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(54) **THERMO-OPTIC LIQUID CRYSTAL WAVEGUIDES**

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G02F 1/295 (2006.01)

(52) **U.S. Cl.** **349/63**; 349/61; 349/62; 385/8

(58) **Field of Classification Search** 349/61, 349/62, 63; 385/8
See application file for complete search history.

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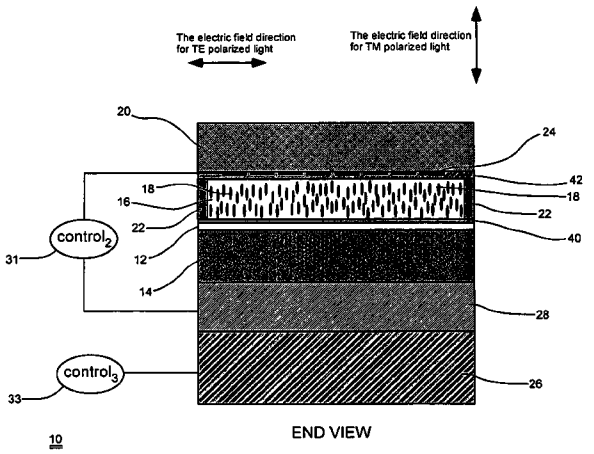
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(57) **ABSTRACT**

A waveguide having an adjustable index of refraction (or an adjustable optical path length, or for providing an adjustable optical phase delay) based in part on thermal effects in the waveguide. In one example, the waveguide may include a core for guiding a light beam through the waveguide; at least one cladding; liquid crystal material disposed within the waveguide; and at least one temperature control element, such as resistive heater, for receiving at least one control signal to control a temperature of at least a portion of the liquid crystal material; wherein the index of refraction (or the optical path length, or the optical phase delay of the light beam) of the waveguide is altered by an amount that is controlled by the control signal.

9 Claims, 2 Drawing Sheets



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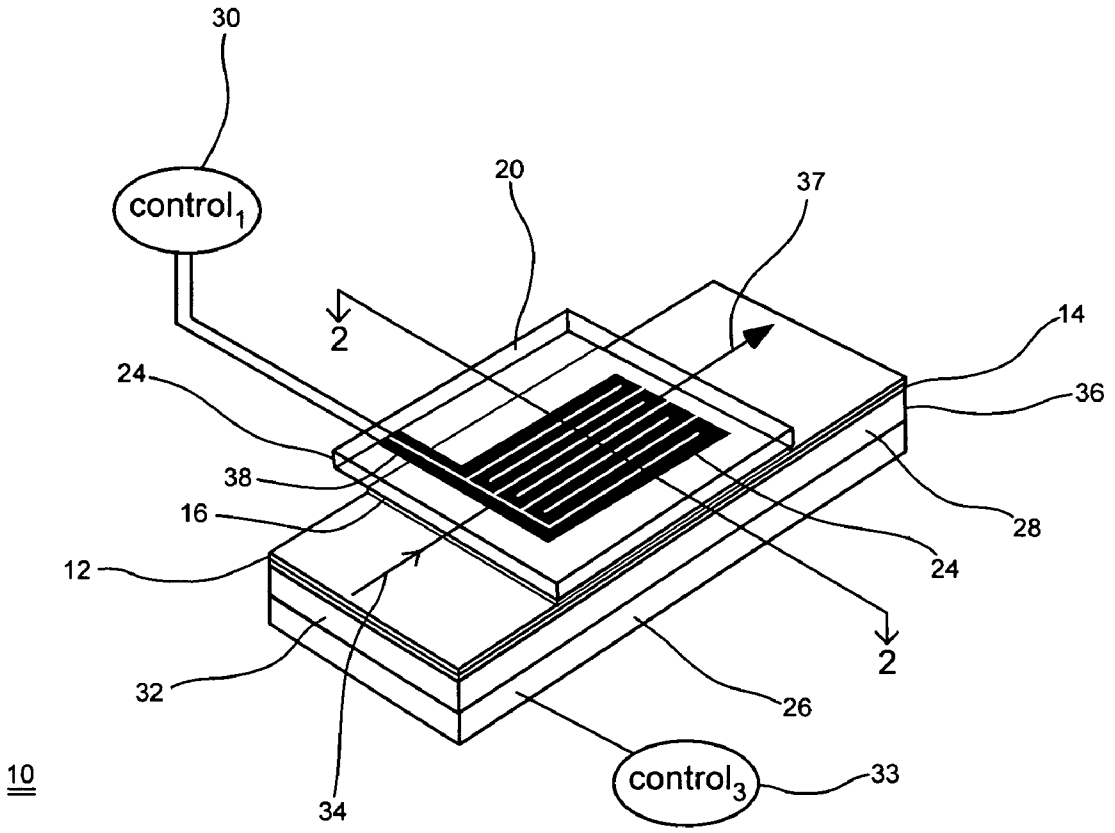

30
control1
20
37
2
14
24
36
38
16
28
12
24
2
32
26
10
34
control3
33

Fig. 1

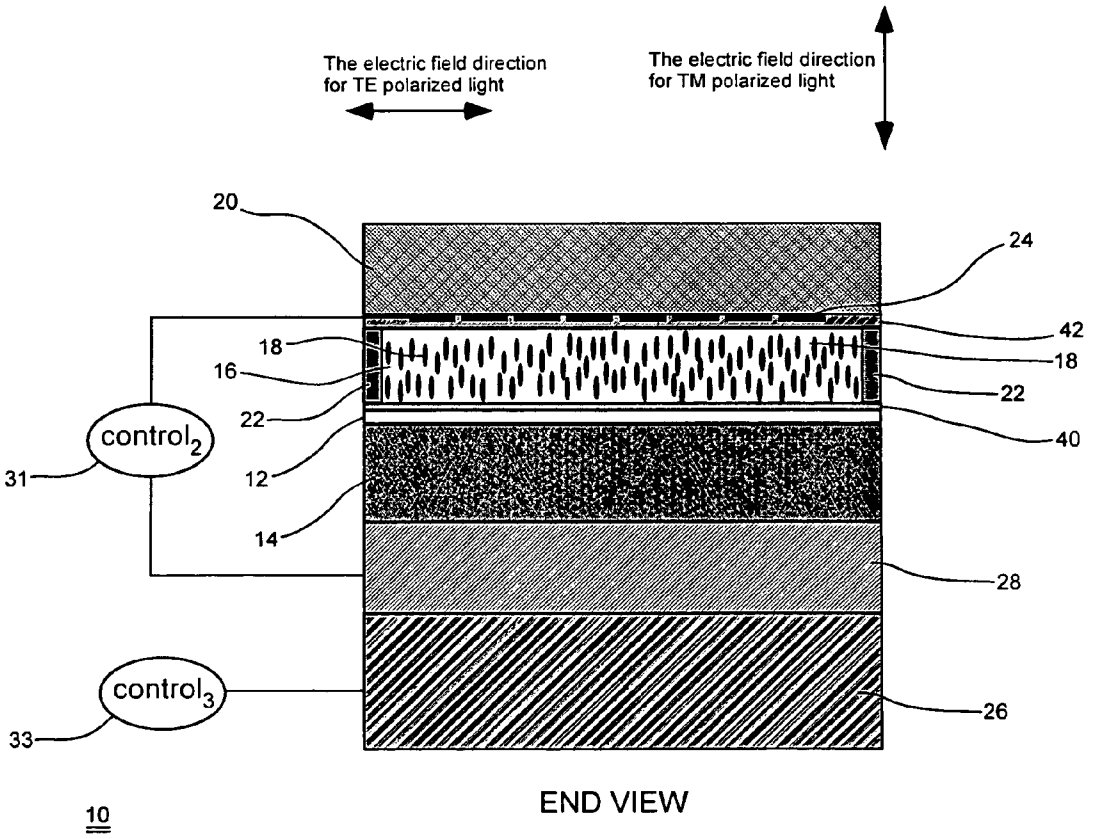

The electric field direction for TE polarized light
The electric field direction for TM polarized light
20
24
42
18
16
18
22
22
40
control2
31
12
14
28
control3
33
26
10
END VIEW

Fig. 2

THERMO-OPTIC LIQUID CRYSTAL WAVEGUIDES

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims under 35 U.S.C. § 119(e) the benefit of U.S. provisional patent application No. 60/713,393 entitled "Thermo-optic Liquid Crystal Waveguides," filed Sep. 1, 2005, the disclosure of which is hereby incorporated by reference in its entirety.

This application also incorporates by reference U.S. patent application Ser. No. 11/040,549, filed Jan. 21, 2005, entitled "Tunable Laser Having Liquid Crystal Waveguide," and U.S. patent application Ser. No. 10/963,946, filed Oct. 12, 2004, entitled "Liquid Crystal Waveguide Having Refractive Shapes for Dynamically Controlling Light," the disclosures of which are hereby incorporated by reference in their entirety.

BACKGROUND OF THE INVENTION

Light can be controlled using standard lenses and mirrors. These passive methods can be made active via mechanical motion. For example, mirrors can be placed on motorized stages or piezo mounts to move the mirror to control either the direction of light propagation and/or the total optical path length of a system. By altering the total optical path length, the optical phase delay (OPD) of the light may be controlled.

However, mechanical control over light is undesirable for several reasons. First, it is difficult to make such mechanical devices compact. Second, the mechanical nature of such moving devices have limited lifetimes due to mechanical wear and failure issues. Third, mechanical devices are inherently vibration sensitive, which limits the type of environment in which they can be used. Finally, mechanical devices necessitate a level of design complexity including gears, bearings, and other mechanical components, which add cost, expense, and maintenance issues to such designs.

As an alternate to mechanical devices, one may utilize conventional thermally controlled waveguides for the dynamic control of light. In this waveguide technique, the temperature of the waveguide can be used to alter the index of refraction for light traveling through the waveguide. Typically such thermo-optic approaches provide for only limited changes in index of refraction ($dn/dt \approx 1.5 \times 10^{-5}$/° C.), which in turn necessitates large temperature changes (up to 500° C.). These devices are therefore typically power consumptive, which is prohibitive for many applications.

As recognized by the present inventors, what is needed is a thermo-optic waveguide for controlling light that permits active control of the propagation of light through the waveguide.

It is against this background that various embodiments of the present invention were developed.

SUMMARY

In light of the above and according to one broad aspect of one embodiment of the present invention, disclosed herein is a waveguide having an adjustable index of refraction (or an adjustable optical path length, or an adjustable optical phase delay). In one example, the waveguide includes a core for guiding a light beam through the waveguide; at least one cladding; liquid crystal material disposed within the waveguide; and at least one temperature control element for receiving at least one control signal to control a temperature of at least a portion of the liquid crystal material; wherein the index of refraction (or the optical path length, or the optical phase delay) of the waveguide is altered by an amount that is controlled by the control signal.

In one example, the liquid crystal material may be disposed within the at least one cladding, and the liquid crystal material may be a nemetic material. The at least one temperature control element may include a resistive heater and/or may include at least one conductive layer.

In another example, the at least one temperature control element includes an upper temperature control element and a lower temperature control element.

The light beam traveling in the waveguide may include TM polarized light and/or TE polarized light. The at least one control signal may include a DC voltage, an AC voltage, a current (DC or AC), or any other electrical signal depending upon the implementation.

The features, utilities and advantages of the various embodiments of the invention will be apparent from the following more particular description of embodiments of the invention as illustrated in the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates an example of a waveguide having at least one thermal control element, in accordance with one embodiment of the present invention.

FIG. **2** illustrates a sectional view of an example of a waveguide having at least one thermal control element, in accordance with one embodiment of the present invention.

DETAILED DESCRIPTION

Disclosed herein are various embodiments of a liquid crystal waveguide for dynamically controlling the index of refraction (or optical path length) of the waveguide, and thereby controlling the propagation speed of light passing through the waveguide. This thereby enables control of the amount of optical phase delay (OPD) of light passing through the waveguide. Generally, liquid crystal materials can be disposed within a waveguide in a cladding proximate or adjacent to a core layer of the waveguide, however liquid crystal material may be included in all or part of the waveguide core. According to some embodiments of the present invention, the temperature of the liquid crystal material can be controllably altered, thereby altering the index of refraction of the waveguide for light traveling through the waveguide.

Liquid crystals may have indices of refraction that depend on temperature to a much larger extent than more conventional materials such as silicon dioxide (SiO_2) or glass. For example, liquid crystals may have a $dn/dt \approx 1.7 \times 10^{-3}$/° C. The index of refraction of such liquid crystal materials may change by 0.1 or greater over reasonable temperature ranges such as a range of 30° C. For example, the index of refraction for a liquid crystal material known as 5CB can change by 0.1 for a temperature change of less than 30 degrees centigrade.

Referring to FIGS. **1-2**, a waveguide **10** may include a core **12**, a pair of claddings **14**, **16** surrounding the core **12** wherein one of the claddings (e.g., the upper cladding **16**) contains liquid crystal material **18** therein. In one example, a coverplate **20** and glue walls **22** may surround the liquid crystal material **18**, which has been disposed within the upper cladding **16**. Alternatively, the liquid crystal material **18** may also be disposed within the waveguide core **12** and/or within the lower cladding **14**. In one example, one or more thermal control elements **24** are positioned above the upper cladding **16**, and/or one or more thermal control elements **26** are posi-

tioned below the lower cladding **14**. The waveguide **10** may also include a substrate **28**, which may be positioned between the lower cladding **14** and a lower thermal control element **26**. The substrate **28** may provide additional structural support and may also serve as an electrode or conductive plane.

The one or more thermal control elements **24**, **26** may receive a control signal **30**. This control signal may be a DC voltage, an AC voltage, an electric current, or other means of control and may be connected across the thermal element **24** as shown in FIG. **1**, or may be connected between thermal element **24** and substrate **28** with another example shown as **31** in FIG. **2**. As the control signal **30** is controllably altered, the temperature of the liquid crystal material **18** is also controllably altered. As the temperature of the liquid crystal material **18** changes, the index of refraction of the liquid crystal material **18** controllably and dynamically changes as a function of its temperature.

As shown in the example of FIG. **1**, the waveguide **10** may be generally rectangular in shape and may include a core **12** having a generally rectangular cross-section or defining a parallel piped. On the front end **32** of the waveguide **10**, light **34** is introduced into the waveguide core **12** and propagates along the length of the waveguide **10** to the distal end **36** of the waveguide **10**. As shown in FIG. **1**, the direction **37** of propagation of light **34** through the waveguide **10** is generally along the length of the waveguide **10**, and use of embodiments of the present invention permit the index of refraction to be controllably altered depending, in part, on the alignment of the liquid crystals **18** and the temperature of the liquid crystal **18** as determined by the temperature control elements **24**, **26**. Although the waveguide **10** in FIG. **1** is shown as generally rectangular, it is understood that a waveguide **10** made according to one or more embodiments of the present invention could have other shapes such as square, trapezoid, parallelogram, any polygon, or even be diced or scribed so as to have rounded edges producing elliptical, circular, or any curved shape.

In one example, the at least one temperature control element **24** may include a resistive film deposited on the lower surface of the coverplate **20**. As current passes through this resistive film, the temperature of the film will increase. This film may therefore act as a resistive heater and thereby serve as a temperature control element **24**. Furthermore, in this example, at least one control signal **30** may include a DC voltage, which in turn may control the amount of electrical current that passes through the film. By controllably increasing the DC voltage, one may controllably increase the temperature of the resistive heater **24** and therefore also increase the temperature of the liquid crystal material **18**. The resistive film may be deposited on the underside of a coverplate **20** in a pattern such that a uniform temperature may be created over a region of the waveguide **10**. The resistive heater **24** may include one or more tabs or extensions **38** there from which the resistive heater **24** may be electrically connected to other electrical elements, such as the control signal **30**.

Alternatively or additionally, the waveguide **10** may include a temperature control element **26** that is positioned on another layer of the waveguide **10**. In one example, this temperature control element **26** may include a thermo-electric-cooler (TEC), which may be used to increase or decrease the temperature of the waveguide **10**. The temperature of the thermo-electric cooler **26** may be controllably increased or decreased through the use of a control signal **33** (FIG. **2**), which may be the same or different than control signal **30**, and may include a DC voltage or an electric current.

In another example, the waveguide **10** may include both an upper and a lower temperature control element **24**, **26**. For example, a lower temperature control element **26** may include a TEC and an upper temperature control element **24** may include a resistive heater. In this example, the TEC lower temperature control element **26** may serve as a heat-sink or temperature reduction system by maintaining the substrate **28** and lower cladding **14** at a colder temperature relative to the temperature of the liquid crystal material **18**, and the resistive heater upper temperature control element **24** may serve as heater or temperature increase system to increase the temperature of the liquid crystal material **18**. The resistive heater **24**, which may be affixed to the lower surface of the coverplate **20**, may be positioned close to the liquid crystal material **18** and therefore, through an increase in the current flowing through the heater **24**, the temperature of the liquid crystal material **18** may be rapidly increased. Alternatively, as current flowing through the resistive film **24** is decreased, the heat within the liquid crystal material **18** may be removed through the lower temperature control element **26**, i.e., the TEC that is maintaining the waveguide substrate **28** and lower cladding **14** at a cooler temperature. In this way, the temperature of the liquid crystal material **18** within the waveguide **10** may be controllably increased and/or controllably decreased. Therefore, the index of refraction of the waveguide **10** may also be controllably increased and/or controllably decreased.

In another example, the at least one temperature control element **24** may include one or more conductive layers or electrodes. In one example, electrodes or conductive layers may be positioned both above the upper cladding **16** and below the lower cladding **14**. The upper conductive layer may be applied to the lower surface of the coverplate **20**, and the lower electrode surface may be the substrate **28**, which is beneath the lower cladding **14**. The control signal **31** may include an alternating current (AC) voltage applied across these two electrodes. The frequency of the alternating current may be sufficiently high enough, for example above 5 kHz, such that as the amplitude is increased, current will flow through the waveguide upper cladding **16**, core **12**, and lower cladding **14**. As this current flows through the waveguide **10**, from the upper conductive layer **24** to the lower conductive layer **28**, it may heat the liquid crystal material **18** that is disposed within the waveguide **10**. The amount of heating is dependent on the magnitude of current, which may be controllably altered either by altering the amplitude or the frequency of the AC control signal **31**. In this way, either the frequency and/or the amplitude of the AC voltage control signal **31** may be altered to controllably alter the index of refraction of the waveguide **10**.

FIG. **2** illustrates a sectional view, taken along sectional line **2-2** in FIG. **1**, of a waveguide **10** in accordance with one embodiment of the present invention. As shown in FIG. **2**, in one example, a waveguide **10** may include a substrate **28** such as a silicon substrate or a p-doped silicon substrate, which provides structural support for the waveguide **10** and can serve as a conductive layer. The substrate **28** may also be formed from any metal, such as silver, copper, aluminum, gold, titanium, etc. Alternatively, the substrate **28** can be nonconductive, such as a glass or a crystalline material.

A lower cladding layer **14** is provided on the substrate **28** and is preferably made of any dielectric materials with low absorptions whose index of refraction is less than the index of refraction of the core **12**. Suitable materials include but are not limited to Silicon OxyNitride, Silicon-Rich Nitride, Silicon Nitride, Tantalum Pentoxide, Polymers, Pure Silicon, Ion exchange glass on substances such as Lithium Niobate, Sol-Gel, thermally oxidized silicon, and glass. In one example, the interface between the lower cladding **14** and the core layer

12 is transparent so that light can penetrate the lower cladding 14 as it propagates through the core 12.

On top of the lower cladding 14, a waveguide core 12 is provided. In one embodiment, the core 12 does not include any liquid crystal 18 material therein. The core 12 may be made of materials such as any dielectric materials with low absorptions whose index of refraction is greater than the index of refraction of the upper and lower cladding 16, 14. Suitable materials include, but are not limited to, Silicon OxyNitride, Silicon Rich Nitride, Silicon Nitride, Tantalum Pentoxide, Polymers, Pure Silicon, Ion exchange glass on substances such as Lithium Niobate, Sol-Gel, thermally oxidized silicon, glass.

In one example, the core 12 has a thickness that is tapered or includes a channel. Furthermore, a core 12 may have a constant index of refraction along the length of the waveguide 10, or alternatively have an index of refraction that varies across or along the waveguide 10. In another embodiment, the liquid crystal material 18 may be disposed in the core layer 12, or may serve as the core layer 12.

On top of the core layer 12, an alignment layer 40 is provided which is used to initially align or bias the orientation of liquid crystal material 18 that is proximate to or adjacent to the alignment layer 40 and the core 12. Alignment can be achieved, for example, by buffed polyimide, nylon, or other polymer coatings applied to the core 12 and/or the coverplate 20, photo-aligned polyimide, polymer or other photo-aligned material, angle deposited SiO, SiO_2 or other angle deposited material, microgrooves etched into the core 12 and/or coverplate 20, ion-buffing, a dispersed polymer matrix that is photoaligned, or direct buffing. In one example, the alignment layer 40 may induce a homeotropic alignment in the liquid crystal 18. In another example, the alignment layer 40 may induce a homogeneous alignment in the liquid crystal 18. In one example, the lower alignment layer 40 is generally transparent.

On top of the lower alignment layer 40, the upper cladding 16 is provided having liquid crystal material 18 therein. In one example, the interface between the lower alignment layer 40 and the upper cladding 16 is transparent. The liquid crystal material 18 may include, but is not limited to, any nematic liquid crystal, with either a positive dielectric constant or a negative dielectric constant or a mixture of each, polymer dispersed liquid crystal material, Smectic A* and C* liquid crystal material, cholesteric liquid crystal material such as ferroelectrics and surface stabilized ferroelectrics, or dual-frequency liquid crystal material, for example. The liquid crystal material 18 may be laterally contained by glue walls 22, which also serve to affix the coverplate 20.

In one example, the upper cladding 16 is formed using spacer material to define a region or volume wherein liquid crystal material 18 may be contained therein, and optically transparent glue such as Norland 68 may be used to create transparent boundary glue walls 22 to contain the liquid crystal 18.

On top of the upper cladding 16, an upper alignment layer 42 may be provided to initially align or bias the orientation of liquid crystal material 18 that is adjacent to or proximate to the upper alignment layer 42. As with the lower alignment layer 40, the upper alignment layer 42 may include, for example, buffed polyimide coatings applied to the coverplate 20, photo-aligned polyimide, angle deposited SiO and or SiO_2, microgrooves etched or otherwise formed into the coverplate 20, ion-buffed surfaces on the coverplate 20, a dispersed polymer matrix that is photoaligned, or direct buffing. In one example, the upper alignment layer 42 is generally transparent.

The alignment of the liquid crystal 18 between the lower and upper alignment layers 40, 42 can be anti-parallel, parallel, twisted, or hybrid between twisted and parallel or anti-parallel. The direction of liquid crystal alignment can be at any angle with respect to the direction 37 of light propagation. Illustrated in FIG. 2 are alignment layers 40, 42 that provide for the long axis of a nematic liquid crystal to be oriented perpendicular to both the direction 37 of light propagation and the upper surface of the core 12.

On top of the upper alignment layer 42 and below the glass cover 20, a temperature control element or portions of a temperature control element layer 24 may be included. In one example, the temperature control element 24 may be a conductive coating applied to the bottom surface of the glass cover 20. The conductive coating can include, but is not limited to, ITO, tin-oxide, Au, Ag, Al, Cu, or any other conductive coating. In order to serve as a heater element 24, the conductive coating can have an electrical resistance.

In one example, the glass cover 20 may be made of materials such as, but not limited to, standard float glass such as Corning 1737, fused silica, or the like. Since the evanescent portion of the light 34 does not pass through the coverplate 20, the coverplate 20 can be made from non-transparent materials such as silicon wafers, ceramics, or polished metal surfaces. In another embodiment, the coverplate 20 may be a metal to which another heater such as a TEC or resistive heater has been affixed, or any other material whose temperature can be controlled.

Embodiments of the present invention can be used to simultaneously and or independently control the index of refraction for particular types of polarized light, such as TM polarized light and TE polarized light. Generally, TM (Transverse Magnetic) polarized light means that the magnetic field of the light wave is traversing the plane of the waveguide 10, while the electric field is substantially perpendicular to the plane of the waveguide 10. TE (Transverse Electric) polarized light is characterized by the electric field of the light 34 traversing the plane of the waveguide 10, while the magnetic field of the light 34 is substantially perpendicular to the plane of the waveguide 10.

The light 34 may include TE polarized light and/or TM polarized light. Using the structure of FIGS. 1-2 or variations thereof, various different waveguides can be formed to controllably alter the index of refraction of TE and/or TM polarized light as it passes through the waveguide. When one or more temperature control elements 24, 26 are used to alter the temperature of the liquid crystal 18, the index of refraction of the liquid crystal 18 may be controllably altered. This can be used to alter the index of refraction for TE polarized light, TM polarized light, or both simultaneously.

Preferably, the core layer 12 may be surrounded by an upper and lower cladding 16, 14, wherein the interfaces between the lower cladding 14 and the core layer 12 and between the upper cladding 16 and the core layer 12 are transparent. As light 34 enters the core layer 12 and propagates through the core 12 along the length of the waveguide 10, the evanescent portion of the propagating light waves 34 penetrate into both the upper and lower cladding 16, 14.

In one example, the core layer 12 has a substantially fixed index of refraction, and the lower cladding 14 also has a substantially fixed index of refraction. By providing liquid crystal material 18 within the upper cladding 16, a portion of which is controllably subjected to an adjustable temperature, the index of refraction of the upper cladding layer 16 can be controllably altered. Stated differently, the average index of refraction (i.e., the effective index of refraction or the index of refraction) of the upper cladding 16, core 12, and lower clad-

ding **14** as experienced by light **34** (i.e., a single TM or TE mode of light) in the waveguide **10** can be controllably altered by altering the index of refraction of the upper cladding **16**. Hence, as light **34** passes through the waveguide core **12** and upper and lower cladding **16**, **14**, the index of refraction experienced by the light **34** can be controllably altered. In one example, because the liquid crystal material **18** is disposed within the upper cladding **16** and interacts primarily with the evanescent portion of the light wave **34** and the fundamental portion of the light wave **34** passes through the core material **12**, there is no significant attenuation of the intensity of the light **34** as the light **34** passes through the waveguide **10**, which permits the length of the waveguide **10** to be beneficially long to allow large control over the optical phase delay.

Furthermore, in this example, the evanescent portion of the light **34** is generally interacting with the liquid crystal molecules that are close to an alignment layer **40**. These molecules are more highly ordered than liquid crystal molecules further away from the alignment layer **40** and therefore scatter less light. In one example, the losses are sufficiently low (e.g., less than 0.5 dB/cm) that the waveguide length can be lengthy (e.g., 4 inches or greater).

While FIGS. **1-2** show a particular arrangement of layers of a waveguide **10** according to one embodiment of the present invention, it is understood that the present invention contemplates variations of this arrangement. For instance, the at least one temperature control element **24**, **26** may be positioned at different layers within the waveguide **10** if desired. Further, while two alignment layers **40**, **42** are shown, it is believed the invention may be implemented using a single alignment layer (e.g., 40). While the liquid crystal material **18** is shown as disposed within the upper cladding **16**, it is understood that the liquid crystal material **18** may be disposed in the lower cladding **14** if desired, or within the core **12**.

In another example of the present invention, one or more upper thermal control elements **24** may define one or more shapes having at least one edge or interface that is non-normal to the direction **37** of light propagation through the waveguide **10**. The one or more shapes defined by the upper thermal control element **24** may be used to controllably refract or bend or steer light as light **34** passes through the core **12** and upper and lower claddings **16**, **14** of the waveguide **10**. The upper temperature control element **24**, may be shaped or patterned in various manners, including generally triangular or wedge shaped for steering light **34**, or the shapes may include various lens shapes for focusing or defocusing light **34** that passes through the waveguide **10**. The temperature control elements **24** may be shaped or arranged in various configurations depending upon the implementation, and may utilize the same or similar shapes or configurations of the patterned electrodes shown or described in the cross-referenced applications, U.S. patent application Ser. No. 11/040,549, filed Jan. 21, 2005, entitled "Tunable Laser Having Liquid Crystal Waveguide," and U.S. patent application Ser. No. 10/963,946, filed Oct. 12, 2004, entitled "Liquid Crystal Waveguide Having Refractive Shapes for Dynamically Controlling Light," the disclosures of which are hereby incorporated by reference in their entirety.

Many devices may be created with one or more features of embodiments of the present invention, such as tunable lenses, tunable-pitch gratings, polarization control elements, adjustable delay lines, tunable resonators, optical switching elements, dynamically tunable filters, and many others. Other examples include compact Fourier transform spectrometers for chemical sensing; robust tunable diode lasers; continuously tunable lasers; beamsteering and focusing modules for laser printers; optical disk pickups; beamsteerers for free-space laser communications; and reconfigurable optical interconnects for computing and telecommunications.

Thermo-Optic Liquid Crystal Waveguide Example

Described below is one example of a liquid crystal waveguide **10** in which the waveguide **10** is designed to provide for 32π radians optical phase delay for TM polarized light and is described as an example only. It is understood that this example is provided for illustrative purposes only, and does not limit the scope of embodiments of the present invention. In one example, a substrate may be formed utilizing a double-side polished silicon wafer. Upon the silicon wafer, a thermally oxidized lower cladding can be grown with a thickness of approximately 2 microns. The lower cladding refractive index at a wavelength of 1550 nanometers may be approximately 1.45. SiO_xN_y can be applied over the lower cladding by plasma enhanced chemical vapor deposition to a thickness of approximately 550 nanometers to form the core. The SiO_xN_y may be deposited to create a core with a refractive index of approximately 2 at a wavelength of 1550 nanometers. Identical coatings may be applied to both sides of the wafer in order to balance stresses, and therefore mitigate warping or bending of the wafer. Alternatively, the core layer may be created with a tantalum pentoxide layer deposited via an ion beam sputtering process. The tantalum pentoxide may have an index of refraction of approximately 2 and the core layer may have a thickness of approximately 500 nm, in one example.

A cover plate, which may be made of 1.1 millimeter thick 1737 coming glass coated on one side with an indium tin oxide (ITO) film to produce a nominal 100 ohms/square conductive layer, may be used for the upper heating element, and may be diced to a size that would allow for a 10 millimeter interaction length between the coupled light and the liquid crystal and may have sufficient over-hang on both sides of the waveguide to attach 1 millimeter wide and 10 millimeter long bus bar electrodes parallel to the waveguide.

The wafer, which may be generally round with a diameter of 100 mm, may be diced into smaller 20 millimeter by 40 millimeter parts. Each diced part may then be coated with an alignment film approximately 120 angstroms in thickness. The alignment film or layer may be used to induce a homeotropic orientation of the liquid crystal upper cladding. The film or layer may be produced by spin coating an 8:1 mixture of Nissan polyimide varnish solvent # 21 to Nissan polyimide type 1211 filtered at 0.2 microns at 3000 revolutions per minute. The same spin coating process may be performed on the ITO heater cover plate. Once both the wafer and the cover glass are coated with the polyimide, the polyimide may be imidized by baking in an oven at approximately 180 degrees Celsius for approximately one hour. The polyimide coatings may be mechanically buffed with a dense piled cloth to induce preferential alignment along the light wave propagation direction of the waveguide. The 1737 glass coverplate may be spaced from the diced wafer parts with 5-micron borosilicate glass spacers immersed in a ultra-violet curing adhesive such as Norland 68. The cover plate may then be attached to the waveguide so as to create an anti-parallel liquid crystal alignment. The waveguide may then be exposed to 365-nanometer light until fully cured. Straight Norland 68 may be used to backfill via capillary action the remaining exposed edges making up the glue walls. One 3-millimeter opening may be left on a side 90 degrees to the buff direction. 4-cyano-4-n-pentylbyphenyl (5CB) liquid crystal material supplied by EMD Chemicals, Inc., may then be introduced into the upper cladding. While the liquid crystal material is introduced to the waveguide the air pressure may be held at 30 microns of vacuum. Once filled, the hole in the glue wall may

be plugged by using Norland UVS-91 visible-uv curing adhesive. Once fully cured the output edge of the assembled device may be polished utilizing diamond impregnated polishing pads supplied by Ultratec Manufacturing, the final polish may be performed using a 0.2 micron diamond pad. Wires may then be attached to the two ITO electrodes using conductive epoxy, each connection may be elongated to produce 1 millimeter wide and 10 millimeter long bus bars parallel to the waveguide.

A TEC element of approximately the same size as the waveguide may be attached to the waveguide with good thermal contact to the waveguide.

Example of operation may include coupling 1400-nanometer light into the waveguide by means of a silicon 45-45-90 prism. TM light may be introduced into the TM0 mode of the waveguide. The TEC cooler attached to the waveguide may be driven to cool the cell down to just above crystallization of the liquid crystal, which for 5CB is approximately 24 degrees Celsius, thus maximizing the liquid crystal refractive index of n_e. By running sufficient current through the ITO, heating of the liquid crystal layer will result in a reduction on the refractive index n_e. Alternatively, rather than using the ITO as a resistive heating element, one may utilize high conductivity ITO and capacitively heat the liquid crystal directly. For example, a typical liquid crystal waveguide has a capacitance of approximately 0.3 nanofarads. If an AC drive voltage of 10 volts is applied, with a frequency of 100 kHz, then approximately 1.5 milliamps will flow through the cell. This will directly heat the liquid crystal material, at a power rate of approximately 15 milliwatts. This can be controlled either by altering the frequency of the drive waveform, or the amplitude. To measure the resulting phase change in the TM light as temperature is varied a mach-zehnder style interferometer may be set-up by interfering the TM out-put from the waveguide to TE light not coupled into the system. For 1400 nanometer light an InGaAs photo-detector may measure the constructive and destructive interference of the interfering TM and TE light, each subsequent constructive or destructive fringe measured on the detector would represent 2π phase change. Theoretical modeling indicates that the OPD may be tuned by 32π.

Accordingly, it can be seen that embodiments of the present invention provide for dynamic non-mechanical control of light as it propagates through the waveguide. This technology could be replacements for such wide-spread applications as retail store bar-code scanners, CD/DVD optical read/write heads, the emerging markets of optical/holographic datastorage, telecommunications optical switches, bio-sensing (i.e., lab-on-a-chip) applications, optical computer backplanes, for example. In addition to the beam steerer applications, tunable lens designs could permit electro-optic zoom lenses, selective detection for lab-on-a-chip biosensors, tunable collimation lenses for fiber to waveguide couplers, for example.

Embodiments of the present invention may be used in conjunction with conventional digital and analog circuitry, either separately or integrated on a single integrated circuit. For instance, the voltage or current applied to one or more thermal control electrodes may be controlled by a microprocessor or other logic or programmable logic devices, and such logic may be included on-chip with the waveguide.

While the methods disclosed herein have been described and shown with reference to particular operations performed in a particular order, it will be understood that these operations may be combined, sub-divided, or re-ordered to form equivalent methods without departing from the teachings of the present invention. Accordingly, unless specifically indicated herein, the order and grouping of the operations is not a limitation of the present invention.

While the invention has been particularly shown and described with reference to embodiments thereof, it will be understood by those skilled in the art that various other changes in the form and details may be made without departing from the spirit and scope of the invention.

The invention claimed is:

1. A waveguide having an adjustable index of refraction, the waveguide receiving a light beam, the waveguide comprising:

a core for guiding the light beam through the waveguide;

at least one cladding;

liquid crystal material disposed within the at least one cladding of the waveguide; and

at least one temperature control element for receiving at least one control signal to control a temperature of at least a portion of the liquid crystal material;

wherein when the at least one control signal is applied to the at least one temperature control element, a temperature of the temperature control element rises, thereby heating up the temperature of the portion of liquid crystal material, thereby altering the index of refraction of the waveguide by an amount that is controlled by the control signal.

2. The waveguide of claim **1**, wherein the liquid crystal material is a nemetic material.

3. The waveguide of claim **1**, wherein the at least one temperature control element includes a resistive heater.

4. The waveguide of claim **1**, wherein the at least one temperature control element includes at least one conductive layer.

5. The waveguide of claim **1**, wherein the at least one temperature control element includes an upper temperature control element and a lower temperature control element.

6. The waveguide of claim **1**, wherein the light beam includes a TM polarized light beam.

7. The waveguide of claim **1**, wherein the light beam includes a TE polarized light beam.

8. The waveguide of claim **1**, wherein the at least one control signal includes a DC voltage.

9. The waveguide of claim **1**, wherein the at least one control signal includes an AC voltage.

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