achieved without affecting the coupling efficiency and so can be coupled effectively into a second port located at a given translation from the first post such as would be provided in the case of a fibre array

Turning initially to FIG. 1, there is illustrated schematically a side perspective view 11 of the arrangement of the preferred embodiment. An array in the x-dimension of optical input output fibres 1–10 is initially provided with the initial input being along the fibre 3. Each of the fibres can have thermally expanded core ends. The emitted light from core 3 is assumed to be of a single vertical polarisation only (If required, a polarisation alignment means (not shown) can be utilised to obtain the single polarisation light in a known manner). The light is projected to a spherical mirror 12 where it is reflected and collimated before striking a diffraction grating 14. The diffraction grating 14 is arranged at the Littrow condition. At the Littrow condition, as is known in the art, the reflected light is angularly dispersed in the y axis into its spectral components.

The light emitted from the grating 14 will have an angular separation in accordance with wavelengths. The spectral components are reflected back through the cylindrical lens 13 having optical power in the x dimension. The spectral components are focussed in the x dimension near to the mirror 12 but remains collimated in the y dimension. Upon return through the cylindrical lens 13 the spectral components are now collimated in the x dimension but continue to converge in the y dimension so as to focus in that dimension on or near an active or passive Liquid Crystal Display (LCD) device 14 providing a series of elongated spectral bands.

For clarity of understanding, FIG. 2 illustrates a top plan view of the arrangement of FIG. 1. Where the light striking the Liquid Crystal Display 15 undergoes pure reflection, the light traverses the return path 20–23 where it again strikes the grating 14 at the Littrow condition where it is recombined with other frequencies and follows a return paths 26–28 where it passes to output port 8.

The Liquid Crystal Display device 15 can be of an active or passive type with a series of independently controllable areas. It is assumed that the reader is well aware of the understanding of Liquid Crystal Display devices and their operation can be entirely standard. In the first preferred embodiment it is noted that the LCD can be essentially equivalent to that used in Spatial Light Modulators (SLM), in particular a phase only reflective SLM such as that demonstrated by Boulder Nonlinear systems using CMOS technology. The design of the CMOS back plane is readily adapted to the pixel size requirements as would be apparent to one skilled in the art.

In the preferred embodiment we use a reflective LCD device and we illustrate for the case of selection between a purely reflective and 4 different diffraction states. The proposed structure is also designed to achieve high extinction between the selected order and the other orders and also the reflective state. This is achieved by the use of symmetry to ensure that at each of the modes not selected or the purely reflective state the integral of the phase of the components goes to zero in theory. Although higher order diffractions can be excited with some efficiency proper choice of cell size (which determine the slit diffraction numerical aperture) can limit this to small fractions and achieve high through-put.

The order-selection mechanism relies on varying the retardation in the sub cells of the induced grating structure in a way that achieves the necessary selectivity and extinction. In this example a simplified drive is achieved by the use of only 4 levels:

State 0:4λ/8 retardance

State 1:3 λ/8 retardance

State 2:2 λ/8 retardance

State 3:λ/8 retardance

Ideally, the reflected light from the LCD is controlled so that different diffraction orders correspond to different angles of propagated light. In the example given, the first order of diffraction is assumed to be at 0.0955 degrees. By controlling the Liquid Crystal Display device, selective excitation of the positive or negative first order of diffraction line can be achieved. This corresponds to a spatial periodicity of 377.5 μm. Hence, as illustrated in FIG. 4, the diffraction line 40 is assumed to be 337.5 μm in length and is divided into 8 cells 41 with each cell being approximately 42 μm in length. This can be readily achieved utilising standard lithographic techniques for the electrode structure.

In a first embodiment, the Liquid Crystal Display device is utilised to form a reflective diffraction grating such that, as illustrated in FIG. 3, input light 30 is output selectively either in a fully reflective manner 31, to the first order 32, 33 or to the second orders 34, 35.

The cells of the Liquid Crystal structure can be driven so as to select the output order. FIG. 5–FIG. 9 illustrates one form of the various possible driving arrangements for the 8 cells. In a first arrangement in FIG. 5, designed to produce a 0.0955 first order deflection, the driving state can be as illustrated 52 with the states being 0,0,1,1,2,2,3,3. In FIG. 6, for the negative first order 60, the driving states can be 3,3,2,2,1,1,0,0. In FIG. 7, for the second order output 70, the driving states 71 can be 0,1,2,3,0,1,2,3. Next in FIG. 8, for the negative second output order 80, the driving states 81 can be 3,2,10,3,2,1,0. Finally, in FIG. 9, for the purely reflective state 90, the driving state 91 can be all 0's.

Each of these modes can then be used in the arrangement of FIG. 1 and FIG. 2 to couple between different input 1–5 and output 6–10 fibres. At wavelengths where the selected LCD mode is in the pure reflective state (0 degrees), the coupling is as follows

Fibre 1 to fibre 10

Fibre 2 to fibre 9

Fibre **3** to fibre **8** (express path in to out)
Fibre **4** to fibre **7**
Fibre **5** to fibre **6**

At wavelengths where the selected mode is +0.0955 degrees, the wavelength from fibre **3** is now coupled to drop fibre **7** as seen below

Fibre **1** to fibre **9**
Fibre **2** to fibre **8** (add path)
Fibre **3** to fibre **7** (drop path)
Fibre **4** to fibre **6**

At wavelengths where the selected mode is −0.0955 degrees, the wavelength from fibre **3** is now coupled to drop fibre **9**

Fibre **2** to fibre **10**
Fibre **3** to fibre **9** (drop path)
Fibre **4** to fibre **8** (add path)
Fibre **5** to fibre **7**

At wavelengths where the selected mode is +0.1910 degrees, the wavelength from fibre **3** is now coupled to drop fibre **6** as seen below

Fibre **1** to fibre **8** (add path)
Fibre **2** to fibre **7**
Fibre **3** to fibre **6** (drop path)
Fibre **4** to fibre **5**

At wavelengths where the selected mode is −0.1910 degrees, the wavelength from fibre **3** is now coupled to fibre **10** as seen below

Fibre **3** to fibre **10** (drop path)
Fibre **4** to fibre **9**
Fibre **5** to fibre **8** (add path)
Fibre **6** to fibre **7**

Selective attenuation of a particular wavelength channel can be achieved by attenuation of the individual coupling efficiency into modes and having a separate order which is used only for attenuation and is selectively excited at the expense of the efficiency of the selected order. In this way, the power at the selected order can be adjusted to a desired level. Additionally, a diffraction order can be used for monitoring purposes. Light can be coupled at one wavelength into the additional diffraction order—received on a photo detector and used as a monitor or control mechanism for the power levels in the system. This light could be collected by the addition of a fibre (single or multimode).

It is easy to generalize the principles here to other numbers of orders as required.

In a second further embodiment, the diffraction orders be addressed in a simple way and an electrode structure and driving scheme is proposed that can achieve this simply—though many alternative implementations are possible and the scope of the invention is not limited in any way to this method.

In the y-axis in which the wavelengths of light are resolved, one of 5 voltage functions Fyi(t) is applied to the electrode corresponding to the mode we wish to excite. Each of the electrodes corresponding to the subcells in the x-axis have voltage functions Fx(j). The voltage function is chosen such that the relationship between the top and bottom electrodes (Fyi(t)-Fxj(t)) for each of the subcells cells produces an AC component with a corresponding retardance to that required for the particular mode.

The exact form of these functions will depend on the linearity and frequency dependency of the exact liquid crystal used. To exemplify the approach a linear voltage retardance response and no frequency dependence is assumed.

In this case, the modes can be produced by using four different driving frequencies for the different orders of the induced grating. Each of the subcell electrodes is driven by a combination of the four frequencies with equal magnitude but a phase chosen to give Fyi(t)-Fxj(t), the correct AC component to achieve the required retardance. For example, when the phase of the drive frequency and the phase of the corresponding frequency component of the subcell is in phase there is no contribution to the AC voltage (with the only contribution being for the 2^{nd} to 4^{th} frequency components which is equal for all subcells and provides a bias voltage). Equally when the phase of the drive frequency and the phase of the corresponding frequency component of the subcell are π out of phase, then the AC component is a maximum. In this cased the maximum AC component is chosen to achieve a retardance of $\pi/8$ and the minimum AC component is chosen to achieve a retardance of $\pi/2$. The two other states ($\pi/4$ retardance and $3\pi/8$ retardance) are achieved by phase delays in the corresponding subcells of $\pi/3$ and $2\pi/3$. So by control of the drive frequency and phase of Fy it is possible to choose between one of the four diffraction modes. When Fy is zero then the retardance of each subcell is equal so the induced grating is in a purely reflective state. FIG. **10**(*a*) to FIG. **10**(*d*) illustrate the corresponding driving arrangements. By using frequency components of 1 kHz, 2 kHz, 4 kHz and 8 kHz, each of the modes can be successfully driven to give a desired structure of the subcells. Similar approaches have been used to achieve grey level modulation in passive matrix displays by modulating in such a way as to create the correct RMS voltage level for the grey level being modulated.

In a third embodiment the same objective is achieved efficiently employing a micro arrays of cylindrical lenses. The arrangement can be as illustrated in FIG. **11**

In this case, there is provided an input array (in the x axis) of 2 fibres (**101** and **102**) and output array of 2 fibres (**103** and **104**) with a fibre spacing of 250 microns. The output of the fibres is coupled into a first micro cylindrical lens (**110**) to modify the divergence of the beam. The output is then coupled into an x-axis array of cylindrical lenses (**111**) with a separation corresponding to the fibre separation. The focal length of the lens **111** is chosen to be 500 micron so as to form a collimated beam of approximately 100 micron diameter. This beam is split in the x direction into two polarization states by a walk off crystal (**112**) of thickness 1.25 mm and then equalized in polarization by the polarization diversity optics **113** which can comprise an array of waveplates having a spacing of 125 microns. The output from the waveplates **113** consists of polarisation aligned beams. The waveplates can be produced by nano-optic lithographic techniques (as supplied by NanoOpto of Somerset, N.J.) or by an arrangement of standard quartz waveplate techniques.

Each of the output beams is then is projected to a first x-axis cylindrical lens **114** with a focal length of 5 cm which provides collimation in the x axis followed by a y axis cylindrical lens (**115**) with a focal length of 20 cm. Next the beams are reflecting from a grating (**116**) (1200 l/mm) at the near Littrow configuration. After the second pass of the x cylindrical lens the now diffracted beam resulting from the 100 micron diameter beam is collimated in the x direction—the combined effect of the double pass of the lens **115** and reflection from grating **116** being a compound reflective lens with focal length of approximately 10 cm.

The image of the reflected fibre is focused in the y direction by the y cylindrical lens producing a y focused but x-collimated beam. Typically the size of the beam at this point is highly asymmetric with radial dimensions of 20 microns in y and approximately 700 microns in x dimension. The image is wavelength dispersed in the y dimension and the individual channels can be accessed by a liquid crystal spatial light modulator (SLM) (**118**) after being folded down by a prism (**117**) to allow simple mounting of the SLM.

The SLM (**118**) is again able to direct the image of the light from input fibre (**102**) between the fibre drop port(**103**) or express port (**104**) by selection of the correct order of the induced grating when the light retraces its path through the system. Simultaneously, when the input light is directed to the drop port at a particular wavelength, the same wavelength will be directed from the add port (**101**) to the express port (**104**)

The reimaged light at the fibre port is again largely circular symmetric as the effects of the cylindrical lenses are reversed through the return propagation. Further, channel by channel attenuation control of optical power can be achieved by exciting a fraction of the power into an angle that doesn't correspond to an active port thereby attenuating the power in the chosen path.

The grating element (**116**) can be designed to reduce the x angular dependence of the grating by the use of a wedged prism which has an opposite angular dependence.

Further, the first cylindrical lens **114** can be replaced with a reflective cylindrical lens if a more compact design is desired without departing from the scope of this invention—though for clarity a transmissive cylindrical lens system has been described.

Turning now simultaneously to FIG. **12** and FIG. **11**, there is illustrated the optical profile at various points along the optical pathway. The point **210** corresponds to the optical profile of the beams emitted fibres e.g. **110**. The profile **213** corresponds to the optical profile of the light emitted from the element **113**. Here the separate polarisation are split due to the waveplate **112**. The profile **214** corresponds to the light emitted from the lens **114**. The profile **215** corresponds to the light emitted from the lens **115** and the profile **217** corresponds to the light striking the SLM device **117**, **118**.

The foregoing describes preferred embodiments of the present invention. Modifications, obvious to those skilled in the art can be made thereto without departing from the scope of the invention.

I claim:

1. A wavelength selective manipulation device comprising:

at least a first optical input port for inputting an optical signal including a plurality of wavelength channels;

a first wavelength dispersion element for angularly dispersing the wavelength channels of said optical signal into angularly dispersed wavelength signals;

an optical power element for focussing in the dimension of the angular dispersion said angularly dispersed wavelength signals such that said wavelength signals have an elongated optical intensity profile in the focal plane of said optical power element so as to form elongated spatially separated wavelength signals; and

a spatial manipulation element for selectively spatially manipulating the characteristics of said elongated spatially separated wavelength signals to produce spatially manipulated wavelength signals.

2. A device as claimed in claim **1** further comprising:

a first wavelength combining element for selectively combining said spatially manipulated wavelength signals together to produce a first output signal.

3. A device as claimed in claim **1** wherein said first wavelength dispersion element includes a diffraction grating.

4. A device as claimed in claim **3** wherein said diffraction grating is utilised substantially at the Littrow condition.

5. A device as claimed in claim **1** wherein said focussing element includes at least one cylindrical lens.

6. A device as claimed in claim **5** wherein said optical power element includes a spherical mirror.

7. A device as claimed in claim **1** wherein said spatial manipulation element comprises a spatial light modulator or liquid crystal display device.

8. A device as claimed in claim **7** wherein said liquid crystal display device is divided into a series of elongated cell regions substantially matching the optical intensity profile of said elongated spatially separated wavelength signals.

9. A device as claimed in claim **8** wherein said cell regions each include a plurality of drivable cells and wherein, in use, said cells are driven so as to provide a selective driving structure which projects a corresponding optical signal falling on the cell region substantially into one of a series of output order modes.

10. A device as claimed in claim **1** wherein said optical power element also includes a spherical mirror device.

11. A device as claimed in claim **1** wherein:

when said spatial manipulation element is in a first state, first predetermined wavelengths input at said first optical input port are output at a first output port; and

when said spatial manipulation element is in a second state, second predetermined wavelengths input at said first optical input port are output at a second output port.

12. A device as claimed in claim **11** wherein:

when said spatial manipulation element is in said first state, first predetermined wavelengths input at a third optical input port are output at a fourth output port; and

when said spatial manipulation element is in a second state, first predetermined wavelengths input at said third optical input port are output at said first output port.

13. A device as claimed in claim **1** wherein the optical intensity profile of each of the elongated spatially separated wavelength signals has an aspect ratio of greater than 10:1 in the plane of the spatial manipulation element.

14. A device as claimed in claim **1** wherein the optical intensity profile of each of the elongated spatially separated wavelength signals has an aspect ratio of approximately 35:1 in the plane of the spatial manipulation element.

15. A wavelength selective manipulation device comprising:

4-a series of optical input and output ports including a first optical input port inputting an optical signal including a plurality of wavelength channels;

a first wavelength dispersion element for angularly dispersing the wavelength channels of said optical signal into angularly dispersed wavelength signals;

an optical power element for focussing said angularly separated wavelength signals into a series of elongated spatially separated wavelengths bands;

a spatial manipulation element for selectively spatially manipulating the characteristics of said angularly separated wavelength bands to produce spatially manipulated wavelength bands; and

said spatially manipulated wavelength bands being subsequently focused by said optical power element and combined in a spatially selective manner by said first wavelength dispersion element for output at said output ports in a spatially selective manner.

16. A method of providing wavelength selective separation capabilities for an optical input signal having multiple wavelength components, the method comprising the steps of:

(a) projecting the optical input signal against a grating structure so as to angularly separate said wavelength components;

(b) focussing each of said wavelength components into an elongated wavelength component element having an elongated optical intensity profile;

(c) independently manipulating said elongated wavelength component element; and

(d) combining predetermined ones of said manipulated elongated wavelength components.

17. A method as claimed in claim **16** wherein said focussing step includes utilising a cylindrical lens to focus the wavelength components.

18. A method as claimed in claim **16** wherein said focussing step includes utilising a spherical mirror to focus the wavelength components.

19. A method as claimed in claim **18** wherein the optical intensity profile of each of the elongated wavelength component element has an aspect ratio of greater than 10:1.

20. A method as claimed in claim **16** wherein said step (c) includes utilising a liquid crystal display device to separately manipulate each of the wavelength components.

21. A method as claimed in claim **20** wherein said liquid crystal display device is divided into a series of elongated cell regions substantially matching said optical intensity profile of said wavelength component elements.

22. A method as claimed in claim **21** wherein said cell regions each include a plurality of drivable cells and wherein, in use, said cells are driven so as to provide a selective driving structure which projects a corresponding optical signal falling on the cell region substantially into one of a series of output order modes.

23. A method as claimed in claim **16** wherein said focussing step includes utilising a spherical mirror.

24. A wavelength selective manipulation device comprising:

a at least a first optical input port for inputting an optical signal including a plurality of wavelength channels;

polarisation alignment element for aligning the polarisation state of said optical signal;

a wavelength dispersion element for angularly dispersing the wavelength channels of said optical signal into angularly dispersed wavelength signals;

an optical power element for focussing the angularly dispersed wavelength signals into a series of elongated spatially separated wavelength signals; and

a spatial manipulation element for selectively spatially manipulating the characteristics of said spatially separated wavelength bands to produce spatially manipulated wavelength bands.

25. A wavelength selective manipulation device comprising:

a series of optical input and output ports including a first optical input port inputting an optical signal including a plurality of wavelength channels;

a first wavelength dispersion element for angularly dispersing the wavelength channels of said optical signal into angularly dispersed wavelength signals;

an optical power element for focussing said angularly separated wavelength signals such that said wavelength signals have an elongated optical intensity profile in the focal plane of said optical power element so as to form elongated spatially separated wavelength signals;

a spatial manipulation element for selectively spatially manipulating the characteristics of said elongated spatially separated wavelength signals to produce spatially manipulated wavelength signals; and

said spatially manipulated wavelength signals being subsequently focused by said optical power element and combined in a spatially selective manner by said first wavelength dispersion element for output at said output ports in a spatially selective manner.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 7,092,599 B2

APPLICATION NO. : 10/706901

DATED : August 15, 2006

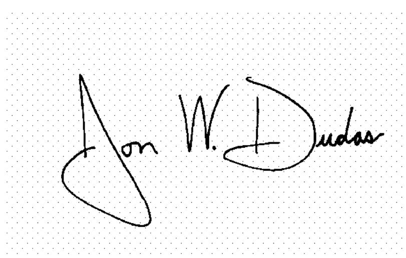
INVENTOR(S) : Steven James Frisken

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 10 at line 49, Claim 15: delete “4-”.

Signed and Sealed this

Twenty-sixth Day of December, 2006



JON W. DUDAS

Director of the United States Patent and Trademark Office

EXHIBIT F

US007397980B2

(12) United States Patent
Frisken

(10) **Patent No.:** **US 7,397,980 B2**
(45) **Date of Patent:** **Jul. 8, 2008**

(54) **DUAL-SOURCE OPTICAL WAVELENGTH PROCESSOR**

(75) Inventor: **Steven James Frisken**, Vaucluse (AU)

(73) Assignee: **Optium Australia PTY Limited**, Evenleigh, New South Wales (AU)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 107 days.

(21) Appl. No.: **10/868,521**

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G02B 6/28 (2006.01)

(52) **U.S. Cl.** **385/24**; 385/15; 385/17; 385/37

(58) **Field of Classification Search** 385/24
See application file for complete search history.

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Assistant Examiner—Erin D Chiem
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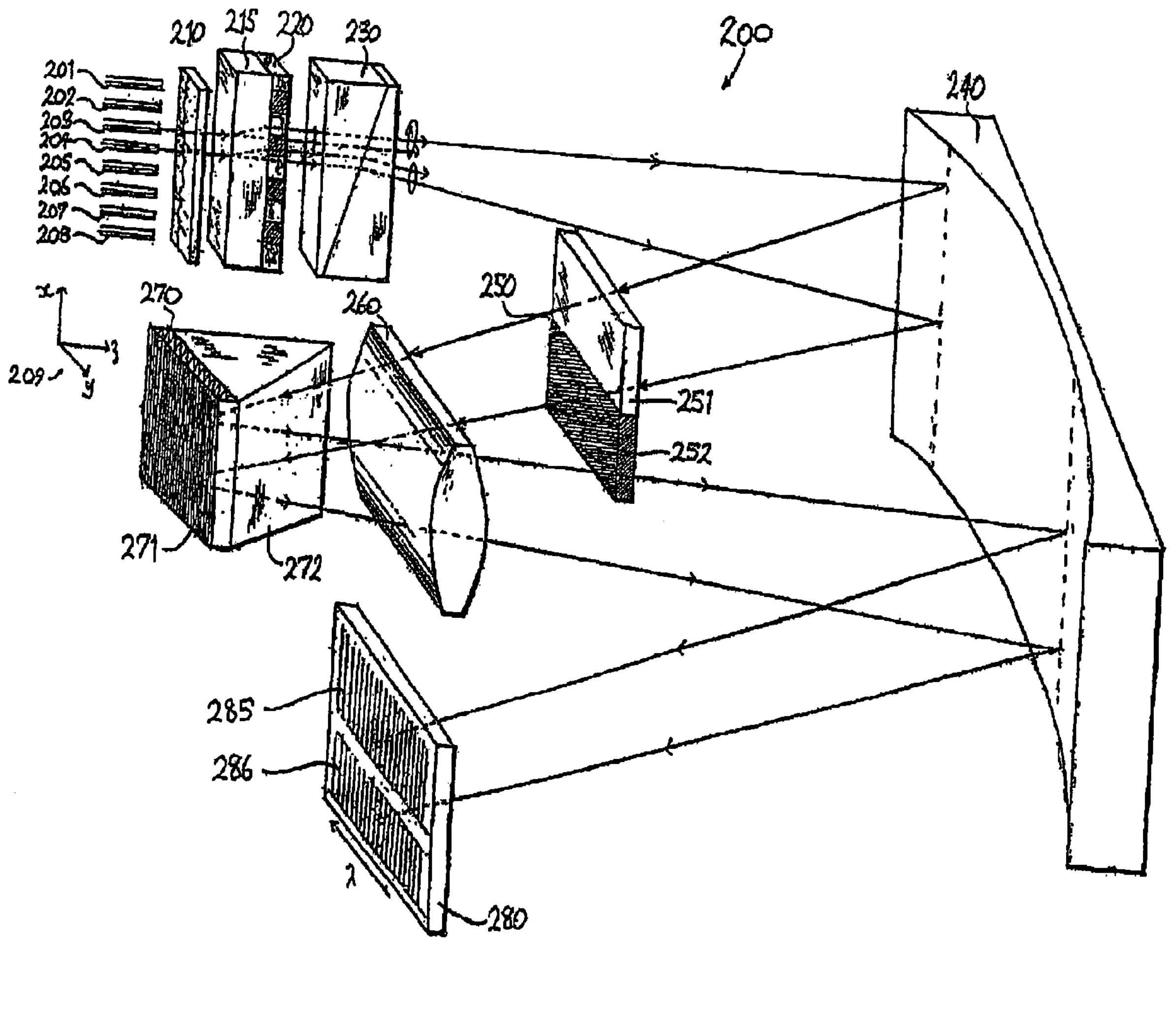
(57) **ABSTRACT**

An optical signal manipulation system including: a series of ports for carrying a series of optical signals to be manipulated; a spatial separating means for spatially separating at least a first and a second group of light from the series of optical signals; wavelength dispersion element subsequently spatially separating wavelengths of the first and second series; wavelength processing means for processing separated wavelengths of the first and second series.

16 Claims, 7 Drawing Sheets



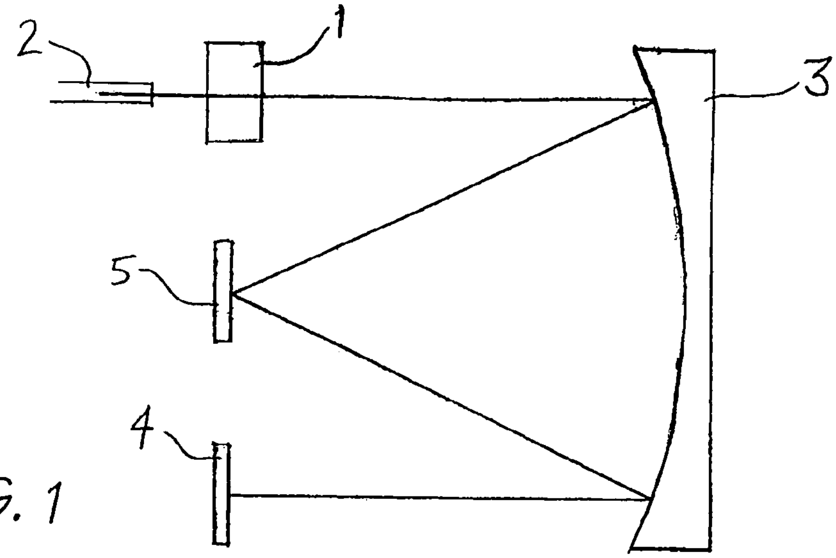


FIG. 1

PRIOR ART

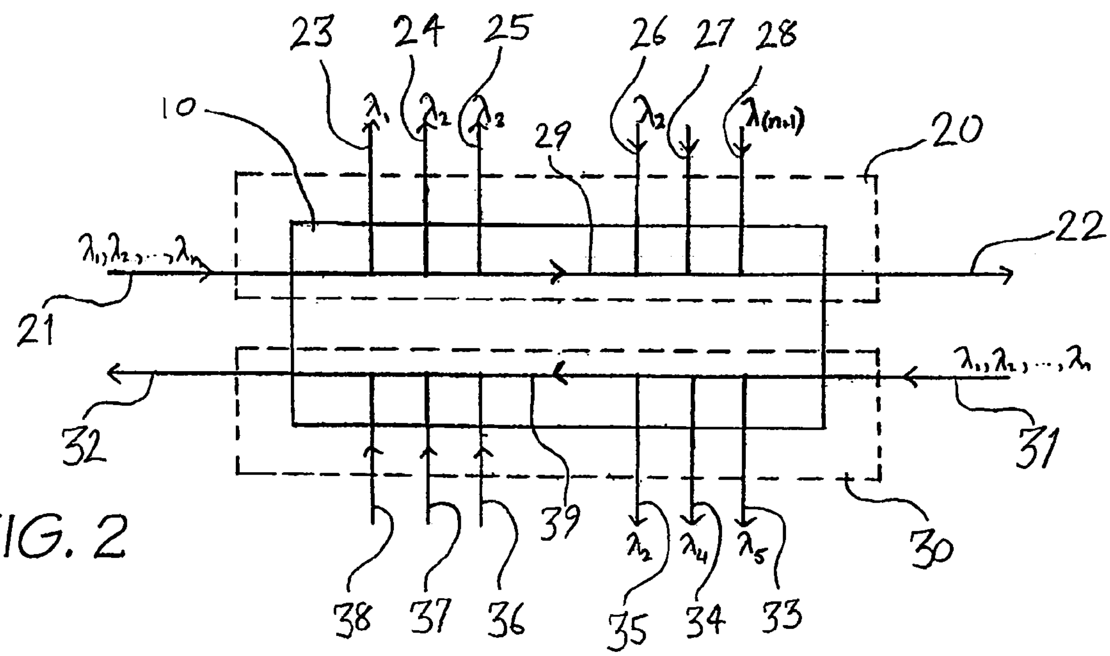


FIG. 2

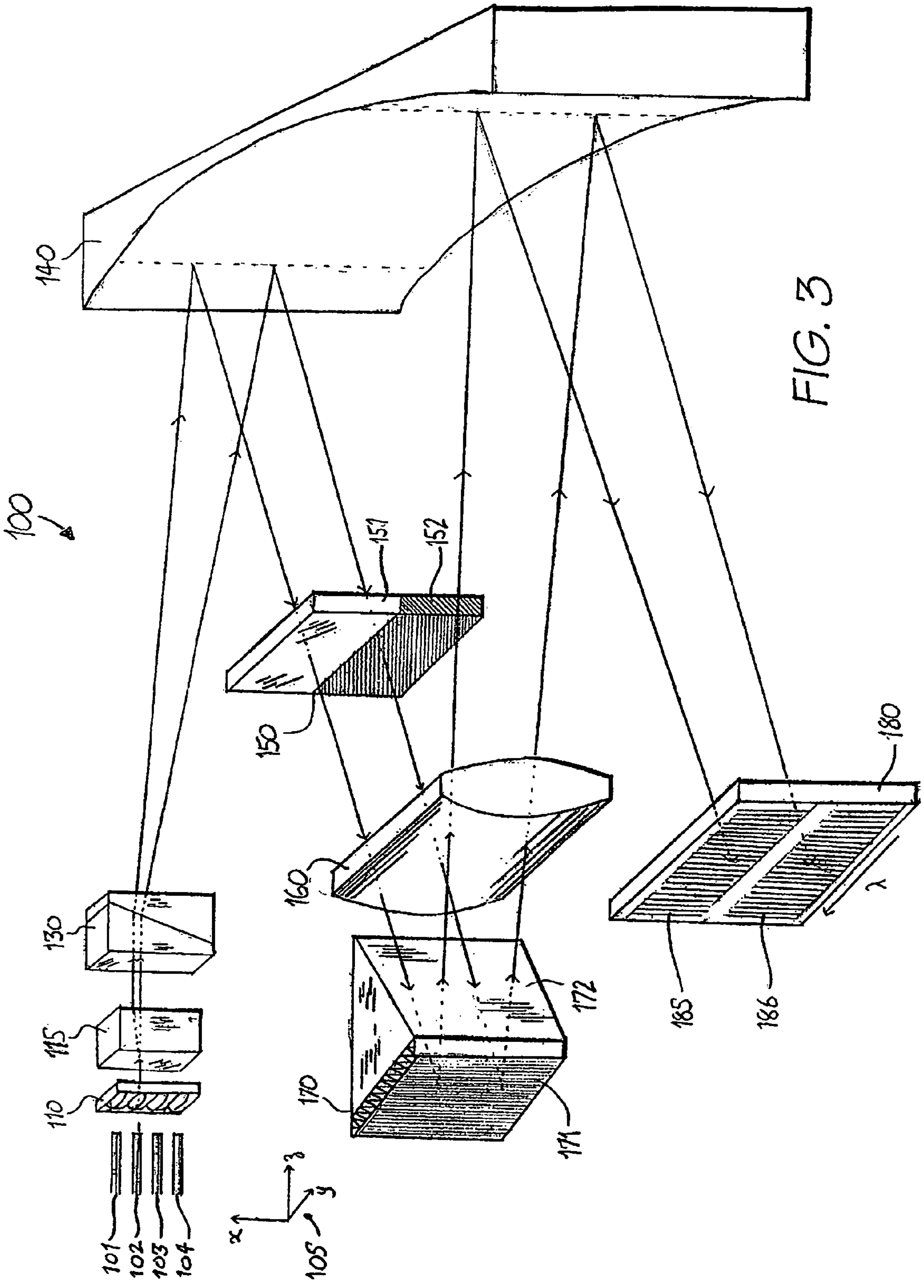

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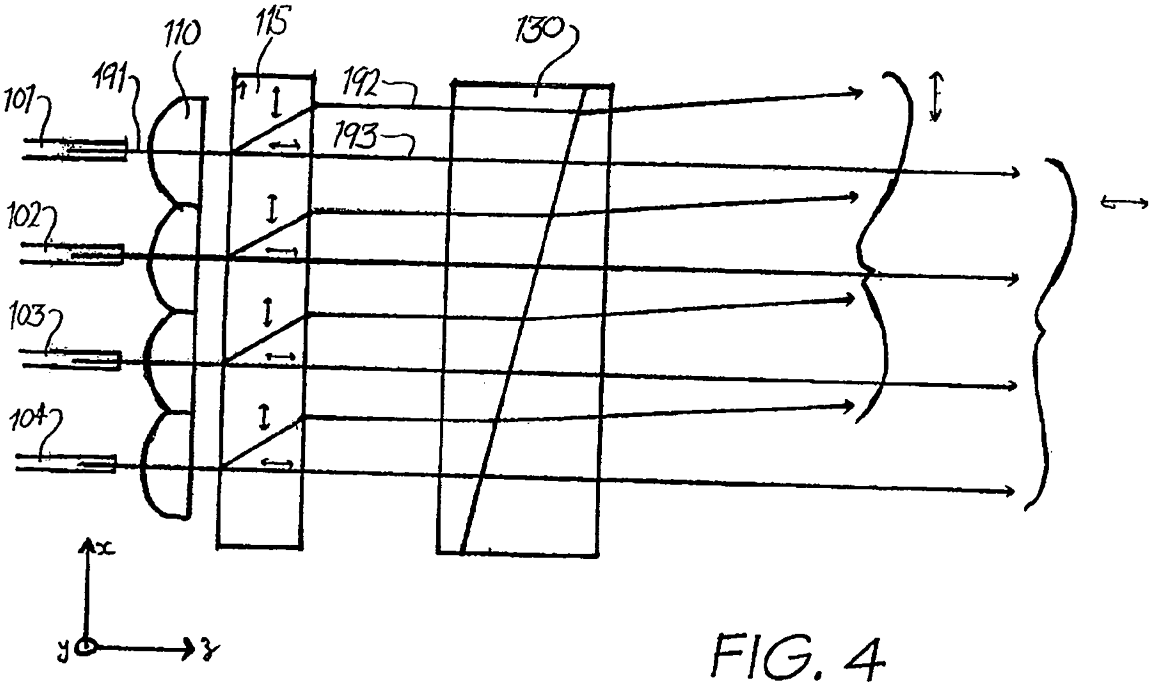
FIG. 3



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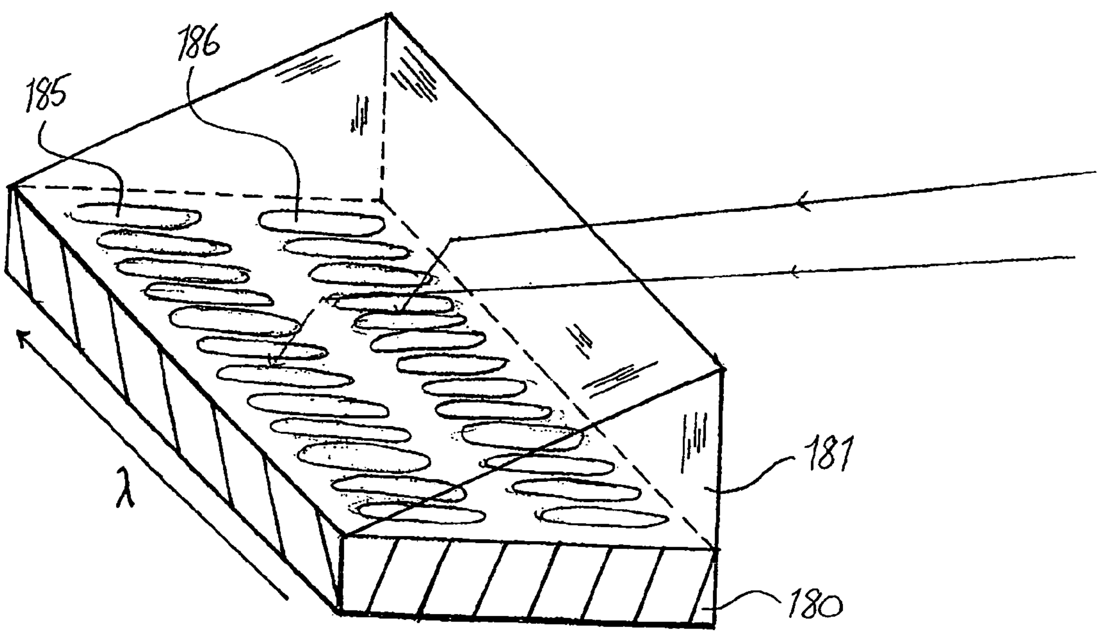

FIG. 5

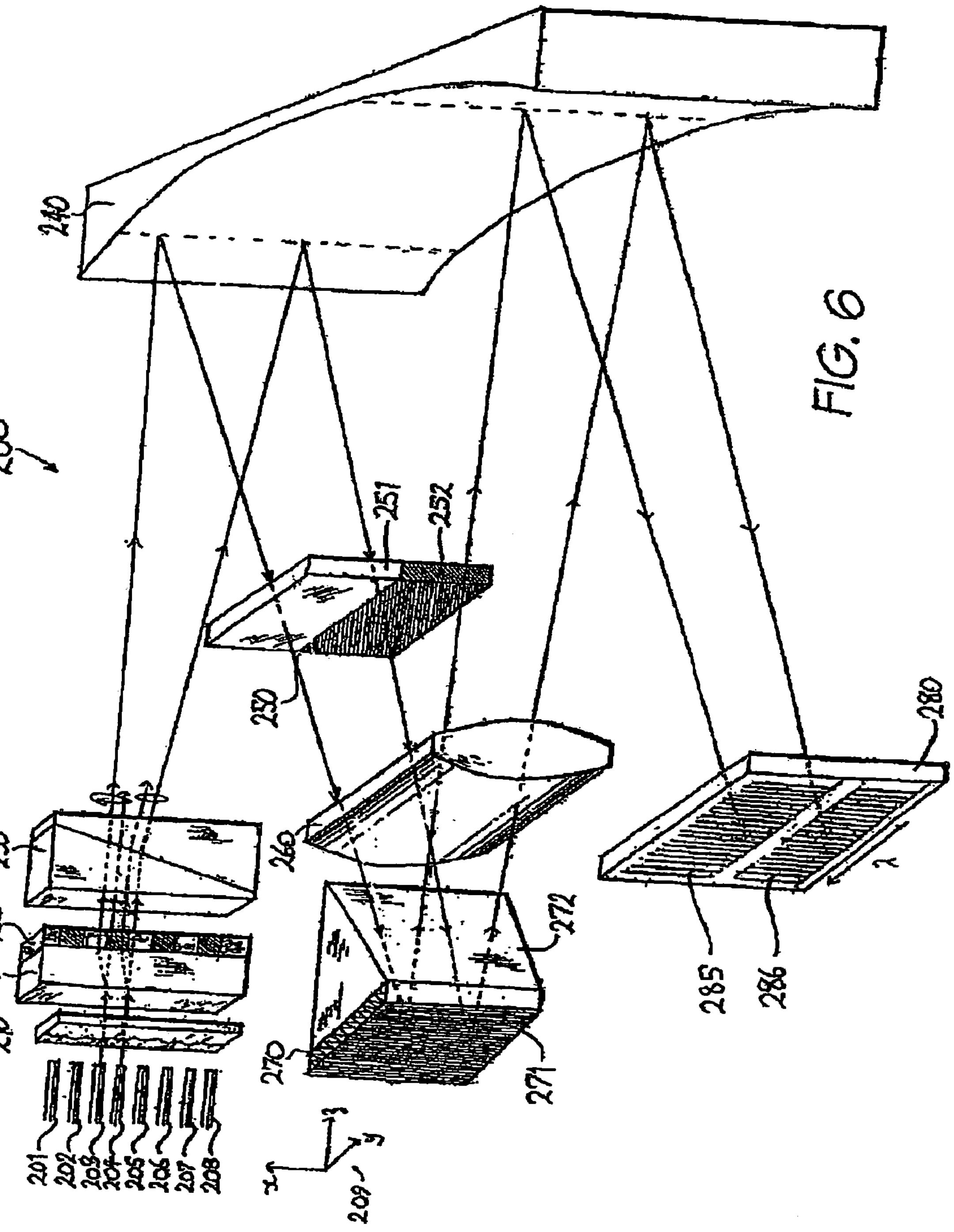
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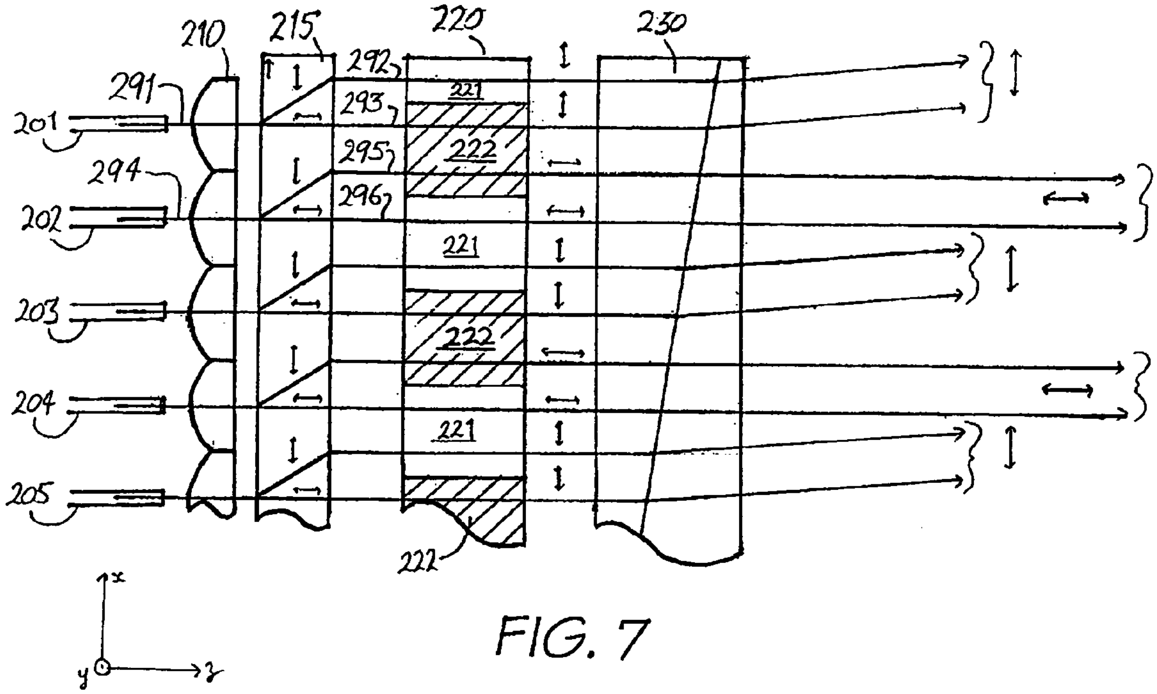
FIG. 6



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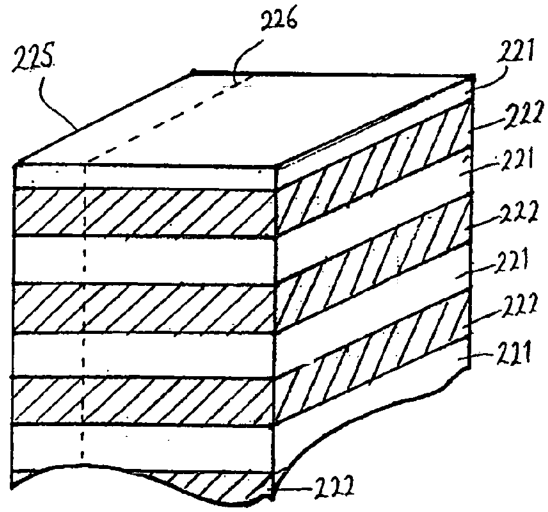

FIG. 8

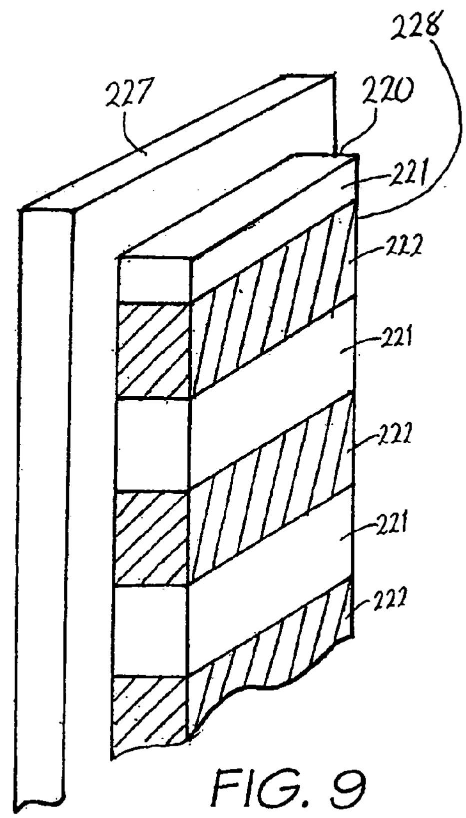

FIG. 9

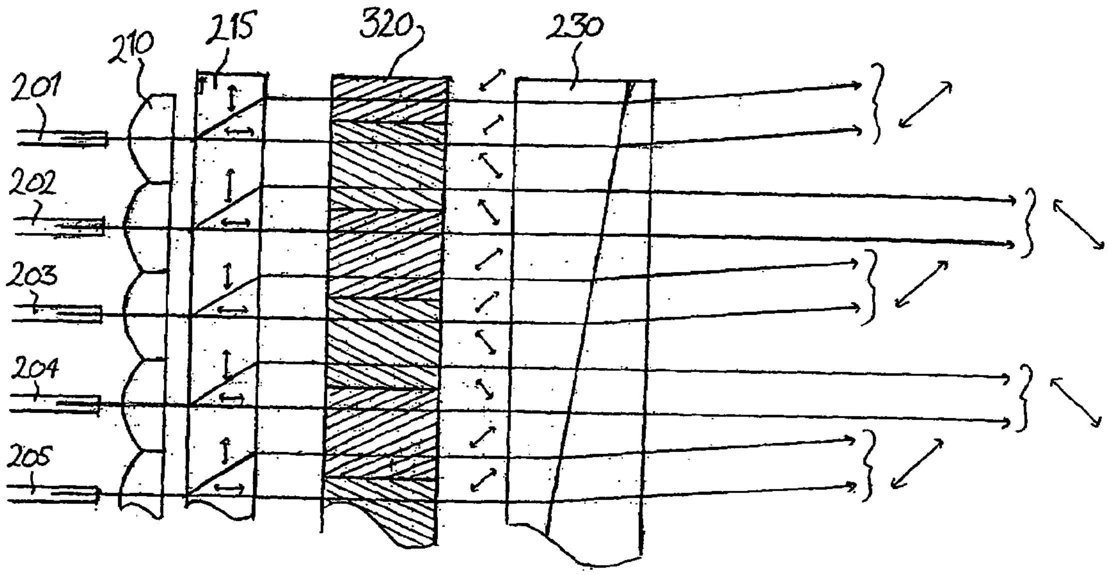

FIG. 10

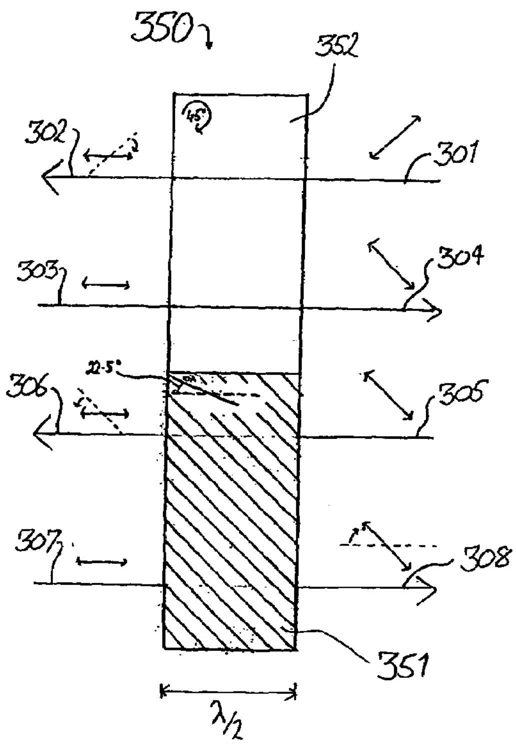

FIG. 11

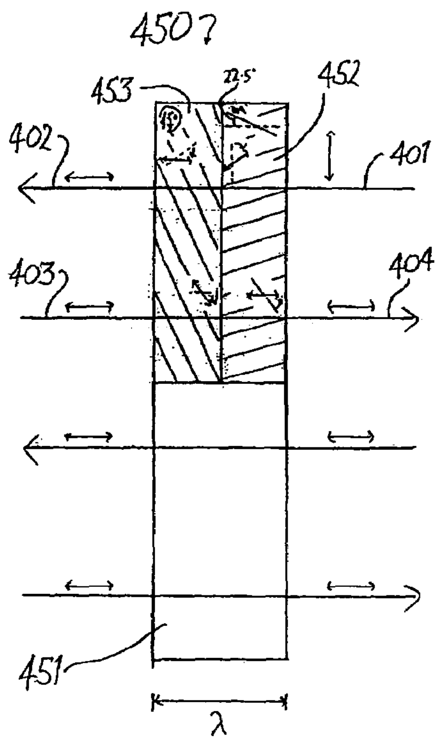

FIG. 12

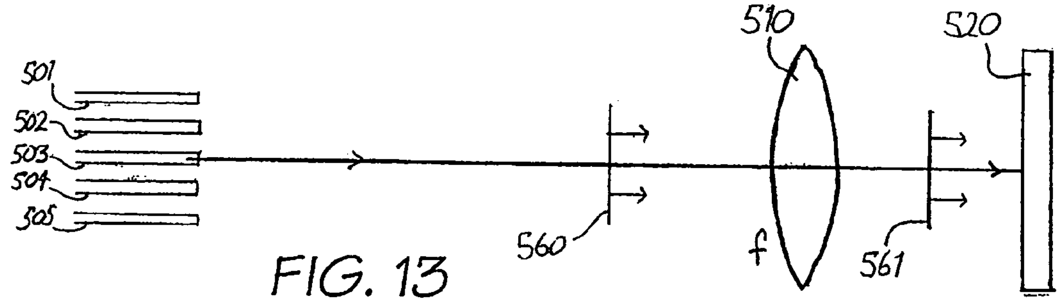

FIG. 13

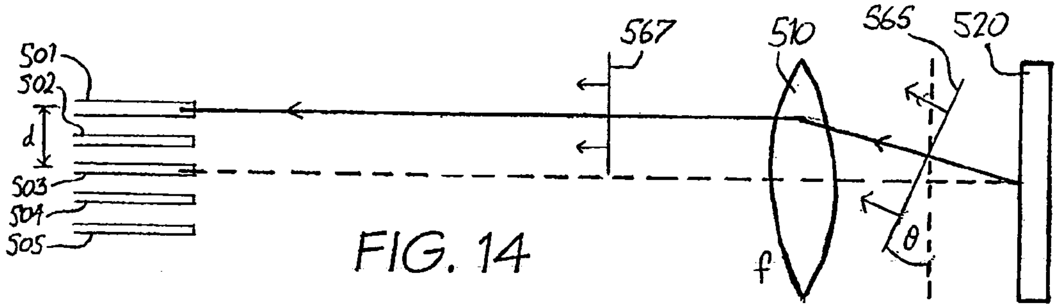

FIG. 14

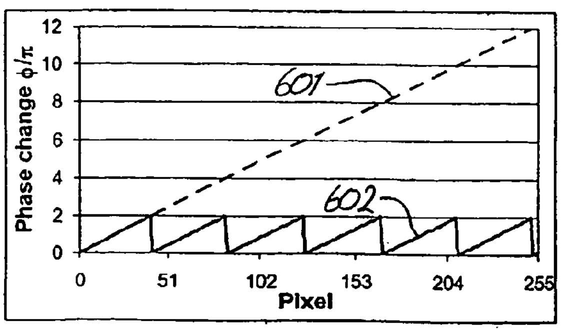

FIG. 15

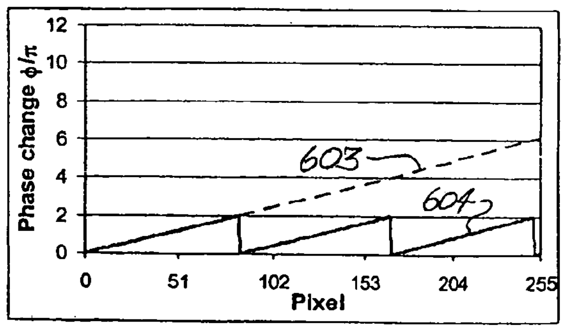

FIG. 16

DUAL-SOURCE OPTICAL WAVELENGTH PROCESSOR

FIELD OF THE INVENTION

The present invention relates generally to optical switches, and in particular to a reconfigurable fibre optic wavelength switch that can operate independently on individual wavelength channels contained in optical signals originating from either of two input sources.

BACKGROUND OF THE INVENTION

The recent growth in the demand for broadband services has resulted in a pressing need for increased capacity on existing communication channels. The increased bandwidth of fibre optic communication fibres is still often insufficient to cope with this demand without utilising the ability of these fibres to carry large numbers of individual communication channels each identified by the particular wavelength of the light. This technique is known as dense wavelength division multiplexing (DWDM). The disadvantage of this technique is that the increasing density of wavelength channels places increasing demand on network functionality for connecting the individual channels to individual destination points on a dynamic basis, and for the ability to add or drop an individual wavelength channel into or out of the optical signal. Currently these functions are primarily performed by electronic techniques but the demand for increased network speed calls for these functions to be performed in the optical domain.

The use of wavelength selective switching for applications of optical cross-connects has attracted much interest because of the goal of fully flexible networks, where the paths of each wavelength can be reconfigured to allow for arbitrary connection between nodes with the capacity appropriate for that link at a particular point in time. Although this goal is still valid, it is clear that optical networks will evolve to this level of sophistication in a number of stages. The first stage of the evolution is likely to be that of a reconfigurable add/drop node where a number of channels can be dropped or and added from the main path, whose number and wavelength can be varied over time—either as the network evolves or dynamically as the traffic demands vary.

A further functionality demanded by optical communications networks is the ability to route incoming signals from two origins in the same fashion independently of each other in a single device. This immediately halves the device count required at any particular location, without the loss of functionality in the adding and dropping of channels from either source.

This present invention is directed to applications such as dual-source reconfigurable optical add/drop multiplexer (ROADM) networks, dual-source wavelength reconfigurable cross-connects referred to generically as Wavelength Selective Switches (WSS), dual-source dynamic channel equalisation (DCE) and for single-source devices for correction of polarisation-dependant loss (PDL) mechanisms.

The characteristics of a wavelength selective element which is ideal for the applications of Optical Add/Drop and Wavelength Selective Switching can be summarized follows:

i) scalable to multiple fibre ports;

ii) one channel per port or multiple channels per port operation;

iii) reconfiguration of wavelength selectivity to different grids e.g. 50 GHz or 100 GHz or a combination of both;

iv) low optical impairment of the express path;

v) low losses on the drop and express paths;

vi) ability to add and drop wavelengths simultaneously;

vii) ability to be reconfigured between any ports or between any wavelengths without causing transient impairments to the other ports;

viii) equalisation of optical power levels on express path (OADM) or all paths (WSS);

ix) provision of shared optical power between ports for a given wavelength (broadcast mode);

x) flat optical passband to prevent spectral narrowing;

xi) power off configurations that leave the express path of an OADM undisturbed; and

xii) small power and voltage and size requirements.

In reviewing the many technologies that have been applied it is necessary to generalize somewhat, but the following observations can be made.

Two basic approaches have been made for the OADM and WSS applications.

i) The first has been based on wavelength blocking elements combined with a broadcast and select architecture. This is an optical power intensive architecture, which can provide for channel equalization and reconfiguration of wavelength selectivity, but is not scalable to multiple ports, has very high loss and because of the many auxiliary components such as wavelength tuneable filters has a large power and footprint requirement.

ii) Wavelength switches have been proposed for OADMs, but do not naturally provide for channel equalization, the channel by channel switching in general leads to dispersion and loss narrowing of optical channels, and in the case of multiple port switches it is generally not possible to switch between ports without causing impairment (a hit) on intermediate ports. In addition the channel spacing cannot be dynamically reconfigured. Tuneable 3-port filters have also been proposed having a lack of impairment to the express paths but do not scale easily to multiple ports and may suffer from transient wavelength hits during tuning. Tuneable components are usually locked to a particular bandwidth which cannot be varied. In addition poor isolation of tunable 3 ports means they are less applicable to many add/drop applications which demand high through path isolation.

One technology that has been applied to optical cross connects has become known as 3-D MEMS utilises small mirror structures which act on a beam of light to direct it from one port to another. Examples of this art are provided in U.S. Pat. Nos. 5,960,133 and 6,501,877. The ports are usually arranged in a 2-dimensional matrix and a corresponding element of the 2-dimensional array of mirrors can tilt in two axes to couple between any one of the ports. Usually two arrays of these mirrors are required to couple the light efficiently and because of the high degree of analogue control required structures based on this technology have proved to be extremely difficult to realize in practice and there are few examples of commercially successful offerings. In this type of structure, a separate component is required to separate each wavelength division multiplexed (WDM) input fibre to corresponding single channel/single fibre inputs.

One of the most promising platforms for wavelength routing application relies on the principle of dispersing the channels spatially and operating on the different wavelengths, either with a switching element or attenuation element. These technologies are advantageous in that the switching element is integrated with the wavelength dispersive element—greatly simplifying the implementation. The trade-off is that in general the switching is more limited, with most implementations demonstrated to date being limited to small port counts—and the routing between ports is not arbitrary. In general a diffraction grating is used for micro-optic implementations or an array waveguide grating for waveguide applications. Most of the switching applications have been based on MEMS micro mirrors fabricated in silicon and based on a tilt actuation in one dimension. The difficulty with this approach has been that to achieve the wavelength resolution required when the angular dispersion is mapped to a displacement. In such cases, an image of the fibre (with or without magnification) is mapped onto the tilt mirror array. In order to couple the light into a second port, additional optical elements are required that convert the angle into a displacement. Different approaches to this have included retroreflection cubes wedges (U.S. Pat. No. 6,097,519) which provide discrete displacements or Angle to Displacement elements (U.S. Pat. No. 6,560,000) which can provide continuous mapping using optical power provisioned at the Rayleigh length of the image. In all of these cases, in order to switch between ports, the tilt mirror needs to pass through the angles corresponding to intermediate ports. In addition, the number of ports is limited in each of these cases by the numerical aperture of the fibre as each of the different switch positions are discriminated by angles. For a fibre with a numerical aperture of 0.1, a switch which can tilt by +−12 degrees could not distinguish 8 different switch positions. One approach that can be used is to decrease the numerical aperture through the use of thermally expanded cores or micro lenses—but this is done at the expense of wavelength resolution.

An alternative has been to use polarization to switch between ports. Obviously this is most appropriate to switching between 2 ports corresponding to the 2 polarisation states. Such a switch is described in Patel (J. S. Patel and Y. Silverberg, IEEE Photonics Technology Letters Vol. 7 No. 5, 1995, pp. 514-516) where an optical dispersion element (in this case a grating) is used to separate an optical signal into spatially separated wavelength channels incident onto a liquid crystal spatial light modulator (LC SLM). The SLM is then configured to rotate the polarisation of the light of a desired wavelength channel by 90° which causes the light to be deflected from the main channel by a birefringent crystal. The wavelengths are then recombined by a second grating element forming two spatially-displaced outputs: one containing the wavelength channels acted on by the LC SLM, and the second output containing the remaining wavelength channels. Since these types of switches are limited to only two polarisation states, they are not readily scalable, though more complicated schemes can be envisaged to allow for switching between multiple ports. With polarization switching, also, dynamic equalization of channels can only be done at the expense of the rejected light being channelled into the second fibre—so it is not applicable to equalization of the express path whilst dropping a number of wavelengths.

A better alternative to switch between multiple ports has been the use of optical beam deflectors such as MEMS mirror arrays or LC SLMs. These devices deflect the light through free space, thus allowing multiple signal beams to be simultaneously interconnected without cross-talk between data channels.

An example of a MEMS-based device is taught by Waverka (U.S. Pat. No. 6,501,877) which disperses the individual wavelength channels with a diffraction grating. The individual channels are each then focused on to spatially separated elements of the MEMS array which imparts an angular displacement on the beams. A retroreflection device is used to convert the angular displacement to a lateral offset, that when passed back through the optical system translates into a coupling to the desired output port. In this implementation the offset states are quantised and determined by the angles of the retroreflection prism.

A similar technique is taught in U.S. Pat. No. 6,707,959 by Ducellier where a particular spatially separated wavelength channel is acted upon by a deflector array implemented either using a MEMS device or a transmissive LC deflector. A schematic block diagram of this device is shown in FIG. **1**. Ducellier introduces an improvement over Waverka by having the angle to offset (ATO) element **1** being able to translate continuously for an arbitrary state by placing an angle to offset lens at the Rayleigh point of the optical array **2**. The angular array is then transmitted through a standard 4-f lens design (telecentric telescope) using a spherical reflector **3** to the deflection array **4** with preservation of the angular multiplex. The individual wavelength channels in the optical signal are separated by an optical dispersion element **5** at the telecentric point of the optical system.

The deflection array **4** can be operated in either reflective or transmissive mode and (similarly to Waverka and Patel) provides a deflection of a desired wavelength channel perpendicularly to the wavelength dispersion direction. The deflection is such that an ATO element at the output array translates the new angular multiplex into an offset corresponding to the desired output port. In this system, the input array, the optical dispersion element, the deflection array, and the output array all lie in the same focal plane due to the spherical symmetry of the optics. The disadvantage of this is that large deflection angles are required to switch between fibre ports and a requirement for large numerical aperture optics. The requirement also of a duplicate optical system in the transmissive deflection array embodiment places severe restrictions on the compactness and cost of the final device.

Additionally, none of the devices described above can operate on the light from two input sources or two groupings of light having the same wavelength channels independently. Due to the existence of polarisation dependent loss and polarisation mode dispersion—it is often convenient to consider two orthogonal polarisation states as two separate sources and it could be advantageous to act on these separately.

Various techniques have been proposed for the correction of polarisation dependent loss (PDL) in optical communication systems on a wavelength basis such as those discussed by Roberts (U.S. Patent Application Publication 2004/0004755). These techniques however are only applicable to a single optical fibre and operate in transmission mode only. To our knowledge, there have been no techniques have been proposed or demonstrated to provide broadband PDL correction for multiple optical fibre devices or in a switching architecture.

It is an object of the present invention to overcome or ameliorate at least some of the disadvantages of the prior art by providing a reconfigurable optical add/drop multiplexer and wavelength selective switch capable of independently operating on arbitrary wavelength channels contained in light from two distinct sources or groups.

SUMMARY OF THE INVENTION

In accordance with a first aspect of the present invention, there is provided an optical signal manipulation system including: a series of ports for carrying a series of optical signals to be manipulated; a spatial separating means for spatially separating at least a first and a second group of light from the series of optical signals; wavelength dispersion element subsequently spatially separating wavelengths of the first and second series; wavelength processing means for separately processing separated wavelengths of the first and second series.

The spatial separating means preferably can include a polarisation manipulation element separating a first and second series of predetermined polarisations from predetermined ones of the ports and projecting the first series in a first angular direction and the second series in a second angular direction. The spatial separating means preferably can also include a series of optical power elements offset from the ports separating at least a first and second series of predetermined optical signals from predetermined ones of the ports and projecting the first series in a first angular direction and the second series in a second angular direction.

Signals processed by the wavelength processing means are preferably transmitted back through the wavelength dispersion element, the polarisation manipulation element for output at the optical signal ports. The particular port to which particular wavelengths are preferably output can be determined by the processing carried out by the wavelength processing means.

The wavelength processing means preferably can include a series of zones and the wavelength processing means separately manipulates the phase front of light striking each of the zones in order to control the output destination of wavelengths striking a particular zone. The wavelength processing means can comprise a spatial light modulator having a plurality of independently addressable pixels with the pixels being manipulated in a predetermined manner so as to manipulate the phase front striking a corresponding zone.

The optical signals received by the wavelength processing means are preferably in the form of wavelength separated elongated bands. The wavelength separated elongated bands are preferably substantially collimated along their major axis and substantially focused along their minor axis. The ratio of the width of the major axis to the width of the minor axis of the bands can be equal to or greater than 5. The width of the bands major axis can be substantially 700 microns and the width of a bands minor axis can be substantially 20 microns.

Preferably, the first series forms a first row of wavelength separated elongated bands and the second series forms a second row of wavelength separated elongated bands. The first and second row are preferably substantially parallel. The first series of predetermined polarisations can be derived from a first polarisation state of the optical signals and the second series of predetermined polarisations can be derived from a second substantially orthogonal polarisation state of the optical signals. Alternatively, the first series of predetermined polarisations can be derived from orthogonal polarisations of a first series of optical signals and the second series of predetermined polarisations can be derived from orthogonal polarisations of a second series of optical signals.

In one embodiment, the wavelength processing means can comprise a liquid crystal display device having a series of light modulating pixels formed thereon. The optical signals traversing the wavelength dispersion element are preferably substantially polarisation aligned. The light emitted from the optical signal ports passes through a numerical aperture modifying means before traversing the polarisation manipulation element. The numerical aperture of the light from the optical signal ports can be modified by a series of lenses having a pitch substantially in accordance with the pitch of the optical signal ports.

The polarisation manipulation element can comprise a first polarisation separation element for spatially separating orthogonal polarisations and a second polarisation deflection element for angularly deflecting an optical signal in accordance with the polarisation state of the signal. The polarisation manipulation element can also include, in series, a polarisation separation element for spatially separating orthogonal polarisations, a polarisation alignment element for aligning the separated orthogonal polarisations and a polarisation deflection element for angularly deflecting an optical signal in accordance with the polarisation state of the signal.

The system can also include a first optical power element for collimating the light emitted from the polarisation manipulation element onto the wavelength dispersion element and a second optical power element for focusing the light emitted from the wavelength dispersion element onto the wavelength processing means. The first and second optical power elements can comprise of reflective mirror surfaces with the first optical power element having optical power in a first optical axis only and the second optical power element having optical power in a first optical axis only. The system can also include a third optical power element for collimating the light emitted from the polarisation manipulation element onto the wavelength processing means. The third optical power element can comprise of a lens that has optical power in a second optical axis only. The second optical axis can be orthogonal to the first optical axis.

In accordance with a further aspect of the present invention, there is provided an optical signal manipulation system including: a series of optical signal ports; numerical aperture modifying means for modifying the numerical aperture of light emitted from the optical signal ports to form modified optical signals; polarisation manipulation means for imparting a different angular projection to substantially orthogonal polarisation states of the modified optical signals; polarisation alignment means for substantially aligning the polarisation state of the substantially orthogonal polarisation states; wavelength dispersion element for angularly dispersing by wavelength the aligned modified optical signals; a wavelength control element having a series of elongated control zones for receipt and manipulation of a region of the wavelength dispersed optical signals.

The different substantially orthogonal polarisation states are preferably manipulated by different elongated control zones. A first polarisation state can be manipulated by a first series of substantially adjacent control zones and a second orthogonal polarisation state can be manipulated by a second series of substantially adjacent control zones. The first and second series of substantially adjacent control zones are preferably substantially parallel with one another. Light from the wavelength control element can be projecting through a second wavelength dispersion element so as to combine wavelengths of the first and second series; Light from the second wavelength dispersion element can be projected through a second polarisation manipulation element for combining the orthogonal polarisations to output at predetermined optical signal ports. Light projected from the optical signal ports to the wavelength control element can undergo at least two reflections on reflective optical power surfaces.

The wavelength dispersion element preferably can include a diffraction grating mounted on an optical prism. Light from the polarisation manipulation means and light from the wavelength control element can strike the prism substantially at Brewster's angle. The path lengths of light in the first and second polarisation states can be substantially equalised on traversal through the prism.

In accordance with a further aspect of the present invention, there is provided an optical system including: a series of optical signal ports; numerical aperture modifying means for modifying the numerical aperture of light emitted from the optical signal ports to form modified optical signals; a polarisation alignment means for substantially aligning the polarisation state of substantially orthogonal polarisation states from the optical signal ports; wavelength dispersion element for angularly dispersing by wavelength the aligned modified optical signals; an optical phase control matrix for receipt and manipulation of a region of the wavelength dispersed optical signals; a series of optical power elements for creating a spatial intensity overlap on the wavelength control element between projections from a first selected optical signal port and a second selected optical signal port.

The optical phase control matrix preferably can include a series of elongated control zones. Each the control zone of the optical phase control matrix can comprise a plurality of individually addressable pixels with each of the pixel modifying the phase of light passing through it.

The projections of optical signals at the optical phase control matrix along a first optical axis are preferably in the image plane of the series of optical power elements. The projections of optical signals at the optical phase control matrix along a second optical axis are preferably substantially in the fourier or telecentric plane of the series of optical power elements. The first optical axis can be substantially orthogonal to the second optical axis. Signals from the first selected optical signal port received by the optical phase control matrix are preferably manipulated and transmitted back through the wavelength dispersion element for output at the second selected optical signal port.

The optical system in the first optical axis can be substantially 2n times the focal length of the series of optical power elements in the first optical axis, where n can be a positive integer. The optical system in the second optical axis can be substantially 2m times the focal length of the series of optical power elements in the second optical axis where m can be a positive integer. In one embodiment n can be an even integer and m can be an odd integer.

The optical signals received by the optical phase control matrix are preferably in the form of wavelength separated elongated bands. Each wavelength separated elongated band aligns with an independent one of the elongated control zones. The minor axis of the elongated bands lies in the first optical axis and the major axis of the elongated bands lies in the second optical axis.

The reconfigurable dual-source optical wavelength processor of the present device includes:

- a series of optical ports for generating and/or receiving an optical beam;
- an optical phased-matrix coupling (OPMC) device for receiving and reflecting said beams;
- a series of optical power elements positioned between said ports and said OPMC device to provide a spatial overlap between the said beams from said ports on the phase coupling device;
- a series of optical path separating elements arrayed in such a way as to create at least two independent groups of light;
- an optical dispersion element designed to separate at least a first and second wavelengths of light; and

wherein said optical phased-matrix device provides for individual control of at least a first and second wavelength's coupling efficiency between an input port and at least one output port.

The device in its preferred embodiments can include:

- a series of optical ports which can include optical fibre arrays;
- a series of optical ports where the optical fibre arrays are single mode fibres;
- a series of optical ports where the optical fibre array includes at least a first input port, a first output port, a first add port and a first drop port;
- a series of optical ports where the optical fibre array includes a plurality of add ports and/or a plurality of drop ports;
- a series of optical ports where the optical fibre array includes a second input ports, a second output port;
- a series of optical ports where the optical fibre array includes a plurality of input ports, and a plurality of output port;
- a series of optical power elements which can include spherical microlens arrays for altering the numerical aperture of each of the optical ports;
- optical power elements including cylindrical lenses with a first focal length and cylindrical mirrors with a second focal length for projecting light from the ports on the optical phased-array coupling means comprising at least a spatially separated first group of spatially dispersed wavelength channels, each wavelength channel being substantially collimated in one axis and substantially focused in the orthogonal axis;
- polarisation diversity elements including a birefringent walk-off crystal composite λ/2 waveplates for 1550 nm light, compensating birefringent wedges, and/or Faraday rotators;
- an optical dispersion element which is a Carpenter's Prism (grism) operating in the reflective mode at near Littrow condition, and a wedge angle substantially at Brewster's angle of the incident light: and
- an optical phased matrix coupling (OPMC) means providing 2-dimensional optical phase only or phase and optical amplitude such as can be provided by a liquid crystal on silicon (LCOS) spatial light modulator (SLM).

Possible practical applications of a dual-source optical switch are:

Device **1**.

A Polarisation Dependent Loss (PDL) correcting Reconfigurable Optical Add/Drop Multiplexer (ROADM) where light from an input optical fibre port is separated into two beams with orthogonal polarisation states, with each beam being dispersed into spatially separated wavelength channels, and the two groups of spatially separated wavelength channels being projected onto spatially separated regions of a liquid crystal spatial light modulator. The orthogonal polarisation states of a particular wavelength channel can then be addressed independently which allows for equalisation of the PDL of the wavelength channel before being directed to a choice of output fibre ports (either an express output port or a drop port).

Device **2**.

A dual-source ROADM consisting of two independent groups of fibre ports, with each group as a minimum containing an input port and an express output port, and optionally a drop port. (In practise each of the independent ROADMs can include a plurality of add and drop ports.) The light corresponding to the paths into and out of the ports corresponding to either group can be tagged, for example by assigning each independent device to an orthogonal polarisation state, spatially separating the light from the two polarisations and imaging the light from each polarisation onto a spatially separated region of the OPMC to act on the channels from each device independently;

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram of a prior art optical add/drop multiplexer.

FIG. **2** is a block schematic of a dual-source optical wavelength processor in accordance with the present invention.

FIG. **3** is a schematic view of a first embodiment of a dual-source optical wavelength processor in accordance with the present invention.

FIG. **4** is a detail schematic view of the front end polarisation tagging mechanism of the first embodiment.

FIG. **5** is a close-up view of an OPMC device with a folding prism to allow for simplified mounting of the device.

FIG. **6** is a schematic view of a second embodiment of a dual-source optical wavelength processor in accordance with the present invention.

FIG. **7** is a detail schematic view of a first embodiment the front end polarisation tagging mechanism of the second embodiment.

FIG. **8** shows a cutaway stack of alternating glass and quartz plates for constructing the first embodiment of a polarisation equalisation element for polarisation tagging.

FIG. **9** is a cutaway of the first polarisation equalisation element mounted to a substrate for polishing to the required thickness.

FIG. **10** is cutaway detail schematic view of a second embodiment the front end polarisation tagging mechanism of the second embodiment.

FIG. **11** is a first embodiment of a non-reciprocal polarisation equalisation element.

FIG. **12** is a second embodiment of a non-reciprocal polarisation equalisation element.

FIG. **13** is a schematic view of a forward propagating beam in the switching plane of an embodiment of the present invention.

FIG. **14** is a schematic view of a backward propagating beam of an embodiment of the present invention showing the operation of the OPMC to impart a phase slope onto an incoming beam resulting in a displacement in the switching plane.

FIG. **15** is a graph showing the phase slope written on to the pixels of the OPMC to switch an incoming beam to a first output port.

FIG. **16** is a graph showing the phase slope written on to the pixels of the OPMC to switch an incoming beam to a second output port.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

The preferred embodiment provides an optical switching device that can operate on individual spatially dispersed wavelength channels contained in an optical signal that originate from either of two input sources. The input sources can be:

a) two unrelated sources possibly delivered to the switch via optical fibre;

b) two orthogonally polarised beams originating from a single source, possibly delivered to the switch via optical fibre;

c) a plurality of input sources, possibly delivered to the switch via optical fibre, separated into orthogonal polarisation states such that the polarisation states of a particular wavelength channel can be acted upon independently;

d) a plurality of input sources, possibly delivered to the switch via optical fibre, optically tagged in a fashion that defines two distinct groups, for example by assigning each of the input sources one of two orthogonal polarisation states.

FIG. **2** shows a schematic block diagram of a dual-source optical wavelength processor constructed in accordance with the preferred embodiment. The wavelength processor device **10** is virtually divided into two distinct devices **20** and **30** where the operation of one is entirely independent of the other. Each of the virtual devices **20** and **30** acts in the preferred embodiment can act as an independent reconfigurable optical add-drop multiplexer (OADM). That is, each of the virtual devices **20** and **30** includes an input ports **21** and **31** respectively, each input port delivering an optical signal to the device, where each signal contains a plurality of channels $\lambda_1, \lambda_2, \ldots, \lambda_n$ distinguished by the centre wavelength of the channel. Each of the virtual devices also includes an output port **22** and **32** respectively. Virtual device **20** includes a plurality of drop ports **23**, **24** and **25**, and a plurality of add ports **26**, **27** and **28**. Virtual device **30** includes a plurality of drop ports **33**, **34** and **35**, and a plurality of add ports **36**, **37** and **38**. Three drop and three add ports are shown in the Figure for each of the virtual devices **20** and **30**, however, more or less can be implemented in other embodiments as required. For a signal arriving at input port **21**, virtual device **20** can be configured to drop an arbitrary selection of the wavelength channels contained therein onto drop ports **23-25**, for example λ_1, λ_2 and λ_3. Simultaneously, for a signal arriving at input port **31**, virtual device **30** can be configured to drop a different arbitrary selection of the wavelength channels contained therein onto drop ports **33-35**, for example λ_2, λ_3 and λ_5. All of the other wavelength channels contained in either signal on port **21** or **31** that are not dropped onto the drop ports are directed to the corresponding output port **22** or **32** respectively via the corresponding express paths **29** or **39** of the device. As is known in the operation of an OADM, the add ports of each of the virtual devices can be used to add signal onto the express path of the device to be transmitted to the output port, however in the case of the present embodiment, the added signals can either be of the same wavelength as any of the dropped signals or a different wavelength entirely for example, the wavelength channels added to virtual device **20** can be λ_2 and $\lambda_{(n+1)}$.

Device **1**

The preferred embodiment of the Device **1** above is shown in schematic form in FIG. **3**. The device **100** includes an array of input and output ports consisting of 4 fibres (**101-104**) comprising a ROADM where fibre port **102** is designated as the express Input port, fibre port **103**, the express Output port, fibre port **101** as a first Add port, and fibre port **104** as a first Drop port. A device such as this in practice may also include a plurality of additional Add and Drop ports (not shown). The fibres are all aligned vertically in what will be referred to as the x-dimension of the 3-axis **105** and separated by about 250 μm.

The output from the fibres is firstly incident on a microlens array of spherical lenses spaced with a separation corresponding to the fibre separation. The focal length of the lens is chosen to be 500 μm positioned to form beam waists of approximately 50 μm diameter. The effect of the spherical microlens array **110** is to decrease the numerical aperture (NA) of the fibres say from their single mode value of 0.1 to about 0.02. This relaxes the requirements on the optical quality of the subsequent optical elements.

The beam emerging from the input fibres is split in the x direction into two polarization states (v in the x-dimension and h in the y-dimension) by the walk off crystal **115** of thickness 1.25 mm. The result of the walk-ff crystal if one were to look back at the fibre array in the −z-direction would be an image of 8 fibres separated by 125 μm.

The beams then enter a birefringent wedge (BRW) element **130** which is shown as a compensating element (CBRW) to give equal path lengths between the fibre ports. The CBRW works on the principle of "double refraction" and causes an angular offset to be imparted on the beams in one polarisation state with respect to the other. In FIG. **3**, this offset is in the vertical or x-dimension. In other embodiments, the CBRW **130** can be a simple non-compensating element however this would correspond to unequal path lengths from each of the fibre ports resulting in a spatial offset on refocusing onto an output port, ultimately affecting the efficiency of the return path.

FIG. **4** shows the fibre ports **101-104**, the NA modifying optical power microlens array **110**, the birefringent walk-off element **115** and the CBRW **130**. An output beam **191** from fibre **101** is split into two beams **192** and **193** by element **115**, where beam **192** is in the vertical or v-polarisation state and beam **193** is in the horizontal or h-polarisation state. The now polarisation tagged beams enter the CBRW **130** which imparts an angular offset on the beams in one polarisation state with respect to the other. This angular offset is in the vertical or x-dimension and propagates through the optical train to result in a spatial separation between beams of different polarisations at the OPMC as will be seen.

Returning to FIG. **3**, each of the input beams is then projected to a first y-cylindrical mirror **140** with a focal length of 5 cm which provides collimation in the y axis. The angular misalignment between the v-polarised and h-polarised beams is unaffected and continues to separate spatially. The reflected beams are then projected onto a polarisation equalisation element **150** where the spatially separated v- and h-polarisations strike the element **150** in the upper and lower halves respectively. The element **150** is a composite λ/2 waveplate where the entire upper half **151** is a crystal-quartz waveplate with its optical axis at 45° with rotates the v-polarised beams into the h-polarisation, and the lower half **152** is simple glass which does not alter the polarisation state of the originally h-polarised beams. Equalisation of the polarisations states in this manner ensures efficient operation of the subsequent wavelength dispersing element and the spatial light modulator in the subsequent optical path.

The beams are then directed to a cylindrical lens **160** having optical power in the x-dimension with a focal length of 20 cm before being incident on a wavelength dispersive element which in this case is a wedged grating prism combination **170**, known commonly as a grism or Carpenter's prism, operating in the reflective orientation and aligned at the near-Littrow condition. The grism is a combination of two common optical elements, namely a diffraction grating **171** which can be of either the transmission or reflection type, and a wedged prism **172**, which are bonded together. In the embodiments described here, **171** is a reflection grating and the beams traverse a double pass through the prism **172**. In an alternative embodiment a grism element is used with the grating operating in transmission mode. In other embodiments of the system, the wavelength dispersive element **170** can be a simple grating operating in the near-Littrow reflective state for the 1.5 μm wavelength of the light (1200 lines/mm) emerging from the input fibre ports, however the addition of the wedged prism bonded to the grating adds significant advantages to the efficiency of the system, being:

a) equalisation of the optical path lengths in the y-dimension;
b) by suitable selection of the refractive index and input face angles the dispersion characteristics (in particular the angular dependence in the x-dimension) of the grating can be controlled and hence correct for effects such as conical diffraction from the grating resulting from non-orthogonal components of the beams striking the grating (since the prism has the opposite angular dependence to that of the grating) which ultimately results in errors in the focused position at the fibre ports on the return paths of the beams;
c) modification of the effective wavelengths of the beams as they strike the grating to enable the use of higher resolution gratings for more efficient dispersion i.e. a 1.5 μm beam in air requires the use of gratings with ~1200 lines/mm whereas in the prism with refractive index ~1.5, the effective wavelength is ~1 μm and thus gratings with 1700 lines/mm can be used.

In the preferred embodiments, the angle of the prism is such that the light beams (which are in the p-polarisation state with respect to the prism) are incident on the prism surface substantially at the Brewster angle to avoid loss of the light due to reflection from the prism interface which is then lost to the system. In the preferred embodiments, the light which has travelled through the prism strikes the grating in the s-polarisation state (with respect to the grating). In the preferred embodiments, the characteristics of the prism **172** are designed to substantially compensate for the chirp of the grating **171**, which in turn substantially eliminates errors due to conical diffraction in the image of the light beams at the output fibre ports.

The now wavelength-dispersed beams then pass back through the prism element of the grism **170** and again are passed through the cylindrical lens **160**. After the second pass of the x-dimension lens **160** the now diffracted beam is collimated in the x direction—the combined effect of the double pass of lens **160** being a lens with focal length of approximately 10 cm, being twice the focal length of the first cylindrical mirror **140**. This condition ensures that the grating acts in the telecentric or Fourier plane of the beams in the y-dimension.

On exiting from the cylindrical lens **160** the now collimated and spatially separated (in the x-dimension) beams pass by the polarisation equalisation element **150** and are incident again on the cylindrical mirror **140** which directs the beams in the y-dimension onto the optical phased-matrix coupling (OPMC) means (in the preferred embodiments this is a liquid crystal on silicon spatial light modulator (LCOS SLM)) **180**.

The projection on the OPMC comprises two groups of spatially separated wavelength channels, one group **185** being on the upper half (in the x-dimension) of the OPMC corresponding to beams originating in the v-polarisation state, and the second group **186** being on the lower half of the OPMC corresponding to beams originating from the h-polarisation state at the fibre input ports. The wavelength channels are separated spatially in the y-dimension and the image of each wavelength channel appears substantially as being highly asymmetric with orthogonal dimensions of 20 μm in the now focused y-dimension and approximately 700 μm in the collimated x-dimension. The individual wavelength channels from the input fibre ports can be accessed by the OPMC **180** independently of any of the other channels, and the orthogonal polarisation states of any particular wavelength channel can also be addressed individually. This offers the ability to be able to control the efficiency of the reflected beams from the OPMC in either polarisation and hence compensate for polarisation dependent loss on any particular channel that may exist in the input beams.

In an alternative embodiment of the system, the mounting of the OPMC device **180** can be simplified as illustrated in FIG. **5** by folding the beams downwards (in the –x-dimension) by a prism **181** to allow simple mounting of the OPMC.

Returning to FIG. **3**, the OPMC is positioned at or near the focal point of the light in the y-dimension being focused by cylindrical lens **140**, which coincides with the telecentric or Fourier plane of the collimated light in the x-dimension. This situation results in a 4-f (8-f for the complete return path) optical system for light in the y-dimension and a 2-f (4-f for the complete return path) optical system for light in the x-dimension. Thus, light in the y-dimension, when it retraces its path back through the optical system, it is focused in the same plane as the optical fibre ports. Conversely for light in the x-dimension, a complete inversion of the magnification occurs such that the focal position of the light at the fibres is inverted about the centre line (i.e. between fibre ports **102** and **103**).

The OPMC device **180** is able to couple any one independently or all the wavelength channels from the input port **102** or the add port **101** to either the drop port **104** or the express port **103**. This coupling is achieved by inducing a phase hologram on the OPMC at each of the wavelength channels of the correct order to impart onto the beam the required amount of phase front correction to partially recreate the phase front of a beam which would approximately retrace its path through the system to be re-imaged on the desired output fibre port. Simultaneously when the input light from the input port **102** is directed to the drop port **104** at a particular wavelength the same wavelength will be directed from the add port **101** to the express output port **103**. The technique used to create the phase hologram on the OPMC will be described later in detail.

The re-imaged light at the output fibre port is again largely circularly symmetric as the effects of the cylindrical lenses and polarisation equalisation elements are reversed through the return propagation. Channel by channel control of optical power can be achieved by exciting a fraction of the power into an angle that doesn't correspond to an active port hence attenuating the power in the chosen path.

Device **2**

A second embodiment **200** is shown in schematic perspective view in FIG. **6** wherein the operation of all the elements with similar numbers as elements in FIG. **3** (eg **130** and **230**) is equivalent. This embodiment **200** displays a multiple of functionalities for each device such as wavelength switching and channel by channel power control, wavelength blocking etc. Clearly a subset of these functionalities could be achieved such as a pure wavelength blocker device.

In the preferred embodiment the input and output ports consist of 8 fibres (**201**-**208**) where the light from the odd-numbered fibres **201**, **203**, **205** and **207** are directed to a ROADM in one direction (ROADM1) and the even-numbered fibres **202**, **204**, **206** and **208** are directed to a second ROADM (ROADM2) operating independently of the first to be utilised in a second direction. The fibres are all aligned vertically in what will be referred to as the x-dimension and separated by about 250 μm. The fibres consisting ROADM**1** include a first input port **203**, a first output port **205**, a first add port **201** and a first drop port **207**. The fibres consisting ROADM2 include a first input port **204**, a first output port **206**, a first add port **2** and a first drop port **208**.

The output from the fibres undergoes adjustment of the NA via the spherical microlens array **210** in an equivalent manner as element **110** in the description of Device **1** above and is again split into orthogonally polarised beams by a walk-off crystal **215**. The result of the walk-off crystal in this case is to generate 16 beams separated by 125 μm with polarisation states alternating between the v- and the h-polarisation.

The beams then enter a polarization diversity optical element **220**. Element **220** is a plate of λ/2 thickness (92 μm) for light with a wavelength of 1.5 μm and is constructed from alternating regions **221** and **222** of glass and crystal quartz respectively. The glass regions do not affect the polarisation state of the beam passing through it, whereas the quartz regions act as a λ/2 waveplate and consequently rotate the polarisation axis by 90° (between the x- and y-directions). To achieve this, the optical axis of the pieces **222** are rotated 45° with respect to the optical axis of the system.

Turning to FIG. **7**, there is shown the first 5 fibre ports **201**-**205**, the NA modifying optical power microlens array **210**, the birefringent walk-off element **215**, the composite waveplate **220** and the CBRW **230** to show in detail the polarisation tagging architecture in more detail. An output beam **291** from fibre **201** is split into two beams **292** and **293** by element **215**, where beam **292** is in the vertical or v-polarisation state and beam **293** is in the horizontal or h-polarisation state. The optical element **220** is shown as comprising of a first glass waveplate of height 125 μm followed by alternating regions of quartz and glass with heights of 250 μm. Beam **292** next passes through a glass region **221** of element **220** which does not alter the polarisation state and beam **293** passes through a quartz region **226** of element **220** which rotates the plane of polarisation by 90° into the v-polarisation. Beams **292** and **293**, being all of the output from fibre port **201**, are now both in the v-polarisation state. Looking now at the output beam **294** from fibre port **202** after being similarly separated into two subsequent beams **295** and **296** by element **215**, the v-polarised beam **295** passes through a quartz region **222** of element **220** and is rotated into the h-polarisation state, whereas the undeviated h-polarised beam **296** passes though a glass region **221** as such is unchanged. All the output from fibre port **202** is now in the h-polarisation state. This sequence is repeated for each alternate fibre port such that the output from all the odd-numbered ports **201**, **203**, **205** and **207** corresponding to ROADM1 are output from **220** in the v-polarisation state and all the outputs from the even-numbered fibre ports **202**, **204**, **206** and **208** corresponding to ROADM2 are in the h-polarisation state. The now polarisation tagged beams enter the CBRW **230** to impart an angular offset on the beams in one polarisation state with respect to the other. This offset is again in the vertical or x-dimension. In other embodiments, element **230** can be a simple, non-compensating element, however this would correspond to unequal path lengths resulting in a spatial offset between say a beam emitted from fibre input port **201** and re-imaged to the output port **207** of approximately 40 μm, affecting the overlap efficiency of the re-imaged light onto the express output or drop fibre ports.

The composite waveplate **220** can be constructed by first bonding alternating sheets each having thickness of about 250 μm as shown in FIG. **8**. The front face **225** of the stack is polished to an optical quality finish and then cut transversely to the direction of the sheets along line **223**. The cut piece is then attached to a substrate **227** as shown in FIG. **9** and polished on the cut face **228** to be the required thickness for a λ/2 waveplate at 1.5 μm (92 μm). The composite waveplate is finally removed from the substrate **227**. Such waveplates can be produced by nano-optic lithographic techniques (as supplied by Nano Opto Corporation of Somerset, N.J. USA) or by an arrangement of standard quartz waveplate techniques as described above.

Referring back to FIG. **6**, the beams from the input ports are next projected to a first cylindrical mirror **240** with optical power in the y-dimension and a focal length of 5 cm which provides collimation in the y axis. The angular misalignment between the v-polarised and h-polarised beams is unaffected and continues to separate spatially. The beams are then projected onto polarisation equalisation element **250** where again, the spatially separated v- and h-polarisations strike **250** in the upper **251** and lower **252** halves respectively. After the element **250**, to the polarisations of the beams are equalised for efficient operation of the wavelength dispersing element and the OPMC.

The beams are then directed to the cylindrical lens **260** having optical power in the x-dimension with a focal length of 20 cm before being incident on a wavelength dispersive element shown as grism element **270** aligned at near-Littrow condition and having diffraction grating **271** and wedged prism **272**. In other embodiments of the system, the wavelength dispersive element can again be a simple grating operating in the near-Littrow reflective state for the 1.5 .mu.m wavelength of the light (1200 lines/mm) emerging from the input fibre ports, however the grism embodiment adds significant advantages to the efficiency of the system as previously described.

The now wavelength-dispersed beams then pass back through the prism element of the grism **270** and again are passed through the cylindrical lens **260**. After the second pass of the x-dimension lens the now diffracted beam is collimated in the x direction—the combined effect of the double pass of the lens **260** being a lens with focal length of approximately 10 cm, being twice the focal length of the first cylindrical mirror **240**. This condition ensures that the grating acts in the telecentric or Fourier plane of the beams in the y-dimension.

On exiting from the cylindrical lens **260** the now collimated and spatially separated (in the x-dimension) beams pass by the polarisation equalisation element **250** and are incident again on the cylindrical mirror **240** which focuses the beams in the y-dimension onto the liquid crystal spatial light modulator (OPMC) **280**.

In practise it may be difficult to efficiently place element **250** into the beam path such that the beams only interact with it before striking the grism and not afterwards as well since:

a) the beams have significantly expanded at this point; and
b) the beams after the grism element are now angularly dispersed in the y-dimension.

To correct this deficiency, it is possible to utilise a non-reciprocal composite element (either **350** of FIG. **11** or **450** of FIG. **12**) incorporating a Faraday rotator and allow the beams to pass through the element twice in each direction.

The first non-reciprocal embodiment of element **250** is shown in FIG. **11** as a composite λ/2 waveplate **350** similar to that of element **150** or **250**, where however the bottom half **351** is a birefringent material such as quartz which has its optical axis at 22.5°, and the upper half **352** is a Faraday rotating material. In order to utilise this device the polarisation equalisation element **220** needs to be replaced with the alternative element **320** shown in FIG. **10**. Element **320** is similarly constructed to **220**, however all of the alternate regions are a birefringent material such as quartz with the optical axes alternately oriented to be ±22.5°. This has the effect of rotating the polarisation state of an incident beam by **±45'** on traversal of the λ/2 waveplate. This result in the odd-numbered fibres corresponding to ROADM**1** being tagged with a polarisation state of +45°, and the even-numbered fibres corresponding to ROADM**2** being tagged with a polarisation state of −45°. Additionally, the CBRW **30** must be rotated about the z-axis to align with the polarisations states thus imparting the angular multiplex between the tagged beams in the correct direction. Returning again to FIG. **11**, beams **301** from ROAMD**1** with polarisation +45° is incident on **352** and which exiting **302** has been rotated 45° clockwise (cw) to be in the h-polarisation state for efficient diffraction by the grism element. The polarisation state is unchanged on reflection **303** and on the second pass through element **352** it is again rotated 45° cw to emerge **308** in the −45° polarisation state. Conversely, beams **305** from ROADM**2** with polarisation −45° incident on element **351** and are rotated 45° counter-clockwise (ccw) to be in the h-polarisation state **306** on exiting for efficient diffraction by the grism element. Again, the polarisation state is unchanged on reflection **307** and on the second pass through **351** it is rotated cw 45° to be in the −45° polarisation **308**. Beams from both ROADMs are now in the same polarisation state and the OPMC can be aligned accordingly to achieve efficient diffraction of the beams.

In a second embodiment of a non-reciprocal polarisation equalisation element to replace element **250**, a composite λ/2 waveplate **450** such as that shown in FIG. **12** can be utilised. In this embodiment, no other changes need to be made in the optical system, such that elements **220** and **230** can be as shown in FIG. **6**. The lower half **451** of the element **450** is simple glass and as such has no effect on the polarisation of the light passing through it in either direction. The upper half however is constructed of two elements in series:

a) a birefringent material **452** such as quartz with its optical axis rotated at an angle of 22.5° and thickness λ/2 such that beam passing though it are rotated in a reciprocal manner by 45°; and
b) a Faraday rotating material **453** of λ/2 thickness that rotates the polarisation state of the light by +45° (cw) in a non-reciprocal manner.

Thus, light from ROADM**1** **401** which strikes element **452** with polarisation in the vertical direction has its polarisation rotated by +45° where it then strikes element **453** where the polarisation is rotated a further 45° to emerge **402** in the horizontal polarisation state before striking the grism.

On the return path after the grism, the light **403** firstly strikes element **453** where it is rotated by 45° cw to be in the −45° polarisation state, and next strikes element **452** where the polarisation is then rotated ccw to emerge in the horizontal polarisation state. Beams from both ROADMs are again now in the same polarisation state for efficient operation of the OPMC.

Returning to FIG. **6** the projection onto the OPMC comprises of two groups of spatially separated wavelength channels, one group **285** being on the upper half (in the x-dimension) of the OPMC corresponding to beams from the input fibre ports of ROADM**1**, and the second group **286** being on the lower half of the OPMC corresponding to beams from the input fibre ports of ROADM**2**. The wavelength channels are separated spatially in the y-dimension and the image of each wavelength channel appears substantially as being highly asymmetric with orthogonal dimensions of 20 μm in the now focused y-dimension and approximately 700 μm in the substantially collimated x-dimension. The individual wavelength channels from either ROADM**1** or ROADM**2** can be accessed by the OPMC **280** independently of any of the other channels.

The OPCM **280** is positioned at approximately one focal length from the cylindrical lens **240**, which coincides with the telecentric or Fourier plane of the collimated light in the x-dimension. This situation results in a 4-f (8-f for the complete return path) optical system for light in the y-dimension and a 2-f (4-f for the complete return path) optical system for light in the x-dimension. Thus, light in the y-dimension, when it retraces its path back through the optical system, is focused in the same plane as the optical fibre ports. Conversely for light in the x-dimension, a complete inversion of the magnification occurs such that the focal position of the light at the fibres is inverted about the centre line (i.e. between fibre ports **204** and **205**). However, since in the present system alternate fibre ports are tagged with alternate polarisation states, such that each of the fibres located at equal distances from the centre line of the fibre port array is tagged with an orthogonal polarisation and no light from the other fibre port will be imaged onto its magnification equivalent since the polarisation equalisation elements in the system will only re-image the light back onto a fibre port if it is of the correct polarisation. This polarisation tagging architecture thus has the significant advantage of eliminating cross-talk between the two ROADMs since the interconnected fibre ports are twice the distance between the individual fibres of the total fibre array, and any light from either of the ROADM devices that appears onto the path of the other is lost to the space between the fibres due to the fact that it will be of incorrect polarisation and will not be combined in the walk-off crystal **215**.

The OPMC **280** is able to direct the image of any one wavelength channel independently or all the wavelength channels from the input fibres between the drop ports, either fibre ports **207** or **208**, or the express ports, either fibre ports **205** or **207**, for either of ROADM1 or ROADM2 respectively. This is achieved by inducing a phase hologram at each of the wavelength channels of the correct order to impart onto the beam the required amount of phase front correction to retrace its path through the system and be re-imaged on the desired output fibre port. Simultaneously when the input light from the input port **203** of ROADM**1** is directed to the drop port **207** at a particular wavelength, the same wavelength will be directed from the corresponding add port **201** to the express output port of ROADM**1** **205**. Similarly for ROADM2, when the input light from the input port **4** of ROADM**2** is directed to the drop port **208** at a particular wavelength the same wavelength will be directed from the corresponding add port **202** to the express output port **206** of ROADM**2**. The re-imaged light at the fibre port is again largely circular symmetric as the effects of the cylindrical lenses and polarisation equalisation elements are reversed through the return propagation. The operation of the OPMC device will now be described.

Description of the Optical Phased Matrix Coupling Device

The optical phased array coupling (OPMC) element in the preferred implementations is a liquid crystal on silicon (LCOS) device. Liquid crystal devices are commonly used for optical modulators. They have a number of advantages over mechanical modulators such as large modulation depths, no moving parts, low power dissipation, potential for large aperture operation and low cost. The LCOS device is a reflective device where a liquid crystal is sandwiched between a transparent glass layer with a transparent electrode and a silicon substrate divided into a 2-dimensional array of individually addressed electrodes. LCOS technology enables very high resolution devices with pixel pitch on the order of 10-20 μm, with each pixel being individually addressed by electrodes on the silicon substrate. The liquid crystals commonly used are dependent on the particular application, where ferroelectric liquid crystals (FLC) are preferred for devices requiring very fast switching times and phase modulations of less than $\pi/2$, and Nematic Liquid Crystals (NLC) are preferred for applications requiring pure phase modulations of up to 2π in reflection on a pixel-by-pixel basis. The LCOS systems in the preferred embodiments use NLCs. Such devices are available from Boulder Nonlinear Systems of Lafayette, Colo., USA.

The diffractive optical phased matrix can be thought of in terms of a diffraction grating formed by quantised multiple level phase grating set up by setting the amount of phase retardation on a pixel-by-pixel basis across the face of the beam to be routed. High efficiency of coupling and high isolation of switching states can be achieved through the use of a large number of elements in the phased matrix particularly in the axis of the x-dimension as is provided by the large size of the optical projection in that axis.

As described in the descriptions above, the image on the OPMC is that of two groups of spatially separated wavelength channels, one group being on the upper half (in the x-dimension) of the OPMC corresponding to beams that have been tagged with a first polarisation state, and the second group being on the lower half of the OPMC corresponding to beams that have been tagged with a second polarisations state, which is orthogonal to the first. Since the LCOS device is highly polarisation dependent, for efficient operation, the light from both groups of beams when they arrive at the device have been manipulated to be in the same polarisation state as previously described. The wavelength channels are separated spatially in the y-dimension and the image of each wavelength channel appears substantially as being highly asymmetric with orthogonal dimensions of 20 μm in the focused y-dimension and approximately 700 μm in the collimated x-dimension.

Due to the individually addressable nature of the LCOS pixels, the individual wavelength channels from either group of beams can be accessed by the OPMC **180** or **280** independently of any of the other channels. The OPMC device is divided into two series' of elongated cell regions substantially matching the elongated spatially separated wavelength bands. The cell regions each can include a plurality of drivable cells and wherein, in use, the cells are preferably driven so as to provide a selective driving structure which projects a corresponding optical signal falling on the cell region substantially into one of a series of output order modes.

One method of visualising the coupling of a particular wavelength channel to a desired output port is that particular wavelength channel occupies on the LCOS device form an optical phase matrix. This matrix is set up in such a fashion so as to recreate the phase of the required output port from the phase front of the input port which will now be described. In this embodiment, for simplicity the beams are assumed to be collimated in the x-axis with a linearly varying phase front though the required functions can be easily calculated for converging or diverging or distorted phase fronts wherein the OPMC will provide optical power and routing simultaneously.

Referring to FIG. **13** and FIG. **14**, the forward propagating beam from an optical fibre input port **503** is generated with a phase-front orthogonal to the direction of propagation. It passes through a lens **510** with a focal length f. The beam is still travelling in the same direction so the phase-front **561** strikes the OPMC device **520** in the plane of the device. To couple this beam into an optical fibre output port **501**, the phase-front of the beam after reflection from the OPMC needs to have a phase front **565** which has a phase slope s with respect to the incoming phase-front **561** in the switching plane given in units of radians per micrometer. Thus, after passing again through the lens **510**, the backward propagating beam has been displaced by a distance d with respect to the forward propagating beam, and so is incident on the output port **501**. The phase slope s that is needed on the backward propagating phase-front to align with a particular output port is found by

$$s = \tan^{-1}\left(\frac{d}{f}\right).$$

This phase slope then needs to be converted into a phase shift on the individual pixels of the LCOS in the form of a voltage ramp in the plane of the elongated image of the wavelength channel on the OPMC device. The phase shift ϕ that each pixel needs to impart on the beam is calculated by

$$\phi = \frac{2 \cdot \pi \cdot X \cdot Y \cdot s}{\lambda}$$

where X is the pixel width in μm, Y is the number of pixels, and λ is the wavelength of the channel in μm. The relationship between the phase shift imparted on the beam by each pixel and the voltage applied to that pixel is determined using a lookup table. This results in an increasing function of voltage (or phase change) with respect to the pixel number as seen by example in the dotted lines **601** and **603** of FIG. **15** and FIG. **16** respectively using 256 pixels. To limit the amount of voltage applied to the pixel, however, it is recognised that a phase shift of 2π is equivalent to a phase shift of 0, so each time the phase shift of a particular pixel reaches 2π, the voltage of the next pixel is reset to give a phase shift of zero and the ramp repeated. This is seen by the solid lines **602** and **604** in FIG. **15** and FIG. **16** respectively.

Channel by channel control of optical power can be achieved by exciting a fraction of the power into a mode that doesn't correspond to an active port hence attenuating the power in the chosen path.

A second way to visualise the coupling is to presume that the optical phased-matrix at a particular wavelength channel is set up in such a fashion so as to create an overlap integral between the input and the desired output ports of that particular wavelength channel. The spatial overlap integral of the input Electric field vector at the OPCM times modified by the applied phase of the OPMC with Electric field vector of the output fibre projection on the OPCM will provide a measure of the coupling efficiency between those ports. It is clear that the OPCM can be used to correct for optical aberrations in the system or deliberate optical aberrations can be introduced to suppress back reflections by suitable design of the optical phased-matrix. Additionally, control over the relative phase of the reflected light in each fibre is provided which could be usefully employed if the optical wavelength processor is used in interferometric applications.

In alternative embodiments the OPCM can provide part or all of the optical power required to allow refocusing of the beam in the y dimension. This can be calculated in an identical fashion as the OPCM only requires spatial overlap of the intensity of the beams to allow coupling to occur and is independent of the state of focus or collimation.

A significant benefit of the phased matrix approach with the LCOS device is that the efficiency of the overlap coupling efficiency can be controlled on a wavelength-by-wavelength basis by active control of the coupling or diffraction efficiency of the phase matrix. This can be achieved by coupling a known amount of the wavelength channel into a mode which does not correspond to an output port and as such, the light is lost to the system. In the same fashion, if desired, known portions of light in any particular group or wavelength channel can be coupled into more than one output fibre.

Although the invention has been described with reference to a specific example, it will be appreciated by those skilled in the art that the invention may be embodied in many other forms.

I claim:

1. An optical signal manipulation system including:

a series of ports for carrying a series of optical signals to be manipulated;

a spatial separating means for simultaneously spatially separating at least a first and a second group of light from said series of optical signals, each of said first and second group including a multiplicity of independent wavelength channels, with the wavelength channels of the first group having overlapping wavelength ranges of the wavelength channels of the second group;

a wavelength dispersion element subsequently spatially separating the multiplicity of wavelength channels of said first and second group and projecting them onto a wavelength processing means; and

wavelength processing means for separately processing each of the separated wavelengths of said first and second group, with each of wavelength channels of the first and second group being processed independently at a separated spatial location, said wavelength processing means having a series of independent wavelength processing elements, with separate wavelength processing elements simultaneously processing the wavelength channels having overlapping wavelength ranges of the first and second group.

2. A system as claimed in claim **1** wherein said spatial separating means includes a polarisation manipulation element separating a first and second series of predetermined polarisations from predetermined ones of said ports and projecting said first series in a first angular direction and the second series in a second angular direction.

3. A system as claimed in claim **1** wherein said spatial separating means includes a series of optical power elements offset from said ports separating at least a first and second series of predetermined optical signals from predetermined ones of said ports and projecting said first series in a first angular direction and the second series in a second angular direction.

4. A system as claimed in claim **1** wherein signals processed by said wavelength processing means are transmitted back through said wavelength dispersion element, said polarisation manipulation element for output at said optical signal ports.

5. A system as claimed in claim **4** wherein the particular port to which particular wavelength channels are output is determined by the processing carried out by said wavelength processing means.

6. A system as claimed in claim **4** wherein said wavelength processing means includes a series of zones and the wavelength processing means separately manipulates the phase front of light striking each of said zones in order to control the output destination of wavelength channels striking a particular zone.

7. A system as claimed in claim **6** wherein said wavelength processing means comprises a spatial light modulator having a plurality of independently addressable pixels with said pixels being manipulated in a predetermined manner so as to manipulate the phase front striking a corresponding zone.

8. A system as claimed in claim 1 wherein the optical signals received by said wavelength processing means are in the form of wavelength separated elongated bands.

9. A system as claimed in claim 8 wherein the wavelength separated elongated bands are substantially collimated along their major axis and substantially focused along their minor axis.

10. A system as claimed in claim 9 wherein the ratio of the width of the major axis to the width of the minor axis of the bands is equal to or greater than 5.

11. A system as claimed in claim 9 wherein the width of the bands major axis is substantially 700 microns and the width of a bands minor axis is substantially 20 microns.

12. A system as claimed in claim 8 wherein said first group of wavelength channels forms a first row of wavelength separated elongated bands and said second group of wavelength channels forms a second row of wavelength separated elongated bands.

13. A system as claimed in claim 12 wherein said first and second row are substantially parallel.

14. A system as claimed in claim 2 wherein said first series of predetermined polarisations is derived from orthogonal polarisations of a first series of optical signals and said second series of predetermined polarisations is derived from orthogonal polarisations of a second series of optical signals.

15. A system as claimed in claim 2 wherein said polarisation manipulation element comprises, in series, a polarisation separation element for spatially separating orthogonal polarisations, a polarisation alignment element for aligning the separated orthogonal polarisations and a polarisation deflection element for angularly deflecting an optical signal in accordance with the polarisation state of the signal.

16. A system as claimed in claim 1 wherein said first and second group include at least one wavelength channel of the substantially the wavelength.

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UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 7,397,980 B2
APPLICATION NO. : 10/868521
DATED : July 8, 2008
INVENTOR(S) : Frisken

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Claim 16, column 22, line 17 should read as follows:

--...substantially the same wavelength...--

Signed and Sealed this

Twenty-sixth Day of August, 2008

JON W. DUDAS
Director of the United States Patent and Trademark Office

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