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CORE OPTICAL TECHNOLOGIES, LLC

UNITED STATES DISTRICT COURT

CENTRAL DISTRICT OF CALIFORNIA

SOUTHERN DIVISION

CORE OPTICAL TECHNOLOGIES, LLC, a California Limited Liability Corporation,

Plaintiff,

v.

CIENA CORPORATION, a Delaware Corporation, and CIENA COMMUNICATIONS, INC., a Delaware Corporation,

Defendants.

Case No. SACV 12-1872 AG (MLGx)

FIRST AMENDED COMPLAINT FOR PATENT INFRINGEMENT

JURY TRIAL DEMANDED

Hon. Andrew J. Guilford

Plaintiff Core Optical Technologies, LLC ("Plaintiff" or "Core Optical Technologies"), by and through its undersigned counsel, files this First Amended Complaint against Defendants Ciena Corporation and Ciena Communications, Inc. (collectively "Ciena" or "Defendants"), and alleges as follows:

JURISDICTION AND VENUE

1. This is an action for infringement of U.S. Patent No. 6,782,211, entitled "Cross Polarization Interface [sic] Canceler," which was duly issued by the United States Patent and Trademark Office on August 24, 2004 ("the '211 patent"). This Court has subject matter jurisdiction over this action pursuant to 28 U.S.C. §§1331 and 1338(a) because the claims arise under the patent laws of the United States, 35 U.S.C. §§1, *et seq*.

2. This Court has personal jurisdiction over Defendants, which conduct continuous and systematic business in the United States, including, upon information and belief, in this judicial district. Defendants market, manufacture, use, offer for sale, sell, import, and/or distribute the infringing products at issue in this case throughout the United States including, upon information and belief, within this judicial district. Defendants also use, induce their customers' use of, and/or contribute to their customers' use of the infringing products at issue in this case to perform one or more patented methods of the '211 patent throughout the United States, including upon information and belief, in this judicial district.

3. Venue is proper within this judicial district under 28 U.S.C. §§1391(b) and (c) because Defendants transact business within this district, offer for sale in this district products that infringe the '211 patent, and, on information and belief, induce their customers to commit infringing acts in this district. In addition, venue is proper because Core Optical Technologies resides in this judicial district and Core Optical Technologies suffered harm in this district. Moreover, a substantial part of the events giving rise to this action occurred in this judicial district, including the inventive activities giving rise to the '211 patent.

THE PARTIES

4. Plaintiff, Core Optical Technologies, LLC, is a limited liability company organized and existing under the laws of California, and having a principal place of business at 18792 Via Palatino, Irvine, CA 92603.

5. Defendant Ciena Corporation is a Delaware corporation with its principal place of business located at 1201 Winterson Road, Linthicum, Maryland 21090, and, on information and belief, does business in this judicial district and elsewhere throughout the United States.

6. Defendant Ciena Communications, Inc. is a Delaware corporation with its principal place of business located at 7035 Ridge Road, Hanover, Maryland 21076, and, on information and belief, does business in this judicial district and elsewhere throughout the United States.

7. At all times relevant to this lawsuit, Defendants made, used, offered to sell, sold, imported, and/or distributed infringing products throughout the United States, and used, induced their customers' use of, or contributed to their customers' use of the infringing products within the United States to perform one or more of the patented methods set forth in the '211 patent.

THE ASSERTED PATENT

8. Mark Core, the sole named inventor of the '211 patent, earned his Ph.D in electrical and computer engineering from the University of California, Irvine, and is the CEO and president of Plaintiff, Core Optical Technologies. The pioneering technology set forth in the '211 patent greatly increases data transmission rates in fiber optic networks by enabling two optical signals transmitted in the same frequency band, but at generally orthogonal polarizations, to be recovered at a receiver. The patented technology that enables the recovery of these signals includes coherent optical receivers and related methods that mitigate cross-polarization interference associated with the transmission of the signals through the fiber optic network. The patented coherent receivers and methods also mitigate the effects of chromatic

dispersion, polarization mode dispersion, and polarization dependent loss that limit the performance of optical networks, thereby greatly increasing the transmission distance and eliminating or reducing the need for a variety of conventional network equipment such as amplifiers, regenerators, and compensators. The patented technology set forth in the '211 patent has been adopted by Defendants in at least their packet-optical transport products and systems described below.

9. On November 5, 1998, Mark Core filed with the United States Patent and Trademark Office ("USPTO") Provisional Patent Application No. 60/107,123 ("the '123 application") directed to his pioneering inventions. On November 4, 1999, Mark Core filed with the USPTO a non-provisional patent application, U.S. Patent Application No. 09/434,213 ("the '213 application"), claiming priority to the '123 application. On August 24, 2004, the USPTO issued the '211 patent from the '213 application. The entire right, title and interest in and to the '211 patent, including all rights to past damages, has been assigned to Plaintiff in an assignment recorded with the USPTO. A copy of the '211 patent is attached as Exhibit 1.

GENERAL ALLEGATIONS

10. Defendants and/or their respective divisions, subsidiaries, and/or agents are engaged in the business of making, using, distributing, importing, offering for sale, and/or selling 40G and 100G solutions that embody the patented inventions disclosed and claimed in the '211 patent ("the Infringing Products"). The Infringing Products include, without limitation, Defendants' eDC40G line card, eDC100G line card, 6500 Packet-Optical Platform, and 4200 Advanced Service Platform and modules that include Defendants' 40G or 100G dual polarization coherent optical receivers, as well as any of Defendants' other products that incorporate their dual polarization coherent optical receivers.

11. Additionally, the only use of certain components of the Infringing Products, such as the eDC40G and eDC100G line cards, is to perform one or more of the claimed methods in the '211 patent.

CLAIMS FOR RELIEF

12. Plaintiff repeats and realleges each and every allegation contained in paragraphs 1-11, inclusive, of this Complaint with the same force and effect as if set forth at length herein.

13. Defendants have been infringing and continue to infringe the '211 patent by making, having made, using, offering for sale, and/or selling directly or through intermediaries, in this district or elsewhere in the United States, the Infringing Products, and/or by importing into the United States the Infringing Products.

14. Defendants have indirectly infringed and continue to indirectly infringe the '211 patent under 35 U.S.C. §271(b) by knowingly and actively inducing infringement of one or more of the claims of the '211 patent. Defendants had knowledge of the '211 patent from a time prior to the filing of this Complaint. Defendants have actively and knowingly encouraged and induced infringement of one or more claims of the '211 patent, for example, by instructing, aiding, assisting, and encouraging the use of their Infringing Products in an infringing manner, and by selling Infringing Products that have no non-infringing uses to customers who in turn use them to perform one or more of the patented methods disclosed and claimed in the '211 patent. The direct infringers of the '211 patent that are being induced by Defendants include their customers that use the Infringing Products.

15. Defendants have also indirectly infringed and continue to indirectly infringe one or more of the claims of the '211 patent under 35 U.S.C. §271(c) through, among other things, unlawfully selling or offering to sell within the United States, or importing into the United States, the Infringing Products, which products constitute a material part of the claimed inventions of the '211 patent, which Defendants know to be especially made or especially adapted for use in infringement of the '211 patent, and which are not staple articles or commodities of commerce suitable for substantial non-infringing use. The direct infringers for Defendants'

contributory infringement under 35 U.S.C. §271(c) include, without limitation, their customers and users of the Infringing Products.

16. Defendants' infringement of the '211 patent has caused and will continue to cause significant damage to Plaintiff. As a result, Plaintiff is thereby entitled to an award of damages adequate to compensate it for the infringement in an amount that is in no event less than a reasonable royalty pursuant to 35 U.S.C. §284. Plaintiff is also entitled to recover prejudgment interest, post-judgment interest, costs, and enhanced damages under 35 U.S.C. §284.

17. Although Defendants had knowledge of the '211 patent before the filing of this Complaint, on information and belief, Defendants have nevertheless continued to directly and indirectly infringe the '211 patent, despite an objectively high likelihood that its actions constitute infringement of the '211 patent. Accordingly, Defendants' infringement has been and continues to be willful.

18. As a result of Defendants' infringement of the '211 patent, Plaintiff has suffered irreparable harm and impairment of the value of its patent rights, and is now suffering, and will continue to suffer, the violation of its patent rights unless and until Defendants are permanently enjoined by this Court from infringing the '211 patent under 35 U.S.C. §283. Plaintiff has no adequate remedy at law and is entitled to a permanent injunction against Defendants and their Infringing Products.

19. This case is an "exceptional" case within the meaning of 35 U.S.C. §285 and Plaintiff is entitled to an award of attorneys' fees.

PRAYER FOR RELIEF

WHEREFORE, Core Optical Technologies prays for relief as follows:

1. Judgment be entered in favor of Core Optical Technologies against Defendants;

2. Core Optical Technologies be awarded costs of the suit;

3. Core Optical Technologies be awarded compensatory and special damages for the infringement of the '211 patent in an amount to be determined at trial;

4. Defendants be preliminary and permanently enjoined from infringing or inducing others to infringe the '211 patent;

5. The Court determines that Ciena's infringement is willful and that Core Optical Technologies is entitled to collect enhanced damages up to three times the actual damages found or assessed;

6. The Court declare this an exceptional case under 35 U.S.C. §285 and award Core Optical Technologies its attorneys' fees and costs incurred in connection with this action;

7. The Court otherwise award Core Optical Technologies its attorneys' fees; and

8. The Court grant such further relief as the Court deems just and proper.

JURY DEMAND

Plaintiff, Core Optical Technologies, LLC demands a trial by jury on all issues so triable.

Dated: July 9, 2013

DICKSTEIN SHAPIRO LLP

By: 

Lawrence R. LaPorte

Attorneys for Plaintiff
CORE OPTICAL TECHNOLOGIES, LLC

EXHIBIT 1

US006782211B1

(12) **United States Patent**
Core

(10) **Patent No.: US 6,782,211 B1**
(45) **Date of Patent: Aug. 24, 2004**

(54) **CROSS POLARIZATION INTERFACE CANCELER**

(76) Inventor: **Mark T. Core**, 738 Royal Stewart Dr., Placentia, CA (US) 92870

(*) 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.: **09/434,213**

(22) Filed: **Nov. 4, 1999**

Related U.S. Application Data

(60) Provisional application No. 60/107,123, filed on Nov. 5, 1998.

(51) **Int. Cl.**[7] **H04B 10/00**
(52) **U.S. Cl.** **398/205**; 398/204; 398/207
(58) **Field of Search** 359/192, 122, 359/190, 142, 193; 398/202, 204, 205, 208, 65

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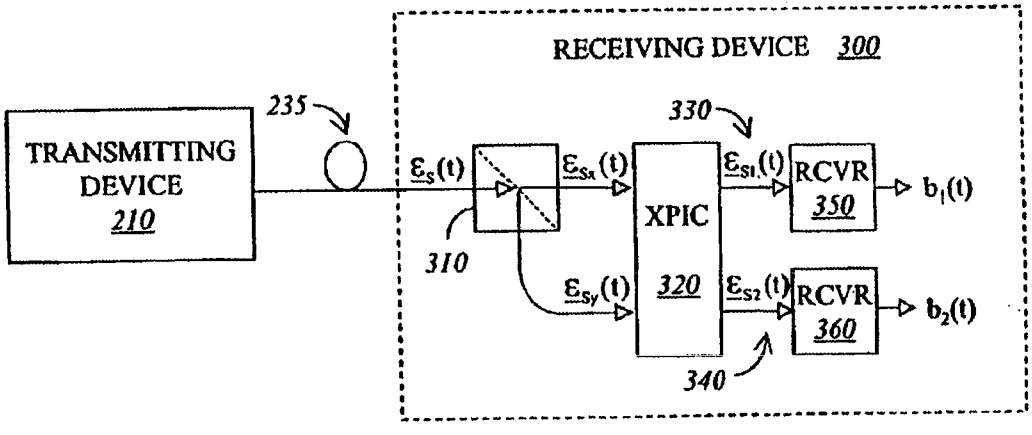
Primary Examiner—Jason Chan
Assistant Examiner—Agustin Bello
(74) *Attorney, Agent, or Firm*—Blakely Sokoloff Taylor & Zafman LLP

(57) **ABSTRACT**

Implemented in both coherent and non-coherent optical systems, a receiving device including a cross polarization interference canceler (XPIC) is described. For these embodiments, the XPIC optimizes bandwidth efficiency of an optical communication link by enabling the reconstruction of two optical signals transmitted with generally orthogonal polarization states and routed over a single fiber optic transmission medium in the same frequency band.

37 Claims, 7 Drawing Sheets



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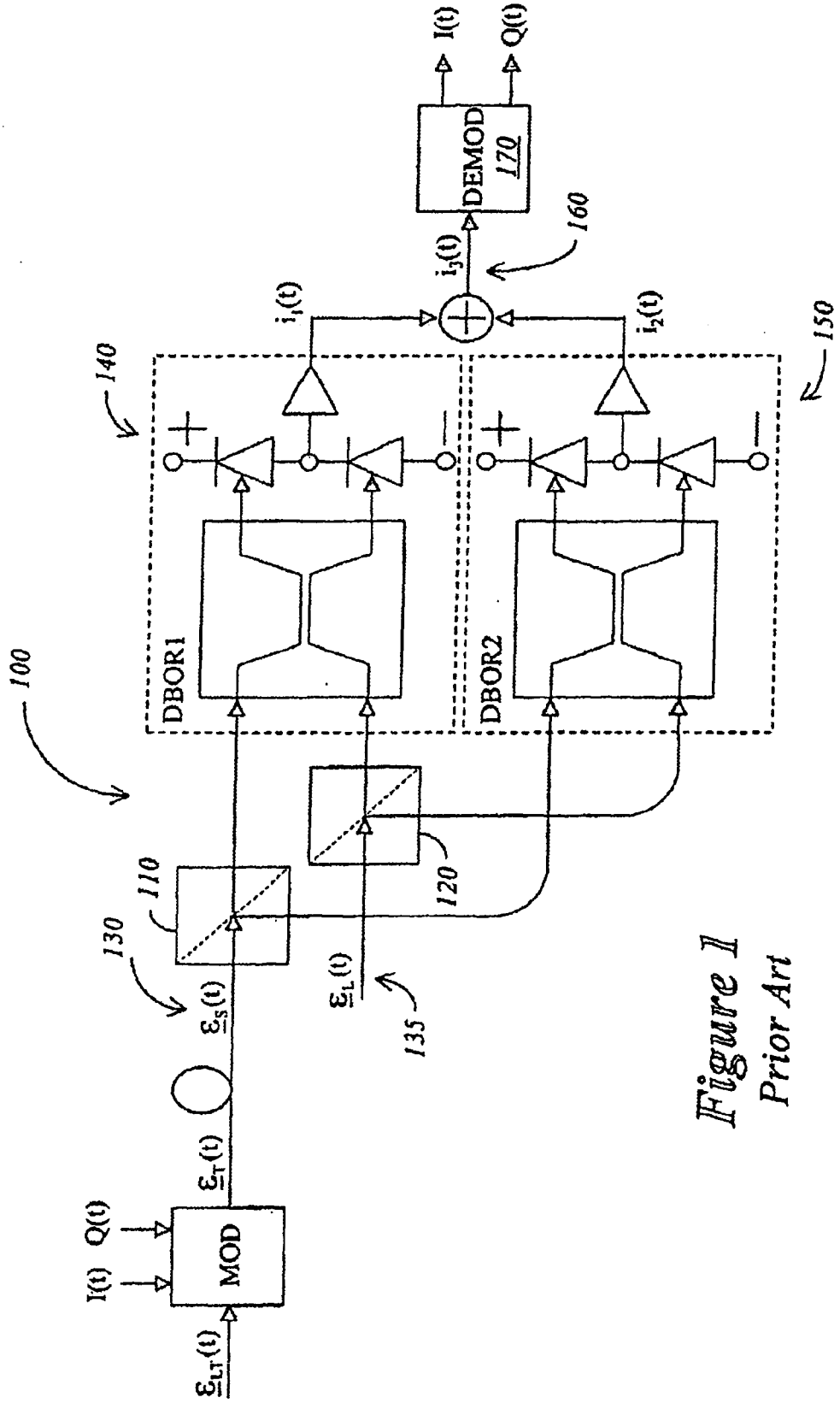


Figure 1
Prior Art

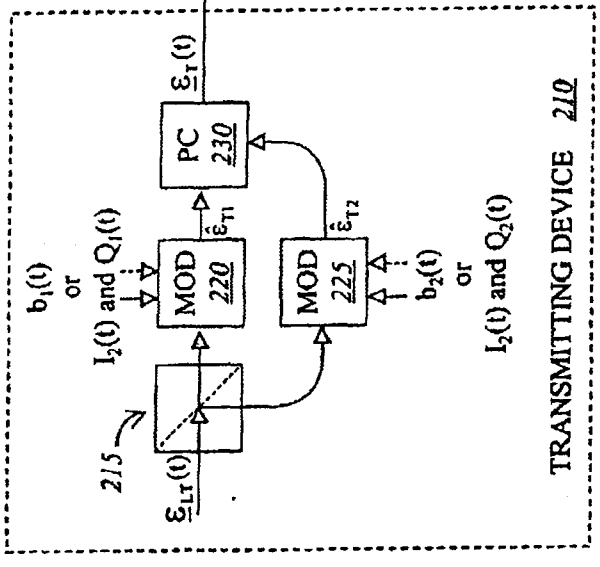


Figure 2

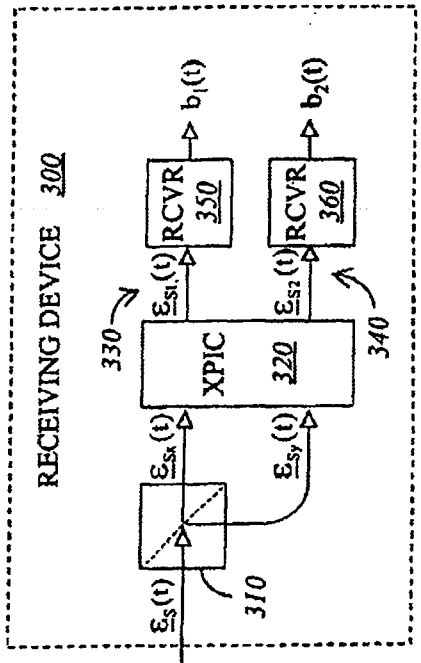


Figure 3

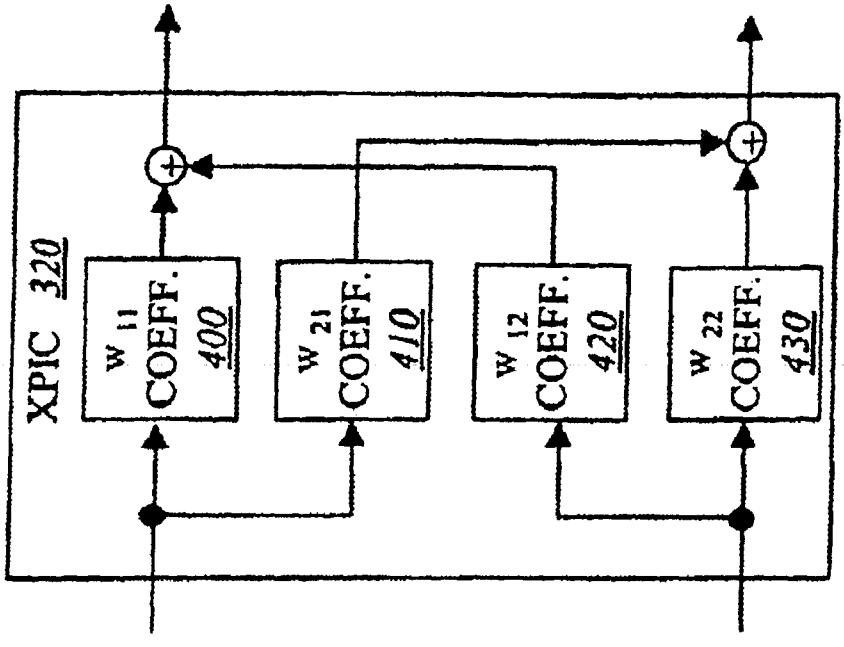


Figure 4B

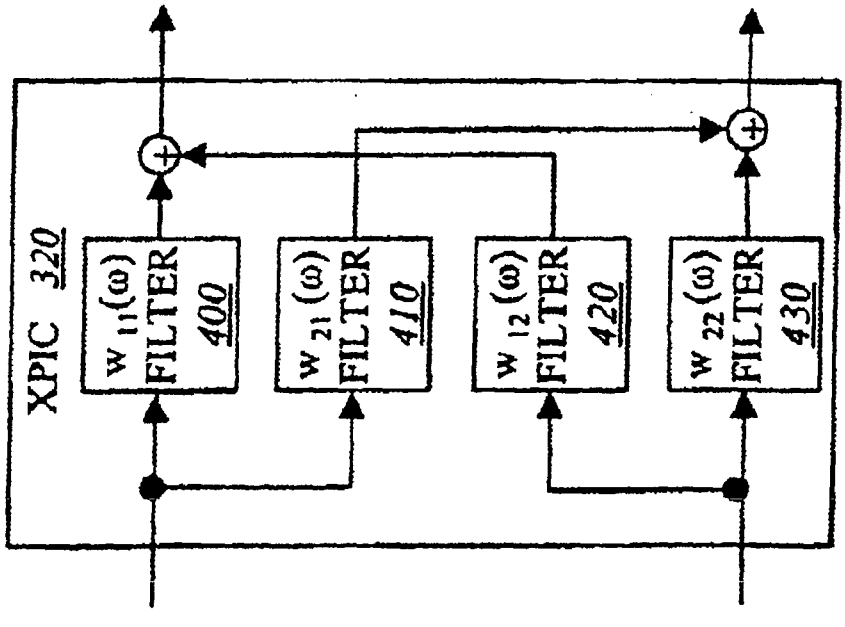


Figure 4A

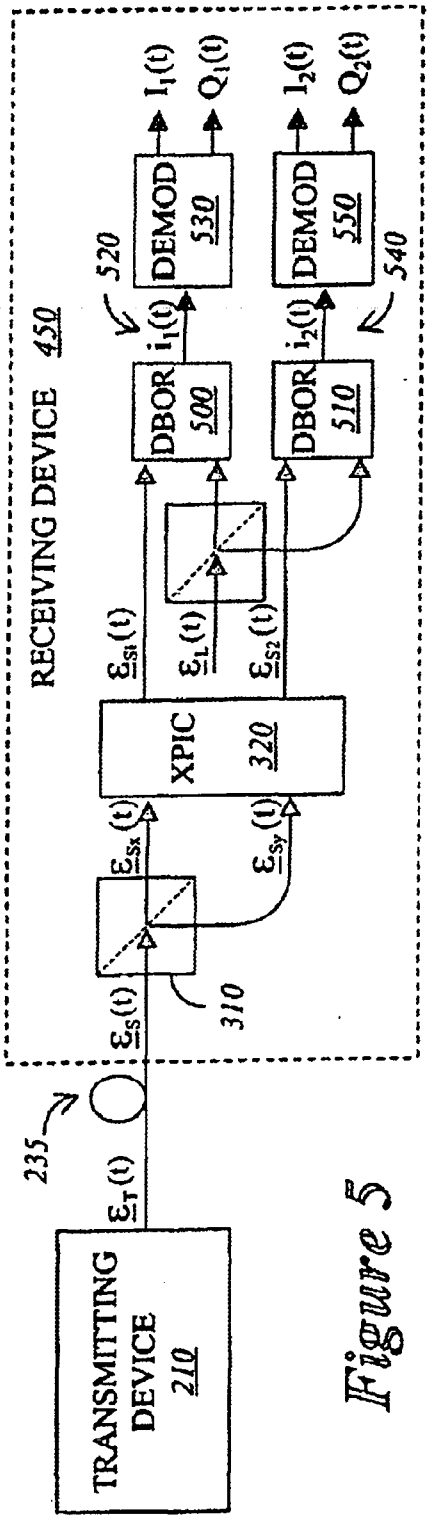


Figure 5

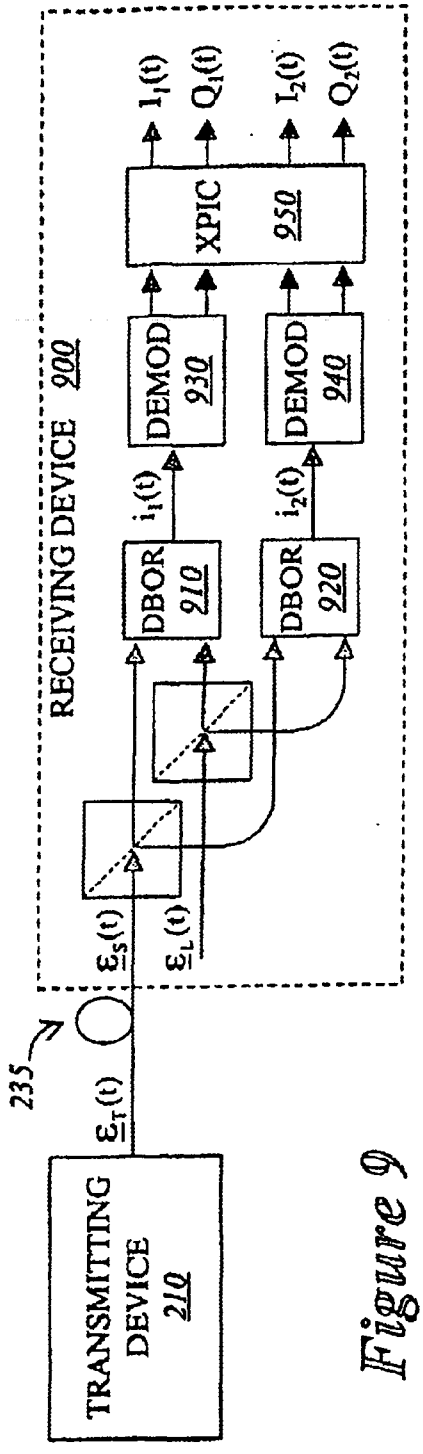
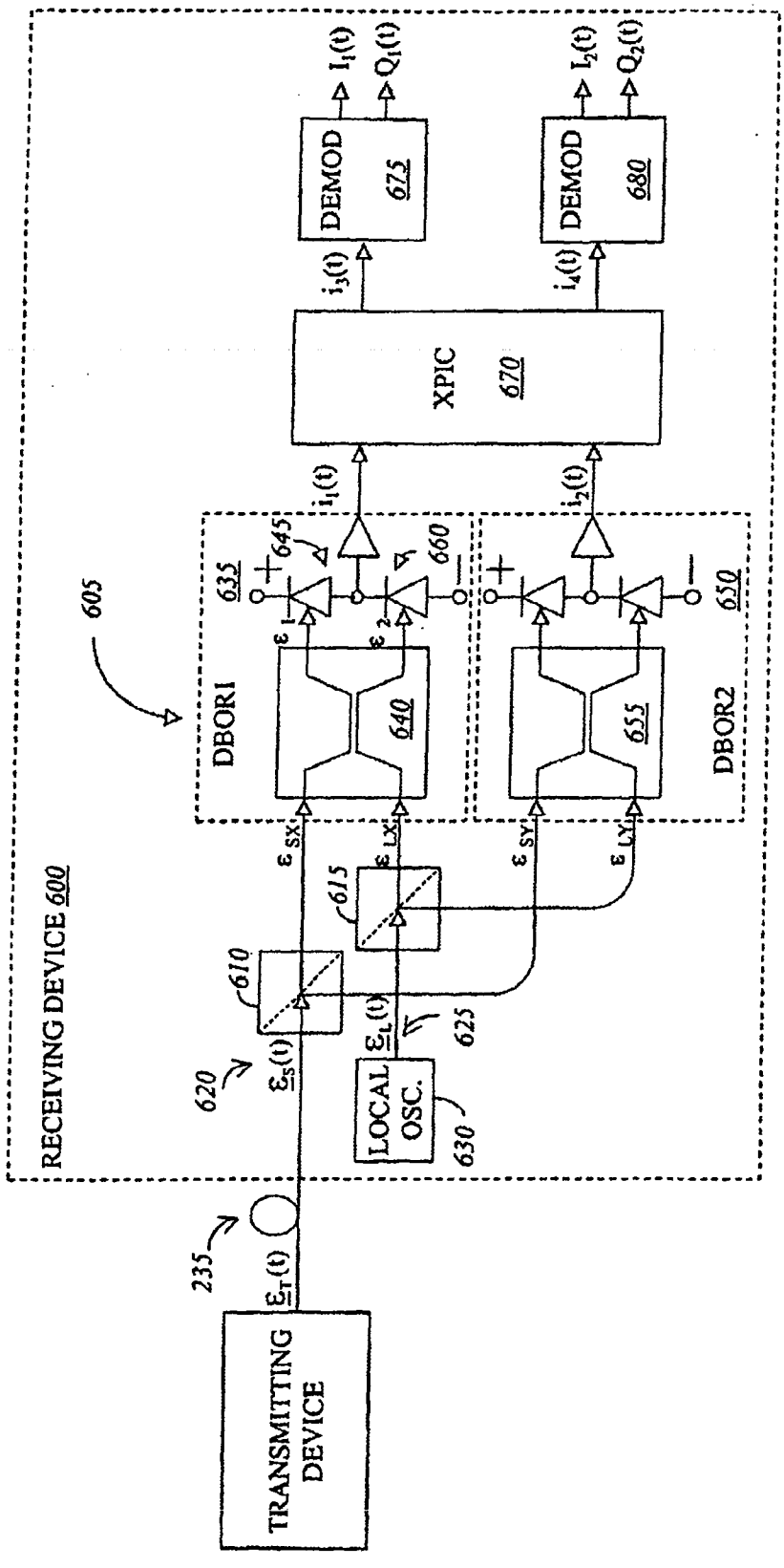


Figure 9


RECEIVING DEVICE 600
605
DBOR1
DBOR2
635
640
645
650
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XPIC 670
DEMOD 675
DEMOD 680
LOCAL OSC.
TRANSMITTING DEVICE
$I_1(t)$ $Q_1(t)$
$I_2(t)$ $Q_2(t)$
$i_1(t)$ $i_2(t)$ $i_3(t)$ $i_4(t)$
ε_1 ε_2
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Figure 6

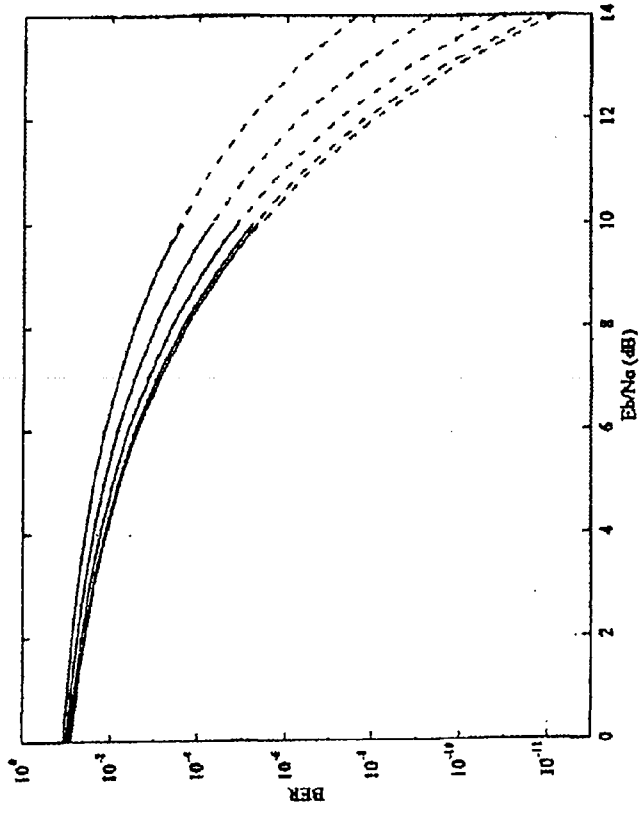

Figure 8

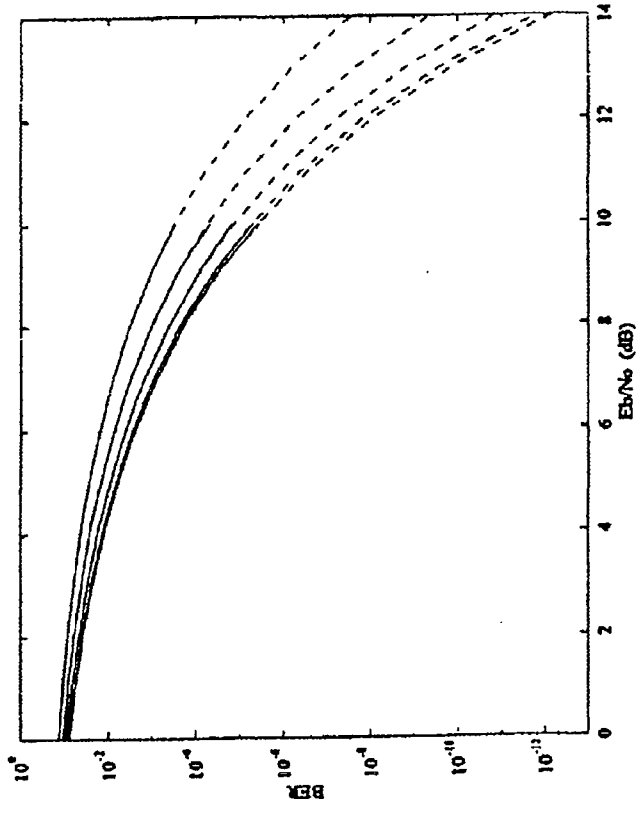

Figure 7

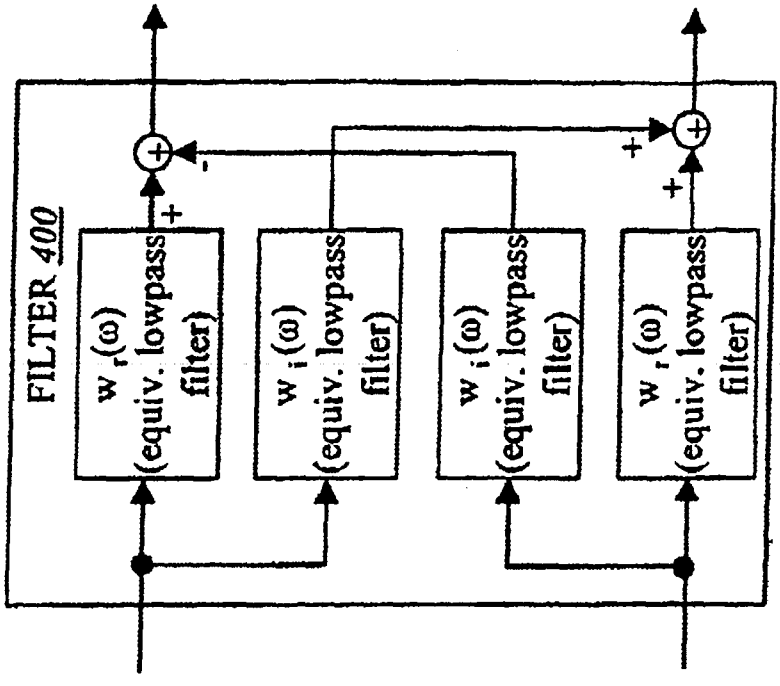

Figure 10B

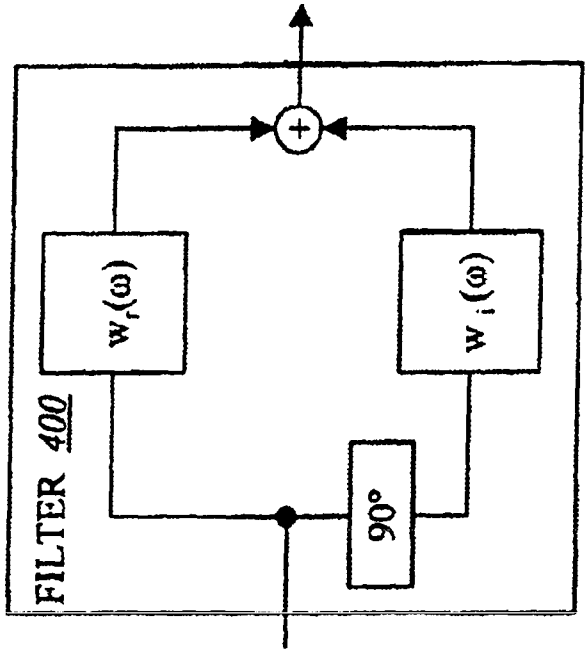

Figure 10A

CROSS POLARIZATION INTERFACE CANCELER

CROSS-REFERENCES TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application No. 60/107,123 filed Nov. 5, 1998.

BACKGROUND

1. Field

The present invention relates to the field of fiber optics. In particular, the present invention constitutes a cross-polarization interference canceler (XPIC) and its corresponding method of operation that optimizes bandwidth efficiency over an optical fiber transmission medium and mitigates dispersion effects or any loss of optical field orthogonality incurred during propagation through the optical fiber.

2. Related Art

Due to increased demand for fast data transmissions, optical communication networks are being utilized more frequently. Normally, a fiber optic communication link includes a set of transceivers coupled together by optical fiber supporting one or more fiber optic transmission channels. Each transceiver includes a transmitter and receiver. The transmitter converts an electrical signal to a single optical signal, which is applied to a fiber optic transmission medium. The receiver converts the optical signal back to an electrical signal, which may be routed through electrical wire or processed by a computer for example.

Typically, the electric field of the received optical signal has time varying polarization, and the optical receiver must either be insensitive to the field polarization, or track the optical field polarization to recovery the transmitted information.

Referring to FIG. 1, a block diagram of a conventional coherent fiber optic communication link utilizing a polarization diversity receiver **100** is shown. This type of receiver is insensitive to the polarization of the received optical signal field. Receiver **100** includes a pair of polarization beam splitters **110** and **120**. A first polarization beam splitter **110** receives an, incoming optical signal from the optical fiber. This incoming optical signal comprises an electromagnetic (EM) plane wave with an electric field **130** (referred to as "$\underline{\epsilon}_S(t)$") that is amplitude and/or phase modulated with information bearing in-phase (I(t)) and quadrature (Q(t)) waveforms.

For clarity sake, the horizontal ($\hat{x}$) and vertical ($\hat{y}$) directions are defined to coincide with the polarization axes of the polarization beam splitters at receiver **100**. The polarization states of the transmitted electric field (referred to as "$\underline{\epsilon}_T(t)$") and received electric field ($\underline{\epsilon}_S(t)$) **130** are assumed arbitrary with respect to the $\hat{x}$ and $\hat{y}$ directions.

Polarization beam splitter **110** separates received electric field $\underline{\epsilon}_S(t)$ **130** into a horizontal ($\hat{x}$) field component and a vertical ($\hat{y}$) field component. These $\hat{x}$ and $\hat{y}$ components of $\underline{\epsilon}_S(t)$ **130** are routed into double-balanced optical receivers (DBORs) **140** and **150**. Polarization beam splitter **120** receives an optical signal from a local oscillator (LO) laser, in particular a non-modulated EM plane wave with an electric field ($\underline{\epsilon}_L(t)$) **135**. A "DBOR" is a device that performs the function of an optical mixer, multiplying the optical inputs and removing the resulting high frequency components through the inherent bandlimiting of the photodiodes. This multiplication process is polarization sensitive, however, and only the component of $\underline{\epsilon}_S(t)$ **130** with the same polarization as $\underline{\epsilon}_L(t)$ **135** is detected.

The frequency of the LO laser is adjusted such that the difference between the optical LO frequency and the carrier frequency of $\underline{\epsilon}_S(t)$ is equal to the desired intermediate carrier frequency ω_{IF} of the DBOR output current. A demodulator **170** then demodulates the IF signal and recovers the baseband information bearing waveforms I(t) and Q(t).

More specifically, the $\hat{x}$ component of $\underline{\epsilon}_S(t)$ is routed to DBOR **140** and the $\hat{y}$ component is routed to DBOR **150**. Each DBOR **140** or **150** includes, for example, a directional coupler and photodiodes connected in series. The $\hat{x}$ component of $\underline{\epsilon}_L(t)$ is also routed to DBOR **140** and the $\hat{y}$ component is routed to DBOR **150**. If the polarization state of $\underline{\epsilon}_L(t)$ is adjusted to be linearly polarized at forty-five (45) degrees with respect to the $\hat{x}$ axis, then DBOR **140** will respond with an electrical current (referred to as "$i_1(t)$") having a magnitude that is proportional to the $\hat{x}$ component of $\underline{\epsilon}_S(t)$ **130**, and DBOR **150** will respond with a current (referred to as "$i_2(t)$") having a magnitude that is proportional to the $\hat{y}$ component of $\underline{\epsilon}_S(t)$ **130** and having the same phase as $i_1(t)$.

The output electrical currents of DBORs **140** and **150** are combined to produce a resultant electrical signal current **160** (referred to as "$i_3(t)$"). Thus, since any polarization state can be resolved into $\hat{x}$ and $\hat{y}$ components, polarization diversity receiver **100** will respond to a received optical signal field with arbitrary polarization. Although polarization diversity receiver **100** is able to detect a received optical signal field with arbitrary polarization, it fails to take advantage of the potential to transmit independent optical signals across the optical medium in the same frequency band, but with orthogonal polarization states, and thereby increase the link bandwidth efficiency.

Under ideal conditions, two conventional polarization tracking receivers (not shown) could reconstruct two received optical signals having fields with orthogonal polarization states by tracking the polarization of each signal field. Theoretically, if the polarization of the optical LO in each receiver is adjusted to match the polarization of the electric field of one of the optical signals, then the other optical signal will be rejected. However, in practice, the orthogonality of the two optical signal fields would be lost to some extent during propagation through the optical fiber. Therefore, a system having two conventional polarization tracking receivers would incur a signal crosstalk penalty, also known as cross polarization interference (XPI). This would have adverse effects on the quality and reliability of the optical signaling.

Besides cross polarization interference, the optical signal may experience chromatic and/or polarization mode dispersion. In general, dispersion is problematic when a light pulse, normally associated with a particular period of time, begins to occupy portions of the time period associated with adjacent light pulses. A solution to overcome dispersion involves reducing the transmission length of the optical fiber. One way to reduce the transmission length is to place regenerative repeaters at selected intervals of the optical fiber. Regenerators require signal detection, electrical clock recovery circuitry, and means of generating a new optical signal from the recovered electrical signal. The use of repeaters, therefore, significantly increases the construction costs for an optical communication network.

It would therefore be desirable to develop a cross-polarization interference canceler (XPIC) and a method that optimizes bandwidth efficiency over the optical fiber by

enabling two optical signals transmitted in the same frequency band but with orthogonal polarization to be recovered at the receiver. This could correct for dispersion effects or any loss of optical field orthogonality incurred during propagation through the optical fiber, and optimally reconstruct the information bearing modulation waveforms at the receiver.

SUMMARY

As described herein, implemented in both coherent and non-coherent optical systems, exemplary embodiments of a receiving device including a cross polarization interference canceler (XPIC) are shown. For each of these embodiments, the XPIC optimizes bandwidth efficiency of an optical link by enabling the reconstruction of two optical signals transmitted with generally orthogonal polarization states and routed over a single fiber optic transmission medium in the same frequency band.

BRIEF DESCRIPTION OF THE DRAWINGS

The features and advantages of the present invention will become apparent from the following detailed description of the present invention in which:

FIG. **1** is a block diagram of a conventional coherent fiber optic communication link utilizing a polarization diversity receiver **100**.

FIG. **2** is an exemplary embodiment of a transmitting device capable of being utilized by either non-coherent or coherent systems.

FIG. **3** is an exemplary embodiment of an intensity modulation direct detection (IM-DD) fiber optic link having a receiving device utilizing an optical XPIC **320**.

FIG. **4**A is an exemplary embodiment of a frequency dependent, optical XPIC comprised of four complex optical filters.

FIG. **4**B is an exemplary embodiment of a frequency independent, optical XPIC comprised of four complex elements.

FIG. **5** is an exemplary implementation of a coherent fiber optic link having a receiving device utilizing an optical XPIC.

FIG. **6** is an exemplary implementation of a coherent fiber optic link having a receiving device utilizing an IF XPIC.

FIG. **7** is a graphical representation of the theoretical (dashed) and simulated (solid) bit error rate for a fiber optic link using binary phase shift keying with varying amounts of loss of orthogonality in accordance with FIG. **6** using a diagonalizer XPIC.

FIG. **8** is a graphical representation of the theoretical (dashed) and simulated (solid) bit error rate for a fiber optic link using binary phase shift keying with varying amounts of loss of orthogonality in accordance with FIG. **6** using a MMSE XPIC.

FIG. **9** is an exemplary embodiment of a coherent fiber optic link having a receiving device utilizing a baseband XPIC.

FIG. **10**A is an exemplary embodiment of a passband optical or IF filter of FIG. **4**A that is appropriate for the passband XPIC of FIGS. **3**, **5**, and **6**.

FIG. **10**B is an exemplary embodiment of a baseband filter of FIG. **4**A that is appropriate for the baseband XPIC of FIG. **9**.

DETAILED DESCRIPTION

Certain embodiments of the invention are described to provide a cross polarization interference canceler that optimizes bandwidth efficiency of an optical link by enabling the reconstruction of two optical signals transmitted with generally orthogonal polarization states and routed over a single fiber optic transmission medium in the same frequency band. The cross polarization interference canceler (XPIC) may also be directed to mitigate the effects of chromatic and/or polarization mode dispersion that currently limit the performance of high data rate optical communication networks.

Herein, various examples of circuitry and methods of operation are described. These examples should broadly be construed as illustrative in nature in order to represent the spirit of the invention. Also, certain terminology is used to describe various embodiments of the link. For example, a "signal" is a detectable physical quantity used to convey information for operating or controlling a device. There exist a variety of signal types, including optical, electrical and the like. A "device" is hardware and/or software operating to process, transmit and/or receive signals. Examples of a device include a computer, a router, a bridge, a modem and the like. A "cross polarization interference canceler" (XPIC) is circuitry and/or software designed to at least improve bandwidth efficiency of a fiber optic communication link by reconstructing two optical signals that are transmitted with generally orthogonal polarization states.

Because cross polarization interference cancellation is a form of coherent signal processing, the XPIC must be implemented optically for direct detection fiber optic systems. This is because all phase information is lost in the optical-to-electrical conversion process of direct detection receivers. Since phase information is retained during optical-to-electrical conversion in a coherent receiver, XPIC can be implemented either optically or electrically in coherent systems. In the context of optical communications, the term "coherent" refers to the use of a receiver with an optical local oscillator (LO) that translates the received optical signal from optical frequencies to either baseband (homodyne detection) or to an intermediate frequency (heterodyne detection).

Herein, four exemplary implementations of optical links employing a cross polarization interference canceler are shown. In particular, FIG. **3** illustrates an exemplary implementation for an intensity modulation direct detection (IM-DD) fiber optic system using an optical XPIC; FIG. **5** illustrates an exemplary implementation of a coherent receiving device utilizing an optical XPIC; FIG. **6** illustrates an exemplary implementation of a coherent receiving device utilizing an electrical IF XPIC; and FIG. **9** illustrates an exemplary implementation of a coherent receiving device utilizing an electrical baseband XPIC.

A. Transmit Signal Generation

Referring now to FIG. **2**, an exemplary embodiment of a transmitting device capable of being utilized by any of the exemplary embodiments of FIGS. **3**, **5**, **6** and **9** is shown. In one embodiment, the transmitting device is configured to separate the electric field $\underline{\epsilon}_{LI}(t)$ of the local oscillator beam into two orthogonally polarized field components. Each field component is independently modulated with information bearing waveforms to produce two modulated optical signals having electric fields $\underline{\epsilon}_{T1}(t)$ and $\underline{\epsilon}_{T2}(t)$. The two modulated optical signals with orthogonally polarized electric fields are recombined before transmission over the optical fiber.

As shown, transmitting device **210** includes of a local oscillator (LO) laser having an electric field denoted by

$\underline{\epsilon}_{LT}(t)$. In this embodiment, the polarization state of the local oscillator is adjusted so that the LO power is equally divided by a polarization beam splitter **215** into orthogonally polarized components. Again, the horizontal ($\hat{x}$) and vertical ($\hat{y}$) directions are defined to coincide with the polarization axes of one or more polarization beam splitters at a receiving device. For generality, the polarization axes of polarization beam esplitter **215** are assumed to have an arbitrary orientation with respect to the $\hat{x}$ and $\hat{y}$ directions.

The outputs from polarization beam splitter **215** are individually modulated with independent information bearing waveforms by modulators **220** and **225**. In the case of coherent modulation formats, in-phase ($I_k(t)$) and quadrature ($Q_k(t)$) waveforms may be used for arbitrary amplitude and/or phase modulation. In the case of intensity modulation, however, a single waveform $b_k(t)$ may be used by modulators **220** and **225**. The resulting modulated optical signals having fields $\underline{\epsilon}_{T1}(t)$ and $\underline{\epsilon}_{T2}(t)$ are recombined using a polarization combiner **230**. Polarization combiner **230** produces a transmit optical signal to be routed over an optical fiber transmission medium **235**.

Suppressing the $\hat{z}$ dependence and the radial field distribution, and neglecting noise, the simplified expression for the electric field of the transmitted optical signal, namely $\underline{\epsilon}_T(t)$, when applied to optical fiber transmission medium **235** is defined in equation (A.1), where

$$\underline{\epsilon}_T(t)=Re\{([\epsilon_{Tx1}e^{j\delta_{Tx1}}v_1(t)+\epsilon_{Tx2}e^{j\delta_{Tx2}}v_2(t)]\hat{x}+[\epsilon_{Ty1}e^{j\delta_{Ty1}}v_1(t)+\epsilon_{Ty2}e^{j\delta_{Ty2}}v_2(t)]\hat{y})e^{j\omega_S t+\phi_S(t)}\}. \quad (A.1)$$

The term "$\phi_S(t)$" denotes the phase noise of the LO laser of transmitting device **210** and "$v_1(t)$" and "$v_2(t)$" are the complex envelope representations of the modulating functions

$$v_k(t)=a_k(t)e^{j\theta_k(t)}=I_k(t)+jQ_k(t)k=1,2. \quad (A.2)$$

For intensity modulation, v(t) is real and has the form

$$v_k(t)=b_k(t)k=1,2. \quad (A.3)$$

The polarization states of the independently modulated, electric field components may be specified by their respective Jones vector as set forth in equations (A.4) and (A.5) below.

$$\hat{\varepsilon}_{T1}=\begin{bmatrix}\varepsilon_{Tx1}e^{j\delta_{Tx1}}\\ \varepsilon_{Ty1}e^{j\delta_{Ty1}}\end{bmatrix} \quad (A.4)$$

$$\hat{\varepsilon}_{T2}=\begin{bmatrix}\varepsilon_{Tx2}e^{j\delta_{Tx2}}\\ \varepsilon_{Ty2}e^{j\delta_{Ty2}}\end{bmatrix}. \quad (A.5)$$

From these Jones vectors, a matrix (U) may be created with columns consistent with the Jones vectors of the two modulated field components as shown in equation (A.6).

$$U=\begin{bmatrix}\varepsilon_{Tx1}e^{j\delta_{Tx1}} & \varepsilon_{Tx2}e^{j\delta_{Tx2}}\\ \varepsilon_{Ty1}e^{j\delta_{Ty1}} & \varepsilon_{Ty2}e^{j\delta_{Ty2}}\end{bmatrix}. \quad (A.6)$$

Because the polarization state of the transmit LO laser is adjusted such that the optical power is equally divided by polarization beam splitter **215** in this embodiment, and because splitter **215** divides the local oscillator field into orthogonally polarized components, the columns of matrix U are orthogonal, and matrix U is therefore proportional to a unitary matrix.

The angle between any two polarization states specified by Jones vectors $\hat{\epsilon}_{S1}$ and $\hat{\epsilon}_{S2}$ is defined by equation (A.7).

$$\gamma=\cos^{-1}\left(\sqrt{\frac{|\hat{\varepsilon}_{S1}^H\hat{\varepsilon}_{S2}|^2}{\hat{\varepsilon}_{S1}^H\hat{\varepsilon}_{S1}\hat{\varepsilon}_{S2}^H\hat{\varepsilon}_{S2}}}\right), \quad (A.7)$$

where the terms "$\hat{\epsilon}_{S1}$" and "$\hat{\epsilon}_{S2}$" denote Jones vectors and the superscript "H" denotes the conjugate transpose of that vector.

B. Effect of the Optical Fiber Transmission Medium

If the optical signal is sufficiently narrowband then the transfer function of the optical medium will exhibit no frequency dependence over the bandwidth of the signal. When this assumption holds, the effect of the fiber optic medium **235** on the matrix (U) of Jones vectors for the transmitted optical fields can be represented as

$$V=TU, \quad (B.1)$$

where "T" is a complex 2×2 fiber transmission matrix that accounts for the effect of the fiber optic medium **235** on the transmitted signal polarizations, and "V" is a matrix with columns corresponding to the Jones vectors of the received optical fields as shown in equation (B.2).

$$V=\begin{bmatrix}\varepsilon_{Sx1}e^{j\delta_{Sx1}} & \varepsilon_{Sx2}e^{j\delta_{Sx2}}\\ \varepsilon_{Sy1}e^{j\delta_{Sy1}} & \varepsilon_{Sy2}e^{j\delta_{Sy2}}\end{bmatrix}. \quad (B.2)$$

When the symbol rate exceeds a few gigahertz (GHz), this narrowband approximation is no longer valid for standard single mode fiber, and the optical medium exhibits significant distortion in the form of chromatic and polarization mode dispersion. In this case, the matrix of Jones vectors for the received optical fields is expressed as

$$V(\omega)=T(\omega)U, \quad (B.3)$$

where "T(ω)" is a 2×2 frequency dependent complex transmission matrix for the fiber optic medium. Therefore, when the fiber transmission matrix (T) is frequency dependent, the Jones vectors of the received optical fields are also frequency dependent, and the matrix V(ω) has the following form:

$$V(\omega)=\begin{bmatrix}\varepsilon_{Sx1}(\omega)e^{j\delta_{Sx1}(\omega)} & \varepsilon_{Sx2}(\omega)e^{j\delta_{Sx2}(\omega)}\\ \varepsilon_{Sy1}(\omega)e^{j\delta_{Sy1}(\omega)} & \varepsilon_{Sy2}(\omega)e^{j\delta_{Sy2}(\omega)}\end{bmatrix} \quad (B.4)$$

In the absence of polarization dependent loss, T(ω) is a unitary matrix, but in general the fiber transmission matrix is not unitary.

C. Optical XPIC for IM-DD Systems

For IM-DD systems implemented with the present invention, a receiving device would split the received optical signal having an electric field $\underline{\epsilon}_S(t)$ into two orthogonally polarized components $\underline{\epsilon}_{Sy}(t)$ and $\underline{\epsilon}_{Sy}(t)$. These components would be applied as inputs to an optical XPIC, which would perform complex filtering or weighting and subsequent recombining of these inputs to mitigate cross polarization interference (XPI). Namely, each output of the XPIC is an optical signal with an electric field that has significant intensity modulation from only one of the originally transmitted signals. IM-DD receivers would accept the outputs of the XPIC and produce corresponding electrical signals.

Referring to FIG. **3**, an illustrative embodiment of a link having a receiving device **300** utilizing an optical XPIC **320** is shown. If the $\hat{x}$ and $\hat{y}$ directions are defined to coincide with the polarization axes of the polarization beam splitters in the receiver, then the polarization beam splitter **310** acts on the received optical signal by separating the optical field into $\hat{x}$ and $\hat{y}$ components. The separated field components are processed by an optical XPIC **320**, and the outputs of the XPIC are routed to standard intensity modulation direct detection (IM-DD) fiber optic receivers.

For the special case where the fiber transmission matrix (T) exhibits no frequency dependence, the outputs of polarization beam splitter **310** include two optical signal components with electric fields that can be expressed in matrix form as shown in equation (C.1)

$$\begin{bmatrix} \varepsilon_{Sx}(t) \\ \varepsilon_{Sy}(t) \end{bmatrix} = \mathrm{Re}\left\{\begin{bmatrix} \hat{x} & 0 \\ 0 & \hat{y} \end{bmatrix}\left(V\begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix} + \begin{bmatrix} n_1(t) \\ n_2(t) \end{bmatrix}\right)\right\} \tag{C.1}$$

where "$s_1(t)$" and "$s_2(t)$" are the complex representations of the optical signals

$$s_k(t)=v_k(t)e^{j\omega_s t+\phi_s(t)}k=1,2 \tag{C.2}$$

and "$n_1(t)$" and "$n_2(t)$" are independent complex white Gaussian noise processes resulting from the amplified spontaneous emission (ASE) of the optical amplifiers in the fiber optic medium. The one-sided power spectral density of the ASE produced by each optical amplifier in each polarization is given by

$$N_{ASE}=(G-1)n_{sp}h\nu \tag{C.3}$$

where "G" is the amplifier gain, "n_{sp}" is the excess spontaneous emission factor related to the amplifier noise figure, and "hv" is photon energy.

For the general case of a frequency dependent fiber transmission matrix T(ω), the outputs of polarization beam splitter **310** are given by

$$\begin{bmatrix} \varepsilon_{Sx}(t) \\ \varepsilon_{Sy}(t) \end{bmatrix} = \mathrm{Re}\left\{\begin{bmatrix} \hat{x} & 0 \\ 0 & \hat{y} \end{bmatrix}\left(F^{-1}\{V(\omega)\} * \begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix} + \begin{bmatrix} n_1(t) \\ n_2(t) \end{bmatrix}\right)\right\}, \tag{C.4}$$

or equivalently

$$\begin{bmatrix} \varepsilon_{Sx}(t) \\ \varepsilon_{Sy}(t) \end{bmatrix} = \mathrm{Re}\left\{\begin{bmatrix} \hat{x} & 0 \\ 0 & \hat{y} \end{bmatrix}\left(F^{-1}\{T(\omega)\} * U\begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix} + \begin{bmatrix} n_1(t) \\ n_2(t) \end{bmatrix}\right)\right\}, \tag{C.5}$$

where $F^{-1}\{\cdot\}$ denotes the inverse Fourier transform and * indicates the convolution operator.

1. Diagonalizer XPIC Signal Reconstruction

Provided that optical fiber transmission medium **235** is not perfectly polarizing, the fiber transmission matrix T(ω) is nonsingular and the inverse $T^{-1}(\omega)$ will exist. The form of XPIC **320** that will diagonalize the overall link transmission matrix (e.g., W(ω) V(ω)) and eliminate all cross polarization interference and dispersion effects has a transfer function matrix W(ω)) proportional to $V^{-1}(\omega)$ and is therefore represented by equation (C.6) as follows:

$$W(\omega) = \frac{\sqrt{P_S}}{P_T} U^H T^{-1}(\omega) = \begin{bmatrix} w_{11}(\omega) & w_{21}(\omega) \\ w_{12}(\omega) & w_{22}(\omega) \end{bmatrix} \tag{C.6}$$

where the superscript "H" denotes the conjugate transpose of that vector, "P_T" is the average transmitted optical power, and "P_S" is the average received optical power

$$P_T = \frac{1}{2}(\varepsilon_{Tx1}^2 + \varepsilon_{Ty1}^2 + \varepsilon_{Tx2}^2 + \varepsilon_{Ty2}^2) \tag{C.7}$$

$$P_S = \frac{1}{2}(\varepsilon_{Sx1}^2 + \varepsilon_{Sy1}^2 + \varepsilon_{Sx2}^2 + \varepsilon_{Sy2}^2). \tag{C.8}$$

In general, XPIC **320** is comprised of four independent optical filters **400**, **410**, **420**, and **430** as shown in FIG. **4**A. These filters have transfer functions that are specified by the frequency dependent complex elements $w_{11}(\omega)$, $w_{21}(\omega)$, $w_{12}(\omega)$, and $w_{22}(\omega)$ of the XPIC matrix W(ω). An exemplary implementation of a passband filter with complex frequency response is shown in FIG. **10**A where "$w_r(\omega)$ A refers to the real portion of the frequency response and "$w_i(\omega)$" refers to the imaginary portion of the frequency response. Since T(ω) is time varying, filters **400**, **410**, **420**, and **430** are adaptive in order to track this variation. Suitable implementations of adaptive optical filters **400**, **410**, **420** and **430** specified by the elements of equation (C.6) have been demonstrated. One example of a well-known adaptation procedure for these filters is the method of differential steepest descent. Other methods from the theory of blind source separation are also appropriate.

If XPIC **320** is configured according to equation (C.6), then inputs ($\underline{\varepsilon}_{S1}$ (t),$\underline{\varepsilon}_{S2}$(t)) **330** and **340** to receivers **350** and **360** are given by

$$\begin{bmatrix} \underline{\varepsilon}_{S1}(t) \\ \underline{\varepsilon}_{S2}(t) \end{bmatrix} = \mathrm{Re}\left\{\begin{bmatrix} \hat{x} & 0 \\ 0 & \hat{y} \end{bmatrix}\left(\sqrt{P_S}\begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix} + F^{-1}\{W(\omega)\} * \begin{bmatrix} n_1(t) \\ n_2(t) \end{bmatrix}\right)\right\} \tag{C.9}$$

or equivalently

$$\underline{\varepsilon}_{S1}(t)=Re\{(\sqrt{P_S}s_1(t)+n_3(t)\hat{x}\} \tag{C.10}$$

$$\underline{\varepsilon}_{S2}(t)=Re\{(\sqrt{P_S}s_2(t)+n_4(t)\hat{y}\} \tag{C.11}$$

where $n_3(t)$ and $n_4(t)$ are Gaussian distributed noise processes with power spectral density (psd) specified by $N_3(\omega)$ and $N_4(\omega)$

$$N_3(\omega)=|w_{11}(\omega)|^2N_1+|w_{12}(\omega)|^2N_2 \tag{C.12}$$

$$N_4(\omega)=|w_{21}(\omega)|^2N_1+|w_{22}(\omega)|^2N_2 \tag{C.13}$$

These results show that the electric field at each output of the optical diagonalizer XPIC **320** consists of a desired signal with additive noise. The diagonalizer XPIC therefore completely eliminates cross polarization interference (XPI), polarization mode dispersion (PMD), and chromatic dispersion effects.

The diagonalizer XPIC solution is particularly useful for analytic purposes since the bit error rate (BER) can be computed for a receiver with known noise performance. While in practice, XPIC **320** would normally be converged according to a minimum mean square error (MMSE) criterion, the BER performance with XPIC **320** configured according to the diagonalizer solution has been found to produce a tight upper bound to the BER performance with the MMSE solution as described in detail with respect to the intermediate frequency (IF) XPIC implementation.

Of course, it is contemplated that complex matrix coefficients w_{11}, w_{12}, w_{21} and w_{22} as shown in FIG. 4B may represent the XPIC matrix W without frequency dependence. These elements are complex in general, and apply both amplitude scaling and phase shifting to the input waveforms.

D. Optical XPIC With Coherent Systems

In general, for coherent systems implemented with an optical XPIC, a receiving device would split the received optical signal having an electric field $\underline{\varepsilon}_S(t)$ into two orthogonally polarized components $\underline{\varepsilon}_{Sy}(t)$ and $\underline{\varepsilon}_{Sy}(t)$. These components would be applied as inputs to an optical XPIC, which would perform complex filtering or weighting, and recombine the results to mitigate cross polarization interference (XPI). More specifically, each output of the XPIC is an optical signal with an electric field that is significantly amplitude and/or phase modulated by only one of the originally transmitted signals. These outputs are then applied to double balanced optical receivers (DBORs). Each DBOR produces a current $i_1(t)$ or $i_2(t)$, that has an IF carrier and contains significant modulation data from only one of the originally transmitted signals. These currents are demodulated to reconstruct the transmitted baseband in-phase and quadrature waveforms.

More specifically, with respect to FIG. **5**, optical XPIC **320** of a receiving device **450** operates in the same manner as discussed for FIG. **3**. In this case, however, coherent heterodyne receivers rather than IM-DD receivers are used, and the optical XPIC output fields ($\underline{\varepsilon}_{S1}(t)$) **330** and ($\underline{\varepsilon}_{S2}(t)$) **340** are routed to double balanced optical receivers (DBORs) **500** and **510**. A first DBOR **500** converts output $\underline{\varepsilon}_{S1}(t)$ **330** into a first output current $i_1(t)$ **520**, which is routed to a first demodulator **530**. A second DBOR **510** converts output $\underline{\varepsilon}_{S2}(t)$ **340** into a second output current $i_2(t)$ **540**, which is routed to a second demodulator **550**. If the axes of the LO polarization beam splitter are aligned with the $\hat{x}$ and $\hat{y}$ directions, and the polarization state of the optical LO is adjusted such that the LO power is equally divided by the polarization beam splitter, then the Jones vector specifying the LO polarization state is given by

$$\hat{\varepsilon}_L = \begin{bmatrix} \sqrt{P_L} \\ \sqrt{P_L}\, e^{j\delta_L} \end{bmatrix} \tag{D.1}$$

where P_L is the average LO power.

1. Diagonalizer XPIC Signal Reconstruction

If the optical XPIC is configured in accordance with equation (C.6), then the fields at the DBOR inputs will be given by equation (C.9). The DBOR output currents $i_1(t)$ and $i_2(t)$ are then given by

$$i_1(t)=R\sqrt{P_S P_L}\,a_1(t)\sin(\omega_{IF}t+\phi(t)+\theta_1(t))+n_3(t) \tag{D.2}$$

$$i_2(t)=R\sqrt{P_S P_L}\,a_2(t)\sin(\omega_{IF}t+\phi(t)+\theta_2(t)+\delta_L)+n_4(t) \tag{D.3}$$

where "R" is the responsivity of the photodiodes. The intermediate frequency (IF), denoted "ω_{IF}", is equal to the difference between the received carrier frequency and the frequency of the local oscillator ($\omega_{IF}=\omega_S-\omega_L$). Also, "$\phi(t)$" is the difference between the phase noise of the incoming optical signal and the phase noise of optical local oscillator ($\phi(t)=\phi_S(t)-\phi_L(t)$). The components $n_3(t)$ and $n_4(t)$ are noise terms that account for shot and thermal noise, and also ASE if optical amplifiers are present in the fiber optic transmission-medium. These results show that the output of each DBOR is a desired signal plus additive noise. When configured according to the diagonalizer solution, the optical XPIC is therefore able to completely eliminate cross polarization interference (XPI), polarization mode dispersion (PMD), and chromatic dispersion effects in systems with coherent optical receivers.

E. IF XPIC With Coherent Systems

In general, when implemented with an IF XPIC, the receiving device may be configured to split the received optical signal having an electric field $\underline{\varepsilon}_S(t)$ into two orthogonally polarized components $\underline{\varepsilon}_{Sy}(t)$ and $\underline{\varepsilon}_{Sy}(t)$, which are polarized in the $\hat{x}$ and $\hat{y}$ directions, respectively. The receiving device also includes a polarization beam splitter that produces $\hat{x}$ and $\hat{y}$ polarized components from an internal local oscillator. The $\hat{x}$ polarized components of the signal and LO are applied to one DBOR and the $\hat{y}$ polarized components are applied to another DBOR. Thus, the DBORs produce currents $i_1(t)$ and $i_2(t)$ containing modulation components from both originally transmitted signals. These currents are applied to an IF XPIC, which operates on the input currents to produce output currents $i_3(t)$ and $i_4(t)$. Each of these output currents has significant modulation from only one of the transmitted signals. The quadrature demodulators remove the carrier and phase-noise effects and produce the in-phase and quadrature waveforms associated with both transmitted signals.

Referring now to FIG. **6**, a block diagram of an illustrative embodiment of receiving device **600** operating in conjunction with an electrical intermediate frequency (IF) XPIC **670** is shown. IF XPIC **670** has the same form as optical XPIC **320** except that complex filters **400**, **410**, **420**, and **430** of FIG. **4A** are now electrical and operate at microwave frequencies rather than optical frequencies. As shown, receiving device **600** comprises optical receiver **605** including a pair of polarization beam splitters **610** and **615** to receive polarized optical signal fields. In particular, polarization beam splitter **610** receives an optical signal field **620** over optical fiber transmission medium **235**. This received optical signal field **620** ($\underline{\varepsilon}_S(t)$) is formed by the superposition of two modulated electric fields (identified as "$\underline{\varepsilon}_{S1}(t)$" and "$\underline{\varepsilon}_{S2}(t)$"). The electric fields $\underline{\varepsilon}_{S1}(t)$ and $\underline{\varepsilon}_{S2}(t)$ are representative of the first and second polarized signal fields, respectively. The polarization state of received electric field components $\underline{\varepsilon}_{S1}(t)$ and $\underline{\varepsilon}_{S2}(t)$ and the local oscillator $\underline{\varepsilon}_L(t)$ are specified by their respective Jones vector

$$\hat{\varepsilon}_{S1} = \begin{bmatrix} \varepsilon_{Sx1}\, e^{j\delta_{Sx1}} \\ \varepsilon_{Sy1}\, e^{j\delta_{Sy1}} \end{bmatrix} \tag{E.1}$$

$$\hat{\varepsilon}_{S2} = \begin{bmatrix} \varepsilon_{Sx2}\, e^{j\delta_{Sx2}} \\ \varepsilon_{Sy2}\, e^{j\delta_{Sy2}} \end{bmatrix}$$

$$\hat{\varepsilon}_L = \begin{bmatrix} \varepsilon_{Lx} \\ \varepsilon_{Ly}\, e^{j\delta_L} \end{bmatrix}$$

Though in general the Jones vectors for the received signal fields are frequency dependent as described by equation (B.4), for notational simplicity the frequency dependence of the field parameters will be suppressed in the analysis that follows. Also, polarization beam splitter **615** receives an optical control signal **625** from a local oscillator **630** employed within, or in close proximity to receiving device **600**. The received optical signal electric field (referred to as "$\underline{\varepsilon}_S(t)$") is defined by equation (E.2) and the electric field of the local oscillator **625** (referred to as "$\underline{\varepsilon}_L(t)$") is defined in equation (E.3).

$$\varepsilon_S(t) = [\varepsilon_{Sx1}a_1(t)\cos(\omega_S t + \phi_S(t) + \theta_1(t) + \delta_{Sx1}) + \varepsilon_{Sx2}a_2(t)\cos(\omega_S t + \phi_S(t) + \theta_2(t) + \delta_{Sx2})]\hat{x} + [\varepsilon_{Sy1}a_1(t)\cos(\omega_S t + \phi_S(t) + \theta_1(t) + \delta_{Sy1}) + \varepsilon_{Sy2}a_2(t)\cos(\omega_S t + \phi_S(t) + \theta_2(t) + \delta_{Sy2})]\hat{y} \quad \text{(E.2)}$$

$$\varepsilon_L(t) = [\varepsilon_{Lx}\cos(\omega_L t + \phi_L(t))]\hat{x} + [\varepsilon_{Ly}\cos(\omega_L t + \phi_L(t) + \delta_L)]\hat{y} \quad \text{(E.3)}$$

It is appreciated that the terms "ω_S" and "ω_L" denote the carrier frequency of optical signal **625** and the frequency of the local oscillator **630**; "$\theta_1(t)$" and "$\theta_2(t)$" denote the phase modulation of the independent first and second signals; "$a_1(t)$" and "$a_2(t)$" denote the amplitude modulation of the independent first and second signals, and "$\phi_S(t)$" and "$\phi_L(t)$" are Brownian motion or Wiener phase noise processes for the received optical carrier and the local oscillator respectively.

It is contemplated, but not required, that the first and second signals forming optical signal **620** modulate the same carrier. Also, it is desirable that the polarization of the signal components from local oscillator **630** be maintained such that $\epsilon_{Lx} \cong \epsilon_{Ly}$.

Polarization beam splitters **610** and **615** are used to separate the incoming optical field **620** and optical local oscillator field **625** into $\hat{x}$ and $\hat{y}$ (polarized) field components. Each of these field components is routed to different directional coupler; namely, the $\hat{x}$ components are routed to a directional coupler **640** of a first double balanced optical receiver (DBOR1) **635** and the $\hat{y}$ component is routed to a directional coupler **655** of a second double balanced optical receiver (DBOR2) **650**. As shown, each directional coupler **640** or **655** is a four port device that independently performs the following transformation on the $\hat{x}$ and $\hat{y}$ components

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{bmatrix} = \begin{bmatrix} \sqrt{1-\alpha} & \sqrt{\alpha}\, e^{j\frac{\pi}{2}} \\ \sqrt{\alpha}\, e^{j\frac{\pi}{2}} & \sqrt{1-\alpha} \end{bmatrix} \begin{bmatrix} \varepsilon_S \\ \varepsilon_L \end{bmatrix} \quad \text{(E.4)}$$

where "α" is the power coupling coefficient ranging from 0 to 1. Thus, the outputs of directional coupler **640** that receives the $\hat{x}$ components of the signal and LO electric fields are defined as follows:

$$\varepsilon_1(t) = \left[\sqrt{1-\alpha}\,(\varepsilon_{Sx1}a_1(t)\cos(\omega_S t + \phi_S(t) + \theta_1(t) + \delta_{Sx1}) + \varepsilon_{Sx2}a_2(t)\cos(\omega_S t + \phi_S(t) + \theta_2(t) + \delta_{Sx2})) - \sqrt{\alpha}\,\varepsilon_{Lx}\sin(\omega_L t + \phi_L(t))\right]\hat{x} \quad \text{(E.5)}$$

$$\varepsilon_2(t) = \left[-\sqrt{\alpha}\,(\varepsilon_{Sx1}a_1(t)\sin(\omega_S t + \phi_S(t) + \theta_1(t) + \delta_{Sx1}) + \varepsilon_{Sx2}a_2(t)\sin(\omega_S t + \phi_S(t) + \theta_2(t) + \delta_{Sx2})) + \sqrt{1-\alpha}\,\varepsilon_{Lx}\cos(\omega_L t + \phi_L(t))\right]\hat{x} \quad \text{(E.6)}$$

As further shown in FIG. **6**, each of the photodetector diodes **645** and **660** respond with a current proportional to the incident instantaneous optical power $|\varepsilon(t)|^2$. High frequency components are neglected when outside the bandwidth of diodes **645** and **660**. Expressions for the optical power at the two photodiodes **645** and **660** are set forth in equations (E.7, E.8).

$$|\varepsilon_1(t)|^2 = \left(\frac{1-\alpha}{2}\right)\varepsilon_{Sx1}^2 a_1^2(t) + \left(\frac{1-\alpha}{2}\right)\varepsilon_{Sx2}^2 a_2^2(t) + \left(\frac{\alpha}{2}\right)\varepsilon_{Lx}^2 + (1-\alpha)\varepsilon_{Sx1}\varepsilon_{Sx2}a_1(t)a_2(t)\cos(\theta_1(t) - \theta_2(t) + \delta_{Sx1} - \delta_{Sx2}) + \sqrt{(1-\alpha)\alpha}\,\varepsilon_{Sx1}\varepsilon_{Lx}a_1(t)\sin(\omega_{IF}t + \phi(t) + \theta_1(t) + \delta_{Sx1}) + \sqrt{(1-\alpha)\alpha}\,\varepsilon_{Sx2}\varepsilon_{Lx}a_2(t)\sin(\omega_{IF}t + \phi(t) + \theta_2(t) + \delta_{Sx2}) \quad \text{(E.7)}$$

$$|\varepsilon_2(t)|^2 = \left(\frac{\alpha}{2}\right)\varepsilon_{Sx1}^2 a_1^2(t) + \left(\frac{\alpha}{2}\right)\varepsilon_{Sx2}^2 a_2^2(t) + \left(\frac{1-\alpha}{2}\right)\varepsilon_{Lx}^2 + (\alpha)\varepsilon_{Sx1}\varepsilon_{Sx2}a_1(t)a_2(t)\cos\theta_1(t) - \theta_2(t) + \delta_{Sx1} - \delta_{Sx2}) - \sqrt{(1-\alpha)\alpha}\,\varepsilon_{Sx1}\varepsilon_{Lx}a_1(t)\sin(\omega_{IF}t + \phi(t) + \theta_1(t) + \delta_{Sx1}) - \sqrt{(1-\alpha)\alpha}\,\varepsilon_{Sx2}\varepsilon_{Lx}a_2(t)\sin(\omega_{IF}t + \phi(t) + \theta_2(t) + \delta_{Sx2}) \quad \text{(E.8)}$$

The intermediate frequency (IF) is denoted as "ω_{IF}" and is the difference between the received carrier frequency and the frequency of the local oscillator ($\omega_{IF}=\omega_S-\omega_L$). Also, "$\phi(t)$" is the difference between the phase noise of incoming optical signal **620** and the phase noise of optical local oscillator **625** ($\phi(t)=\phi_S(t)-\phi_L(t)$).

For DBOR1 **635**, the output current ($i_1(t)$) is computed in accordance to equation (E.9).

$$i_1(t) = R(|\varepsilon_1(t)|^2 - |\varepsilon_2(t)|^2) + n_1(t) \quad \text{(E.9)}$$

The term "R" is equal to the responsivity of photodiodes **645** and **660**. The component "$n_1(t)$" accounts for the shot and thermal noise and is a white Gaussian noise process with power spectral density (psd) specified by

$$N_1 = eR\varepsilon_{Lx}^2 + \frac{4kTF}{R_L}, \quad \text{(E.10)}$$

where "e" is the electronic charge (1.602×10^{-19} C), "k" is the Boltzmann constant (1.38×10^{-23} J/° K.), "T" is the absolute temperature (° K.), "F" is the noise factor of the amplifier following the photodiodes of DBOR1 **635**, and "R_L" is the equivalent load resistance seen by DBOR1 **635**. For example, using a selected power coupling coefficient (e.g., $\alpha=½$), the output of DBOR1 **635** is the following:

$$i_1(t) = R[\epsilon_{Sx1}\epsilon_{Lx}a_1(t)\sin(\omega_{IF}t30\ \phi(t) + \theta_1(t) + \delta_{Sx1}) + \epsilon_{Sx2}\epsilon_{Lx}a_2(t)\sin(\omega_{IF}t + \phi(t) + \theta_2(t) + \delta_{Sx2})] + n_1(t) \quad \text{(E.11)}$$

Similarly, the output ($i_2(t)$) of DBOR2 **650** that receives the $\hat{y}$ polarized signal and LO components is computed as

$$i_2(t) = R[\epsilon_{Sy1}\epsilon_{Ly}a_1(t)\sin(\omega_{IF}t + \phi(t) + \theta_1(t) + \delta_{Sy1} - \delta_L) + \epsilon_{Sy2}\epsilon_{Ly}a_2(t)\sin(\omega_{IF}t + \phi(t) + \theta_2(t) + \delta_{Sy2} - \delta_L)] + n_2(t) \quad \text{(E.12)}$$

where the power spectral density of the noise current for this channel is given by

$$N_2 = eR\varepsilon_{Ly}^2 + \frac{4kTF}{R_L} \quad \text{(E.13)}$$

If optical amplifiers are present in the fiber optic transmission medium, then an appropriate ASE component should be added to equations (E.10) and (E.13). Thus, the outputs ($i_1(t)$, $i_2(t)$) of DBORs **635** and **650** can be expressed in matrix form.

$$\begin{bmatrix} i_1(t) \\ i_2(t) \end{bmatrix} = \mathrm{Re}\left\{ R \begin{bmatrix} \varepsilon_{Sx1}\varepsilon_{Lx} e^{j(\delta_{Sx1}-\frac{\pi}{2})} & \varepsilon_{Sx2}\varepsilon_{Lx} e^{j(\delta_{Sy2}-\frac{\pi}{2})} \\ \varepsilon_{Sy1}\varepsilon_{Ly} e^{j(\delta_{Sy1}-\delta_L-\frac{\pi}{2})} & \varepsilon_{Sy2}\varepsilon_{Ly} e^{j(\delta_{Sy2}-\delta_L-\frac{\pi}{2})} \end{bmatrix} \begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix} + \begin{bmatrix} n_1(t) \\ n_2(t) \end{bmatrix} \right\}, \quad \text{(E.14)}$$

which has the form

$$\begin{bmatrix} i_1(t) \\ i_2(t) \end{bmatrix} = \mathrm{Re}\left\{ X \begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix} + \begin{bmatrix} n_1(t) \\ n_2(t) \end{bmatrix} \right\} \quad \text{(E.15)}$$

where

$$s_1(t)=v_1(t)e^{j(\omega_{IF}t+\phi(t)} \quad \text{(E.16)}$$

is the complex form of the first IF signal,

$$s_2(t)=v_2(t)e^{j(\omega_{IF}t+\phi(t)} \quad \text{(E.17)}$$

is the complex form of the second IF signal, and

$$v_k(t)=a_k(t)e^{j\theta_k(t)}=I_k(t)+jQ_k(t) \quad \text{(E.18)}$$

is the complex envelope representation of the information bearing signal component.

The 2×2 complex matrix X in equation (E.15) represents the cross polarization interference (XPI) of the two received signals as set forth in equation (E.19).

$$X = R \begin{bmatrix} \varepsilon_{Sx1}\varepsilon_{Lx} e^{j(\delta_{Sx1}-\frac{\pi}{2})} & \varepsilon_{Sx2}\varepsilon_{Lx} e^{j(\delta_{Sx2}-\frac{\pi}{2})} \\ \varepsilon_{Sy1}\varepsilon_{Ly} e^{j(\delta_{Sy1}-\delta_L-\frac{\pi}{2})} & \varepsilon_{Sy2}\varepsilon_{Ly} e^{j(\delta_{Sy2}-\delta_L-\frac{\pi}{2})} \end{bmatrix} \quad \text{(E.19)}$$

When the polarization states of the received optical fields are frequency dependent due to the effects of the fiber optic transmission medium, then the form of the frequency dependent XPI matrix X(ω) is

$$X(\omega) = R \begin{bmatrix} \varepsilon_{Sx1}(\omega)\varepsilon_{Lx} e^{j(\delta_{Sx1}(\omega)-\frac{\pi}{2})} & \varepsilon_{Sx2}(\omega)\varepsilon_{Lx} e^{j(\delta_{Sx2}(\omega)-\frac{\pi}{2})} \\ \varepsilon_{Sy1}(\omega)\varepsilon_{Ly} e^{j(\delta_{Sy1}(\omega)-\delta_L-\frac{\pi}{2})} & \varepsilon_{Sy2}(\omega)\varepsilon_{Ly} e^{j(\delta_{Sy2}(\omega)-\delta_L-\frac{\pi}{2})} \end{bmatrix} \quad \text{(E.20)}$$

with the frequency response of the optical signal field polarization parameters now translated to the IF range by the downconversion process of DBORs **635** and **650**. The form of equation (E.15) in this case is

$$\begin{bmatrix} i_1(t) \\ i_2(t) \end{bmatrix} = \mathrm{Re}\left\{ F^{-1}\{X(\omega)\} * \begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix} + \begin{bmatrix} n_1(t) \\ n_2(t) \end{bmatrix} \right\} \quad \text{(E.21)}$$

Thus, the output from XPIC **670** can be expressed in matrix form as follows:

$$\begin{bmatrix} i_3(t) \\ i_4(t) \end{bmatrix} = \mathrm{Re}\left\{ F^{-1}\{W(\omega)\{X(\omega)\} * \begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix} + \begin{bmatrix} n_3(t) \\ n_4(t) \end{bmatrix} \right\}, \quad \text{(E.22)}$$

where "W(ω)" represents the frequency dependent 2×2 complex XPIC matrix and $n_3(t)$ and $n_4(t)$ are Gaussian processes with one-sided power spectral densities as defined by "N_3" and N_4"

$$N_3(\omega)=|w_{11}(\omega)|^2N_1+|w_{12}(\omega)|^2N_2 \quad \text{(E.23)}$$

$$N_4(\omega)=|w_{21}(\omega)|^2N_1+|w_{22}(\omega)|^2N_2. \quad \text{(E.24)}$$

The input noise power spectral densities "N_1" and "N_2" are specified by equations (E.10) and (E.13) and "$w_{mn}(\omega)$" (m=1,2; n=1,2) are the corresponding elements of the complex XPIC matrix W(ω). Equations (E.23) and (E.24) are easily verified by anyone with knowledge of linear system theory.

In order to completely cancel cross polarization interference (XPI) and fiber dispersion effects, it is contemplated that the XPIC transfer function matrix W(ω) should be configured in order to force the cross polarization interference to zero.

1. Diagonalizer XPIC Signal Reconstruction

Referring back to FIG. **6**, one method of achieving interference cancellation is to determine the form of the XPIC matrix W(ω) that forces the cross polarization interference to zero, which is equivalent to diagonalizing the overall link transmission matrix W(ω)X(ω) (referred to as "zero-forcing cancellation"). Provided that the XPI matrix X(ω) is invertible then the form of the diagonalizer XPIC matrix is

$$W(\omega)_{diag} = X(\omega)^{-1} = K(\omega) \begin{bmatrix} \frac{\varepsilon_{Sy2}(\omega)}{\varepsilon_{Lx}} e^{j(\delta_{Sy2}(\omega)-\delta_L)} & -\frac{\varepsilon_{Sx2}(\omega)}{\varepsilon_{Ly}} e^{j\delta_{Sx2}(\omega)} \\ -\frac{\varepsilon_{Sy1}(\omega)}{\varepsilon_{Lx}} e^{j(\delta_{Sy1}(\omega)-\delta_L)} & \frac{\varepsilon_{Sx1}(\omega)}{\varepsilon_{Ly}} e^{j\delta_{Sx1}(\omega)} \end{bmatrix} \quad \text{(E.25)}$$

where the complex scaler K(ω) is given by

$$K(\omega) = \frac{e^{j\frac{\pi}{2}}}{R\left(\varepsilon_{Sx1}(\omega)\varepsilon_{Sy2}(\omega)e^{j(\delta_{Sx1}(\omega)+\delta_{Sy2}(\omega)-\delta_L)} - \varepsilon_{Sx2}(\omega)\varepsilon_{Sy1}(\omega)e^{j(\delta_{Sx2}(\omega)+\delta_{Sy1}(\omega)-\delta_L)}\right)} \quad \text{(E.26)}$$

Equations (E.25) and (E.26) are easily verified by anyone with knowledge of linear algebra. If XPIC **670** is configured according to the matrix $W(\omega)_{diag}$, then the desired signals will be identically reconstructed and the input to demodulators **675** and **680** will be the following:

$$\begin{bmatrix} i_3(t) \\ i_4(t) \end{bmatrix} = \mathrm{Re}\left\{ \begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix} + \begin{bmatrix} n_3(t) \\ n_4(t) \end{bmatrix} \right\} \quad \text{(E.27)}$$

or equivalently

$$i_3(t)=a_1(t)\cos(\omega_{IF}t+\phi(t)+\theta_1(t))+n_3(t) \quad \text{(E.28)}$$

$$i_4(t)=a_2(t)\cos(\omega_{IF}t+\phi(t)+\theta_2(t))+n_4(t) \quad \text{(E.29)}$$

where "$n_3(t)$" and "$n_4(t)$" are Gaussian noise processes with psd specified by equations (E.23) and (E.24) respectively.

From equations (E.28) and (E.29), it is evident that the transmitted signals can be recovered at the receiving device provided that the XPI matrix of equation (E.25) is invertible. This requirement will be met unless the optical fiber transmission medium is perfectly polarizing and the received signals therefore have identical polarization states or states that differ only in magnitude. That is, if

$$\frac{\varepsilon_{Sx2}(\omega)}{\varepsilon_{Sy2}(\omega)} e^{j(\delta_{sx2}(\omega)-\delta_{sy2}(\omega))} = \frac{\varepsilon_{Sx1}(\omega)}{\varepsilon_{Sy1}(\omega)} e^{j(\delta_{sx1}(\omega)-\delta_{sy1}(\omega))} \quad \text{(E.30)}$$

then the XPI matrix is singular and the zero-forcing solution does not exist. Fortunately it has been shown theoretically

and experimentally that when optical signals with orthogonal polarizations are launched into a long fiber, orthogonality is substantially preserved. Measurements made for 150 kilometers of standard, single mode optical fiber indicate a loss in orthogonality of less than 6 degrees.

To serve as an example of the expected XPIC link performance, the bit-error rate (BER) of the diagonalizer XPIC receiver for binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK) modulation and an XPI matrix with no frequency dependence will be evaluated. The well-known expression for the probability of bit error or bit error rate for BPSK with ideal carrier phase recovery and detection is

$$P_E = \frac{1}{2}erfc\left(\sqrt{\frac{E_s}{N_0}}\right) \tag{E.31}$$

where E_s and N_0 are the symbol energy and AWGN one-sided psd at the demodulator input, respectively. In order to characterize the XPIC receiver this relation must be modified to account for the effect of the XPIC network on the signals and AWGN. Since the diagonalizer XPIC identically reconstructs the transmitted signals at the demodulator inputs, the expression for E_s is given by

$$E_S = E\left\{\frac{1}{2}\int_0^{T_s} |v(t)|^2\, dt\right\} \tag{E.32}$$

where $E\{\cdot\}$ represents the expectation operator. If the average symbol energy E_{sk} for polarization channel k is defined as the total average energy per symbol at the both XPIC inputs due to signal $s_k(t)$

$$E_{s1} = (|x_{11}|^2 + |x_{21}|^2)E\left\{\frac{1}{2}\int_0^{T_s} |v_1(t)|^2\, dt\right\} \tag{E.33}$$

$$E_{s2'} = (|x_{12}|^2 + |x_{22}|^2)E\left\{\frac{1}{2}\int_0^{T_s} |v_2(t)|^2\, dt\right\} \tag{E.34}$$

then the expression for the bit error rate for the first polarization channel of an XPIC receiver is

$$P_E = \frac{1}{2}erfc\left(a_1\sqrt{\frac{E_{s1}}{N_3}}\right) \tag{E.35}$$

where N_3 is the psd at the XPIC output specified by equation (E.23) and the parameter a_1 is given by

$$a_1 = \frac{1}{\sqrt{|x_{11}|^2 + |x_{21}|^2}} \tag{E.36}$$

Each BPSK symbol carries one bit of information and the symbol energy E_s is therefore equal the bit energy E_b. It should be noted that for the diagonalizer XPIC system using QPSK with ideal quadrature demodulation there is no interaction between the in-phase and quadrature components and by simply replacing the symbol energy E_{s1} with bit energy E_b, equation (E.35) specifies the bit error rate for both BPSK and QPSK. In addition, if $\epsilon_{Lx}=\epsilon_{Ly}$ then from equations (E.10) and (E.13) $N_1=N_2$. Substituting E_b for E_{s1} and using equation (E.23) with a single noise psd parameter N_0 for both N_1 and N_2, equation (E.35) becomes

$$P_E = \frac{1}{2}erfc\left(\frac{a_1}{\sqrt{|w_{11}|^2 + |w_{12}|^2}}\sqrt{\frac{E_b}{N_0}}\right) \tag{E.37}$$

Equation (E.37) is plotted in FIG. 7 for varying amounts of loss of orthogonality (dashed) along with monte-carlo simulation results (solid). Curves are shown for received optical signals having 0, 10, 20, 30, and 40 degrees loss of orthogonality. The plots show that the BER performance with the diagonalizer XPIC is equal to that of the optimum receiver when the received signals are orthogonally polarized and the degradation from ideal performance is negligible when the loss of orthogonality is less than ten degrees. The XPIC receiver is therefore able to double the link bandwidth efficiency with almost no degradation in BER performance relative the conventional optimum receiver.

2. MMSE XPIC Signal Reconstruction

The diagonalizer solution completely eliminates XPI, but at the expense of a degraded signal-to-noise ratio (SNR) when the components forming the received optical electric field **620** of FIG. **6** are non-orthogonal. Another solution that would produce a compromise between interference cancellation and SNR reduction is the minimum mean square error (MMSE) XPIC solution. The analysis of the MMSE XPIC solution is complicated by the fact that it is dependent on implementation issues such as the demodulator architecture and IF carrier frequencies and symbol rates of the two received signals.

To facilitate analysis of the MMSE XPIC solution, a number of conditions are assumed. First, the XPI matrix X is assumed to have no frequency dependence over the IF bandwidth of interest. Second, receiving device **600** uses ideal quadrature demodulators that are able to track the phase noise of the desired signal in each channel. Third, the received signals are assumed to be mean zero and independent with stationary distribution, and the noise of each channel is assumed to be independent stationary additive white Gaussian noise (AWGN). Finally, the IF carrier frequencies and symbol rates are identical for both channels and the symbols are time aligned. The last assumption corresponds to a worst case XPI scenario and results in an upper bound to the system bit error rate (BER) performance. Under these conditions the MMSE solution can be determined.

In the most general system where separate lasers are used for the orthogonal components at either transmitting device **210** or receiving device **600**, the phase noise on each channel will be different. In this case, ideal carrier phase recovery removes the phase fluctuations from the desired signals in each channel and creates additional phase noise in the interference signal. The mean square error caused by the interference signal in a quadrature demodulator depends only on the magnitude of the interference and is independent of the phase. Consequently, the optimum MMSE XPIC solution for a receiving device with ideal carrier phase recover is independent of phase noise, and the system model used to derive the form of the network need not include phase noise or phase recovery effects.

For the purpose of deriving the MMSE XPIC solution, the complex decision variable vector representing the outputs of two ideal quadrature demodulators and detectors at sample time nT_s can therefore be represented as

$$z(n) = \frac{1}{2}\int_{(n-1)T_s}^{nT_s} u(t-(n-1)T_s)W(X\underline{v}(t)+\underline{n}(t))\,dt \quad \text{(E.38)}$$

where "u(t)" is the signal pulse shape, "X" is the XPI matrix of equation (E.19), "W" is the XPIC matrix, "$\underline{v}(t)$" is a vector representing the signal complex envelopes $v_1(t)$ and $v_2(t)$, and "$\underline{n}(t)$" is an AWGN noise vector with components $n_1(t)$ and $n_2(t)$. That is, the IF carrier frequency is removed in the ideal quadrature demodulation process and the resulting baseband in-phase and quadrature signals are processed with ideal correlation detection. Any residual phase noise following the ideal quadrature demodulation process can be neglected for the reasons previously stated. The power spectral densities of $n_1(t)$ and $n_2(t)$ are given by equations (E.10) and (E.13) respectively. For notational simplicity, equation (E.38) will be written as

$$\underline{z}(n)=W<X\,\underline{v}(t)+\underline{n}(t)> \quad \text{(E.39)}$$

where "< >" represents the ideal demodulation and detection operator as previously described. The MMSE value for the XPIC matrix W_{mmse} is equal to $[R^{-1}P]^H$, where "R" is the correlation matrix of the decision variables without XPIC (see equation E.40) and "P" is the cross correlation between the decision variable vector without XPIC and the desired decision variable vector $\underline{d}$ (see equation E.41) as described below.

$$R=E\{<X\underline{v}(t)+\underline{n}(t)><X\underline{v}(t)+\underline{n}(t)>^H\} \quad \text{(E.40)}$$

$$P=E\{<X\underline{v}(t)+\underline{n}(t)>\underline{d}^H\}. \quad \text{(E.41)}$$

If the noise is mean zero and independent of the signals, then the correlation matrix R and the cross correlation matrix P can be expressed as the following:

$$R=XR_sX^H+R_n \quad \text{(E.42)}$$

$$P=XP_{sd} \quad \text{(E.43)}$$

where "R_s" and "R_n" are the correlation matrices of the signal and AWGN components of the decision variables respectively and P_{sd} is the cross correlation between the signal components of the decision variable and the desired decision variables

$$R_s=E\{<\underline{v}(t)><\underline{v}(t)>^H\} \quad \text{(E.44)}$$

$$R_n=E\{<\underline{n}(t)><\underline{n}(t)>^H\} \quad \text{(E.45)}$$

$$P_{sd}=E\{<\underline{v}(t)\underline{d}^H>\}. \quad \text{(E.46)}$$

The desired decision variable vector $\underline{d}=<\underline{v}(t)>$ is simply the response of the ideal detector to the signals without XPI or XPIC. That is, the response of the ideal receiver to the transmitted signals without distortion or polarization misalignment effects.

For wide-sense stationary, mean zero, independent signal and noise components the correlation and cross correlation matrices are

$$R_s = P_{sd} = \begin{bmatrix} \sigma_{s1}^2 & 0 \\ 0 & \sigma_{s2}^2 \end{bmatrix} \quad \text{(E.47)}$$

-continued

$$R_n = \begin{bmatrix} \sigma_{n1}^2 & 0 \\ 0 & \sigma_{n2}^2 \end{bmatrix}, \quad \text{(E.48)}$$

where "σ_{si}^2" and "σ_{ni}^2" are the variances of the decision variable component due to the desired signal and AWGN respectively without XPI or XPIC. For ideal quadrature demodulation and detection of linear modulation formats such as PSK with non-return to zero (NRZ) pulse shape and QAM these variances are given by

$$\sigma_{sk}^2 = \varepsilon E\left\{\frac{1}{2}\int_0^{T_s}|v_k(t)|^2\,dt\right\}\ k=1,2 \quad \text{(E.49)}$$

$$\sigma_{nk}^2 = \varepsilon N_k\ \ k=1,2 \quad \text{(E.50)}$$

where "$v_k(t)$" is the complex envelope of the information-bearing signal component, N_k are the AWGN power spectral densities given by equations (E.10) and (E.13), and "ϵ" is the energy of the spectrum shaping pulse given by

$$\varepsilon = \frac{1}{2}\int_0^{T_s} u^2(t)\,dt. \quad \text{(E.51)}$$

Using equations (E.40–E.43), and the fact that $P_{sd}=R_s$, the MMSE XPIC matrix is specified by

$$W_{mmse} = \left[\left[X^H + [R_n^{-1}XR_s]^{-1}\right]^{-1}\right]^H \quad \text{(E.52)}$$

Using equations (E.47) and (E.48), the signal and noise dependent term is

$$R_n^{-1}XR_s = \begin{bmatrix} \frac{\sigma_{s1}^2}{\sigma_{n1}^2}x_{11} & \frac{\sigma_{s2}^2}{\sigma_{n1}^2}x_{12} \\ \frac{\sigma_{s1}^2}{\sigma_{n2}^2}x_{21} & \frac{\sigma_{s2}^2}{\sigma_{n2}^2}x_{22} \end{bmatrix} \quad \text{(E.53)}$$

If the average symbol energy "E_{sk}" is defined as the total average energy per symbol at both inputs to the XPIC **670** due to signal $s_k(t)$

$$E_{s1} = (|x_{11}|^2+|x_{21}|^2)E\left\{\frac{1}{2}\int_0^{T_s}|v_1(t)|^2\,dt\right\} \quad \text{(E.54)}$$

$$E_{s2} = (|x_{12}|^2+|x_{22}|^2)E\left\{\frac{1}{2}\int_0^{T_s}|v_2(t)|^2\,dt\right\} \quad \text{(E.55)}$$

then from equation (E.49) the variances of the decision variable component due to the signals are the following:

$$\sigma_{s1}^2 = \frac{\varepsilon E_{s1}}{|x_{11}|^2+|x_{21}|^2} \quad \text{(E.56)}$$

$$\sigma_{s2}^2 = \frac{\varepsilon E_{s2}}{|x_{12}|^2+|x_{22}|^2} \quad \text{(E.57)}$$

Substituting (E.50), (E.56), and (E.57) into equation (E.53)

$$R_n^{-1}XR_s=\begin{bmatrix}\frac{E_{s1}}{N_1}\frac{x_{11}}{|x_{11}|^2+|x_{21}|^2} & \frac{E_{s2}}{N_1}\frac{x_{12}}{|x_{12}|^2+|x_{22}|^2}\\ \frac{E_{s1}}{N_1}\frac{x_{21}}{|x_{11}|^2+|x_{21}|^2} & \frac{E_{s2}}{N_2}\frac{x_{12}}{|x_{12}|^2+|x_{22}|^2}\end{bmatrix} \quad (E.58)$$

This result along with equation (E.52) shows the explicit dependence of the MMSE XPIC solution on the XPI matrix X and the SNR at input of XPIC **670** of FIG. **6**. Equation (E.52) reduces the diagonalizer solution in the limit of large SNR in agreement with intuition. For orthogonally polarized and equal power received signals, and for LO power equally divided between the $\hat{x}$ and $\hat{y}$ polarized field components, the MMSE XPIC is also a diagonalizer at any SNR.

To serve as an example of the expected link performance with an MMSE XPIC, the bit error rate for BPSK modulation and an XPI matrix with no frequency dependence will be evaluated. It was previously pointed out that the MMSE solution for the XPIC is independent of phase noise and phase recovery effects. This is not the case in general for the bit error rate, and phase noise effects must be accounted for in the analysis. The expression for the decision variables including ideal phase recovery is

$$z(n)=\frac{1}{2}\int_{(n-1)T_s}^{nT_s}u(t-(n-1)T_s)DW[Xs(t)+\underline{n}(t)]\,dt \quad (E.59)$$

where the vector "$\underline{s}(t)$" is the IF signal vector with components specified by equations (E.16) and (E.17) and "D" is a matrix representing the ideal demodulation process

$$D=\begin{bmatrix}e^{-j(\omega_{IF}t+\phi(t))} & 0\\ 0 & e^{-j(\omega_{IF}t+\phi(t))}\end{bmatrix} \quad (E.60)$$

This form of the demodulation matrix assumes that single lasers are split to generate the orthogonal optical carriers in the transmitter and the optical LO components in the receiver. In this case the IF phase noise on each channel will be identical and is removed in the demodulation process. Assuming a rectangular pulse shape u(t), the component of the decision variable vector corresponding to channel **1** at sample time n=1 is given by

$$z_1=c_{11}\epsilon(I_1+jQ_1)+c_{12}\epsilon(I_2+jQ_2)+N \quad (E.61)$$

where "I_k+jQ_k" are the data symbols of signal "$s_k(t)$" during the first symbol interval and where "c_{11} and c_{12}" are elements of the overall link transmission matrix specified by

$$C=WX. \quad (E.62)$$

The component N is a complex Gaussian distributed random variable with variance

$$\sigma_N^2=\epsilon N_3 \quad (E.63)$$

where "N_3" is the psd at XPIC output specified by equation (E.23). For BPSK $Q_1(n)=Q_2(n)=0$ and the demodulator extracts the real component of the complex decision variable. When the XPIC is configured according to the MMSE solution the diagonal elements of the link transmission matrix C are real but the off-diagonal elements can be complex. The real portion of equation (E.61) can therefore be expressed as the sum of two independent random variables

$$Re\{z_1\}=x+y \quad (E.64)$$

where "x" accounts for the desired signal and the AWGN

$$x=c_{11}\epsilon I_1+Re\{N\} \quad (E.65)$$

and "y" accounts for the effects of the XPI

$$y=\epsilon I_2 Re\{c_{12}\}. \quad (E.66)$$

The probability density function of the decision variable component specified by equation (E.65) is

$$f_x(x)=\frac{1}{\pi\sigma_N}e^{-\frac{1}{2}\left(\frac{x-\mu}{\frac{\sigma_N}{2}}\right)^2} \quad (E.67)$$

where "μ" is the decision variable component due to the desired signal. For I_1 in the 'mark' state the value of μ is

$$\mu=\frac{c_{11}\sqrt{\varepsilon E_{s1}}}{\sqrt{|x_{11}|^2+|x_{21}|^2}} \quad (E.68)$$

where "E_{s1}" is the total symbol energy at the XPIC network input in both channels due to signal $s_1(t)$. The pdf of the XPI decision variable component specified by equation (E.66) assuming equi-probable symbols is

$$f_Y(y)=\frac{1}{2}[\delta(y-\eta_1)+\delta(y+\eta_1)] \quad (E.69)$$

where "$\delta(\cdot)$" represents the Dirac delta function and the parameter "η_1" is given by

$$\eta_1=\frac{\mathrm{Re}\{c_{12}\}\sqrt{\varepsilon E_{s2}}}{\sqrt{|x_{12}|^2+|x_{22}|^2}}. \quad (E.70)$$

From equation (E.64) the pdf of the real component of the decision variable z_1 is the convolution of $f_x(x)$ and $f_y(y)$

$$f_{z_r}(z)=\int_{-\infty}^{\infty}f_X(z-y)f_Y(y)dy \quad (E.71)$$

and the probability of symbol error or bit error rate for I_1 in the 'mark' state is given by

$$P_E=\int_{-\infty}^{0}f_{z_r}(z)dz \quad (E.72)$$

Evaluating equation (E.72), the probability of error is

$$P_E=\frac{1}{4}\left[erfc\left(a_1c_{11}\sqrt{\frac{E_{s1}}{N_3}}+a_2\mathrm{Re}\{c_{12}\}\sqrt{\frac{E_{s2}}{N_3}}\right)+erfc\left(a_1c_{11}\sqrt{\frac{E_{s1}}{N_3}}-a_2\mathrm{Re}\{c_{12}\}\sqrt{\frac{E_{s2}}{N_3}}\right)\right] \quad (E.73)$$

where "N_3" is given by equation (E.23), the parameter "a_1" is given by equation (E.36), and parameter "a_2" is

$$a_2 = \frac{1}{\sqrt{|x_{12}|^2 + |x_{22}|^2}}. \quad \text{(E.74)}$$

Although this result was derived for a transmitted 'mark' state it is also valid for a 'space' state due to the symmetry of the BPSK constellation. Equation (E.73) reduces to the expression obtained for the BER of the diagonalizer XPIC when C=I. Substituting E_b for E_{s1} and E_{s2} and using equation (E.23) with a single noise psd parameter N_0 for both N_1 and N_2, equation (E.73) becomes

$$P_E = \frac{1}{4}\left[erfc\left(\frac{a_1 c_{11} + a_2 \mathrm{Re}\{c_{12}\}}{\sqrt{|w_{11}|^2 + |w_{12}|^2}}\sqrt{\frac{E_b}{N_0}}\right) + erfc\left(\frac{a_1 c_{11} + a_2 \mathrm{Re}\{c_{12}\}}{\sqrt{|w_{11}|^2 + |w_{12}|^2}}\sqrt{\frac{E_b}{N_0}}\right)\right] \quad \text{(E.75)}$$

FIG. **8** shows plots of equation (E.75) with varying amounts of loss of orthogonality (dashed) along with monte-carlo simulation results (solid). The simulations were performed using a 128 length pseudo-random number (PN) sequence with a four symbol offset between the dual polarized bit streams. A Weiner process phase noise model was used and the resulting full width at half maximum (FWHM) line width was 2 percent of the symbol frequency. Curves are shown for received optical signals having 0, 10, 20, 30, and 40 degrees loss of orthogonality. The plots show that, like the diagonalizer XPIC, the BER performance with the MMSE XPIC is equal to that of the optimum receiver when the received signals are orthogonally polarized and the degradation from ideal performance is negligible when the loss of orthogonality is less than ten degrees. The MMSE XPIC receiver is therefore able to double the link bandwidth efficiency with almost no degradation in BER performance relative the conventional optimum receiver. Comparing the BER performance of the diagonalizer XPIC receiver shown in FIG. **7** to that of the MMSE XPIC receiver shown in FIG. **8** demonstrates that their performance is very similar, but the MMSE solution is slightly superior to the diagonalizer solution in general.

As described above, it is contemplated that frequency independent diagonalizer and MMSE XPIC solutions require that IF XPIC **670** consists of four (4) complex elements. These solutions are not unique since any practical demodulator is insensitive to a fixed or slowly varying carrier phase angle. The operations of XPIC **670** can be simplified and a unique solution obtained by factoring out the phase angle terms of the diagonal elements such that the XPIC network consists of two real elements and two complex elements. For example, referring to equation (E.25) through (E.27), if the XPIC matrix W is configured according to

$$W = \begin{bmatrix} |w_{11}| & w_{12}e^{-j\psi_2} \\ w_{21}e^{-j\psi_1} & |w_{22}| \end{bmatrix} \quad \text{(E.76)}$$

then the input to demodulators **675** and **680** specified by equation (E.27) becomes

$$\begin{bmatrix} i_3(t) \\ i_4(t) \end{bmatrix} = \mathrm{Re}\left\{\begin{bmatrix} e^{-j\psi_1} & 0 \\ 0 & e^{-j\psi_2} \end{bmatrix}\left[\begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix} + \begin{bmatrix} n_3(t) \\ n_4(t) \end{bmatrix}\right]\right\} \quad \text{(E.77)}$$

where ψ_1 and ψ_2 are the angles of w_{11} *and* w_{22} respectively. These phase terms have no effect on the noise statistics and can be considered constant as long as the signal polarization variation and consequently the XPIC variation is slow relative to the demodulator phase tracking capability. This requirement is easily met in practice and the implementation using purely real diagonal elements therefore has identical performance to the XPIC with four complex elements.

F. Baseband XPIC Receiver Analysis

When implemented with a baseband XPIC, the receiving device may function to split the received optical signal having an electric field $\underline{\varepsilon}_S(t)$ into components $\underline{\varepsilon}_{Sy}(t)$ and $\underline{\varepsilon}_{Sy}(t)$, which are polarized in the $\hat{x}$ and $\hat{y}$ directions, respectively. The receiving device also includes a polarization beam splitter that produces $\hat{x}$ and $\hat{y}$ polarized components from an internal local oscillator. The $\hat{x}$ and $\hat{y}$ polarized components are applied to different DBORs. Thus, the DBORs produce currents containing components from both originally transmitted signals. After removing the IF carrier and phase noise, the quadrature demodulators produce in-phase and quadrature waveforms that contain components from the in-phase and quadrature waveforms of both transmitted signals. The XPIC reconstructs the in-phase and quadrature components of the transmitted signals by complex filtering or weighting of the demodulated waveforms, and then recombining the results.

More specifically, referring now to FIG. **9**, a block diagram of an exemplary implementation using a coherent receiving device and a baseband XPIC **950** is shown. The structure of receiving device **900** is identical to receiving device **600** of FIG. **6** up to the outputs of DBORs **910** and **920**, and the expressions for $i_1(t)$ and $i_2(t)$ are therefore given by equations (E.15) when the XPI is frequency independent and equations (E.21) when the XPI is frequency dependent. These IF signal currents $i_1(t)$ and $i_2(t)$ are then input to ideal quadrature demodulators **930** and **940**. Demodulators **930** and **940** function to multiply the complex argument of equation (E.15) by a demodulation matrix D of the form

$$D = \begin{bmatrix} e^{-j(\omega_{IF}t+\phi'(t))} & 0 \\ 0 & e^{-j(\omega_{IF}t+\phi'(t))} \end{bmatrix}. \quad \text{(F.1)}$$

where $\phi'(t)$ is the received phase noise taking into account the effect of the fiber transmission medium on the transmitted phase noise $\phi(t)$. This removes the carrier and phase noise dependence from the signal waveforms, and the real portion of the resulting baseband waveforms are outputs $I'_1(t)$ and $I'_2(t)$, while the imaginary portions are outputs $Q'_1(t)$ and $Q'_2(t)$. Performing this procedure, the complex outputs from demodulators **930** and **940** are specified by

$$\begin{bmatrix} z'_1(t) \\ z'_2(t) \end{bmatrix} = F^{-1}[X(\omega)] * \begin{bmatrix} v_1(t) \\ v_2(t) \end{bmatrix} + \begin{bmatrix} n_1(t) \\ n_2(t) \end{bmatrix} \quad \text{(F.2)}$$

where $z'_k(t)=z'_k(t)+jQ'_k(t)$ and the frequency response of $X(\omega)$ is now translated from IF to baseband by the frequency downconversion process of the demodulators. The statistics of the noise processes $n_1(t)$ and $n_2(t)$ are unchanged by the

down conversion operation. The outputs from complex baseband XPIC **950** are now specified by

$$\begin{bmatrix} z_1(t) \\ z_2(t) \end{bmatrix} = F^{-1}[W(\omega)X(\omega)] * \begin{bmatrix} v_1(t) \\ v_2(t) \end{bmatrix} + \begin{bmatrix} n_3(t) \\ n_4(t) \end{bmatrix} \quad \text{(F.3)}$$

where $n_3(t)$ and $n_4(t)$ have power spectral densities specified by equations (E.23) and (E.24) respectively.

1. Diagonalizer XPIC Signal Reconstruction

If XPIC **950** is configured according to the diagonalizer solution of equation (E.25), then XPIC **950** outputs are determined by

$$\begin{bmatrix} z_1(t) \\ z_2(t) \end{bmatrix} = \begin{bmatrix} v_1(t) \\ v_2(t) \end{bmatrix} + \begin{bmatrix} n_3(t) \\ n_4(t) \end{bmatrix} \quad \text{(F.4)}$$

The four (4) outputs of XPIC **950** are the real and imaginary components of equation (F.4) and are given by

$$\mathrm{Re}\left\{\begin{bmatrix} z_1(t) \\ z_2(t) \end{bmatrix}\right\} = \begin{bmatrix} I_1(t) \\ I_2(t) \end{bmatrix} + \mathrm{Re}\left\{\begin{bmatrix} n_3(t) \\ n_4(t) \end{bmatrix}\right\} \quad \text{(F.5)}$$

$$\mathrm{Im}\left\{\begin{bmatrix} z_1(t) \\ z_2(t) \end{bmatrix}\right\} = \begin{bmatrix} Q_1(t) \\ Q_2(t) \end{bmatrix} + \mathrm{Im}\left\{\begin{bmatrix} n_3(t) \\ n_4(t) \end{bmatrix}\right\} \quad \text{(F.6)}$$

The outputs of baseband XPIC **950** are therefore the desired information bearing waveforms and additive noise. Baseband XPIC **950** is, in fact, functionally equivalent to IF XPIC **670** of FIG. **6**. For baseband XPIC systems, the form of the frequency dependent and frequency independent XPIC networks are the same as for the optical and IF XPIC systems and are shown in FIGS. **4**A and **4**B respectively. Unlike the optical and IF XPIC systems, however, for the baseband XPIC system each of the four complex filters of FIG. **4**A has the form shown graphically in FIG. **10**B.

For the receiver as shown in FIG. **9**, the recovered baseband waveforms I(t) and Q(t) would be applied to matched filters or correlation detectors, the resulting waveforms would be sampled, and the decisions based on the resulting samples would serve as optimal estimates of the transmitted symbols. It is appreciated that sampling and analog-to-digital (A/D) conversion could precede baseband XPIC **950**, and the XPIC function could be implemented by digitally processing the sampled decision variable data.

Of course, other embodiments may be employed without departing from the spirit and scope of the present invention. Although the analysis presented concentrated on PSK modulation, XPIC is equally applicable to other coherent modulation formats such as ASK, FSK, and QAM. XPIC can also be used in conjunction with frequency division multiplexing (FDM), wavelength division multiplexing (WDM), or coherent subcarrier multiplexing (SCM). The invention should, therefore, be measured in terms of the claims which follows.

What is claimed is:

1. A system comprising:

a transmitting device to modulate orthogonally polarized optical carriers with independent information bearing waveforms; and

a receiving device including (i) a cross polarization interference canceler that comprises a plurality of optical elements each supporting a transfer function to collectively mitigate cross polarization interference and to reconstruct the information bearing waveforms recovered from the orthogonally polarized optical carriers and (ii) a plurality of receivers each to receive an optical signal from the cross polarization interference canceler.

2. The system of claim **1** further comprising an optical fiber transmission medium coupling the transmitting device and the receiving device.

3. The system of claim **2**, wherein the transmitting device includes

a polarization beam splitter to separate a beam from a local oscillator into the orthogonally polarized optical carriers; and

a plurality of modulators to independently modulate the orthogonally polarized optical carriers with the information bearing waveforms.

4. The system of claim **3**, wherein the transmitting device further includes a polarization combiner to produce a transmit optical signal for transmission over the optical fiber transmission medium.

5. The system of claim **2**, wherein the orthogonally polarized optical carriers modulated with independent information bearing waveforms and propagated through the optical fiber transmission medium constitute an incoming optical signal to the plurality of receivers.

6. The system of claim **1**, wherein the receiving device further comprises a first polarization beam splitter preceding the cross polarization interference canceler, the first polarization beam splitter to separate a received optical signal field into orthogonally polarized field components.

7. The system of claim **6**, wherein each of the plurality of optical elements associated with the cross polarization interference canceler of the receiving device is a complex optical elements to mitigate the non-ideal effects of the transmitter and optical fiber transmission medium on the received optical signal.

8. The system of claim **7**, wherein the complex optical elements include optical filters.

9. The system of claim **6**, wherein the receiving device includes a second polarization beam splitter to separate a beam from a local oscillator into a plurality of orthogonally polarized field components, a first polarized field component being routed to a first set of one or more receivers and a second polarized field component substantially orthogonal to the first polarized field component being routed to a second set of one or more receivers.

10. The system of claim **9**, wherein the plurality of coherent optical receivers of the receiving device produce a plurality of electrical signals for demodulation, each of the plurality of electrical signals include significant modulation data from only one of the transmitted orthogonally polarized field components.

11. The system of claim **1**, wherein each of the plurality of receivers of the receiving device is an intensity modulation direct detection receiver that receives one of the optical signals from the cross polarization interference canceler.

12. The system of claim **11**, wherein the plurality of intensity modulation direct detection receivers of the receiving device are used to detect wavelength division multiplexed (WDM) signals.

13. The system of claim **1**, wherein each of the plurality of receivers of the receiving device is a coherent optical receiver.

14. The system of claim **13**, wherein at least one of the plurality of coherent optical receivers includes a double balanced optical receiver.

15. Implemented to receive an incoming optical signal, a receiving device comprising:

a first polarization beam splitter to separate a received optical signal field of the incoming optical signal into orthogonally polarized components; and

a cross polarization interference canceler following the first polarization beam splitter, the cross polarization interference canceler comprises a plurality of outputs and a plurality of elements each supporting a transfer function, each output of the plurality of outputs being the sum of at least two element outputs.

16. The receiving device of claim **15**, wherein the first polarization beam splitter is in communication with one or more receivers being double balanced optical receivers.

17. The receiving device of claim **16** further comprising one or more demodulators each coupled to one of the double balanced optical receivers.

18. The receiving device of claim **16** further comprising a second polarization beam splitter coupled to the one or more receivers.

19. The receiving device of claim **15**, wherein the cross polarization interference canceller (XPIC) is an optical XPIC.

20. The receiving device of claim **19**, further comprising one or more intensity modulation direct detection (IM-DD) fiber optic receivers in communication with the XPIC.

21. The receiving device of claim **19** further comprising one or more coherent optical receivers in communications with the XPIC.

22. The receiver of claim **15** further comprising:

a local oscillator;

a second polarization beam splitter in communication with the local oscillator, the second polarization beam splitter to receive an optical signal from the local oscillator; and

one or more demodulators in communication with the cross polarization interference canceler.

23. The receiver of claim **15**, wherein the cross polarization interference canceler includes a plurality of generally complex elements.

24. The receiving device of claim **15** further comprising at least two optical receivers and at least two demodulators interposed between the at least two optical receivers and the cross polarization interference canceler, the at least two demodulators to translate intermediate frequency (IF) signals into baseband signals.

25. The receiving device of claim **15**, wherein the cross polarization interference canceller further mitigates polarization mode dispersion associated with the incoming optical signals.

26. A receiving device implemented to receive an incoming optical signal, a receiving device comprising:

a first polarization beam splitter to separate a received optical signal field of the incoming optical signal into orthogonally polarized components; and

a cross polarization interference canceller (XPIC) in communication with the first polarization beam splitter, the XPIC being an electrical intermediate frequency (IF) XPIC.

27. The receiving device of claim **26** further comprising a second polarization beam splitter that, along with the first polarization beam splitter, are in communication with at least two optical receivers, the at least two optical receivers to produce intermediate frequency (IF) signals transmitted to the IF XPIC.

28. The receiving device of claim **27**, wherein the at least two optical receivers are coherent optical receivers.

29. The method of claim **26** further comprising:

mitigating polarization mode dispersion associated with the incoming optical signals.

30. A method comprising:

receiving an optical signal over a single fiber optic transmission medium, the optical signal being one or more polarized field components independently modulated with independent information bearing waveforms; and

processing the optical signal by (i) separating the optical field of the optical signal into orthogonally polarized field components, (ii) routing each of the orthogonally polarized field components to a coherent optical receiver to produce a first output and a second output, and (iii) transmitting the first and second outputs to a cross polarization interference canceller (XPIC).

31. The method of claim **30**, wherein the cross polarization interference canceller is an intermediate frequency (IF) XPIC.

32. The method of claim **30**, wherein the first and second outputs are demodulated prior to transmission to the XPIC.

33. A method comprising:

receiving an optical signal over a single fiber optic transmission medium, the optical signal being at least two polarized field components independently modulated with independent information bearing waveforms; and

mitigating cross polarization interference associated with the at least two modulated polarized field components to reconstruct the information bearing waveforms using a plurality of matrix coefficients being complex values to apply both amplitude scaling and phase shifting to the at least two modulated polarized field components.

34. The method of claim **33**, wherein the mitigating of the cross polarization interference comprises:

separating an optical field of the optical signal into orthogonally polarized field components; and

processing the orthogonally polarized field components by an optical cross polarization interference canceller.

35. A method comprising:

receiving at least two optical signals with independent information bearing waveforms over a single fiber optic transmission medium, the at least two optical signals having been transmitted with generally orthogonal polarization states; and

mitigating cross polarization interference associated with the at least two optical signals to reconstruct the information bearing waveforms, mitigation of the cross polarization interference is accomplished through a matrix multiplication using a cross polarization interference canceler that produces the recovered signals with the minimum mean square error (MMSE) relative to the desired transmitted signals.

36. A method comprising:

receiving an optical signal over a single fiber optic transmission medium, the optical signal being one or more polarized field components independently modulated with independent information bearing waveforms; and

processing the optical signal by (i) separating the optical field of the optical signal into orthogonally polarized field components, (ii) processing the orthogonally polarized field components by an optical cross polarization interference canceller (XPIC), (iii) routing outputs of the optical XPIC to coherent optical receivers that convert the outputs into corresponding current outputs, and (iv) demodulating the current outputs to reconstruct baseband waveforms associated with the received optical signal.

37. A method comprising:

receiving at least two optical signals with independent information bearing waveforms over a single fiber optic transmission medium, the at least two optical signals having been transmitted with generally orthogonal polarization states; and

eliminating cross polarization interference associated with the at least two optical signals to reconstruct the i

nformation bearing waveforms, the elimination of the cross polarization interference is accomplished through matrix multiplication using a diagonalizer cross polarization interference cancellation network being a general inverse of a transmission matrix associated with the transmitter and the single fiber optic transmission medium.

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