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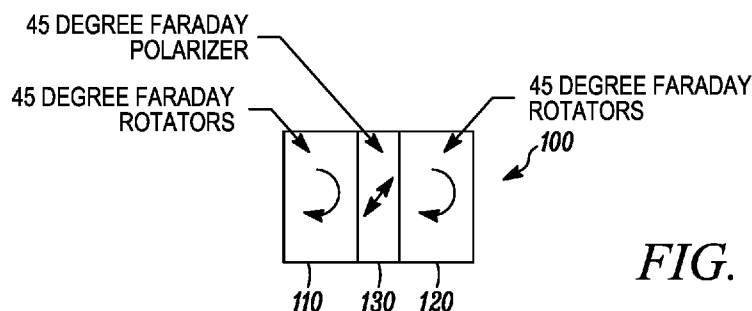


FIG. 1

(57) Abstract: An optical device includes first and second 45° Faraday rotators. A 45° polarizer is located between the first and second Faraday rotators such that light in a prescribed polarization state that is incident on the first 45° Faraday rotator traverses the first 45° Faraday rotator as well as the 45° polarizer and the second 45° Faraday rotator. In one implementation the optical device is operable to receive a light beam traveling in a first direction and output a light beam that is in a predetermined polarization state. Likewise, the optical device is operable to receive an unpolarized light beam traveling in a second direction opposite the first direction and outputs a light beam that is in a predetermined polarization state. The polarization state in which the two output beams are arranged may be the same or orthogonal to one another.



POLARIZATION PRESERVING BIDIRECTIONAL OPTICAL ELEMENT

Background

[0001] Conventional optical isolators are optical components that transmit light in one direction but block it in the backward-propagating direction. They are used when the reversely-propagating light needs to be avoided. For example, optical isolators minimize light reflections into transmitting lasers, and thus reduce instabilities and system noise in optical and electro-optical systems.

[0002] A principal component of an optical isolator is a Faraday rotator, whose operation is based on the Faraday effect. The Faraday effect is a magneto-optical phenomenon that, as a result of interaction between light and a magnetic field in a medium, causes a rotation of a polarization vector of light wave by a degree that is linearly proportional to the strength of a component of the magnetic field collinear with the direction of propagation of light. The empirical angle of rotation of a linear polarization vector of a light wave is given by $\beta = VBd$, where β is the angle of rotation (in radians), V is the Verdet constant for the material through which the light wave propagates, B is the magnetic flux density in the direction of propagation (in teslas), and d is the length of the path (in meters). The Verdet constant reflects the strength of the Faraday effect for a particular material. The Verdet constant can be positive or negative, with a positive Verdet constant corresponding to a counterclockwise rotation when the direction of propagation is parallel to the magnetic field.

Summary

[0003] In accordance with one aspect of the subject matter described herein, an optical device is provided that includes first and second 45° Faraday rotators. A 45° polarizer is located between the first and second Faraday rotators such that light in a prescribed polarization state that is incident on the first 45° Faraday rotator traverses the first 45° Faraday rotator as well as the 45° polarizer and the second 45° Faraday rotator.

[0004] In accordance with another aspect of the subject matter described herein, an optical device is provided that includes first and second 45° Faraday rotators. A 45°

polarizer is located between the first and second Faraday rotators. The first and second 45° Faraday rotators are arranged with respect to one another so that only optical energy that is in a first polarization state is able to propagate through the optical device when the optical energy is incident upon the optical device from a first direction and only optical energy that is in a second polarization state is able to propagate through the optical device when the optical energy is incident upon the optical device from a second direction opposite to the first direction. The first and second polarization states are orthogonal to one another.

[0005] In accordance with yet another aspect of the subject matter described herein, a bidirectional mode-locked laser is provided that includes an optical fiber cavity, a gain element, a mode-locking element and a bidirectional polarization element. The optical fiber cavity includes polarization-maintaining optical fiber. The gain element is located in the optical fiber cavity for amplifying optical signals propagating in the optical fiber cavity. The mode-locking element is located in the optical fiber cavity for mode-locking the laser cavity to thereby generate first and second optical pulse trains traveling in opposite directions in the optical fiber cavity. The bidirectional polarization element is located in the optical fiber cavity. The bidirectional polarization element is configured to only allow optical energy that is in a first polarization state to propagate therethrough in first and second directions. The first and second directions are opposite to one another and the first and second polarization states are orthogonal to one another. The bidirectional polarization element is located between two polarization-maintaining optical fiber segments in the optical fiber cavity that are oriented with respect to one another so that optical energy propagating in the respective optical fiber segments are in orthogonal polarization states with respect to one another.

[0006] This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used as an aid in determining the scope of the claimed subject matter. Furthermore, the claimed subject matter is not limited to

implementations that solve any or all disadvantages noted in any part of this disclosure.

Brief Description of the Drawings

[0007] FIG. 1 shows one example of an optical arrangement that is referred to herein as a bidirectional polarization isolator.

[0008] FIG. 2a shows the polarization state of an initially unpolarized optical beam as it propagates in the forward direction from left to right through the bidirectional polarization isolator of FIG. 1 and FIG. 2b shows the polarization state of an initially unpolarized optical beam as it propagates in the backward direction from right to left through the bidirectional polarization isolator of FIG. 1.

[0009] FIG. 3 shows one example of a bidirectional mode-locked laser in which the bidirectional polarization isolator described herein may be employed.

[0010] FIG. 4 shows a segment of the bidirectional mode-locked laser shown in FIG. 3 with the bidirectional polarization isolator of FIG. 1 inserted between two polarization maintaining optical fiber segments of the laser cavity.

[0011] FIG. 5a and 5b shows, respectively, the forward and backward operation of the bidirectional polarization isolator of FIG. 4.

[0012] FIG. 6 shows another example of a bidirectional polarization isolator.

[0013] FIG. 7a shows the polarization state of an initially unpolarized optical beam as it propagates in the forward direction from left to right through the bidirectional polarization isolator of FIG. 6 and FIG. 7b shows the polarization state of an initially unpolarized optical beam as it propagates in the backward direction from right to left through the bidirectional polarization isolator of FIG. 6.

[0014] FIG. 8 shows one example of the bidirectional polarization isolator of FIG. 1 having an all fiber configuration.

Detailed Description

[0015] FIG. 1 shows one example of an optical arrangement that is referred to herein as a bidirectional polarization isolator. As explained in more detail below, the isolator is operable to receive a light beam traveling in a first direction and output a light beam that is in a predetermined polarization state such as a linear polarization state.

Likewise, the bidirectional polarization isolator is operable to receive an unpolarized light beam traveling in a second direction opposite to the first direction and once again output a light beam that is in a predetermined polarization state, which may also be a linear polarization state. The polarization state in which the two output beams are arranged may be the same or orthogonal to one another.

[0016] More specifically, the bidirectional polarization isolator 100 shown in FIG. 1 includes a first 45 degree Faraday rotator 110, a second 45 degree Faraday rotator 120 and a 45 degree polarizer 130 located between the first and second Faraday rotators 110 and 120. The first and second Faraday rotators 110 and 120 are arranged to rotate the polarization of incoming light in the same direction by 45 degrees.

[0017] In FIG. 1 and the figures that follow, the polarization states are assumed for purposes of illustration to be linear polarization states. One linear polarization state of light is represented by a vertical arrow and the orthogonal linear polarization state is represented by a horizontal arrow.

[0018] FIG. 2a shows the polarization state of an initially unpolarized optical beam as it propagates from left to right through the bidirectional polarization isolator 100. That is, the beam is incident on first Faraday rotator 110 and exits the isolator 100 from second Faraday rotator 120. As shown, the vertical component of the incoming unpolarized optical beam is rotated by 45 degrees in the clockwise direction by the first Faraday rotator 110. Since the rotated component is now aligned with the polarization axis of polarizer 130, it passes through the polarizer 120 and is incident upon the second polarizer 130, which in turn further rotates the polarization state of the beam in the clockwise direction by an additional 45 degrees. Thus, a vertically polarized component of an optical beam is output from the bidirectional polarization isolator 100 in a horizontally polarized state.

[0019] As further shown in FIG. 2a, the horizontal component of the incoming unpolarized optical beam is also rotated by 45 degrees in the clockwise direction by the first Faraday rotator 110. However, since the rotated component is now in a polarization state orthogonal to the polarization axis of the polarizer 130, the beam will be blocked and consequently no light will be output by second Faraday rotator 120. Thus, the net result is that an unpolarized beam incident on the first Faraday rotator 110 produces a horizontally polarized beam at the output of the second Faraday rotator 120.

[0020] FIG. 2b shows the polarization state of an initially unpolarized optical beam as it propagates from right to left through the bidirectional polarization isolator 100. That is, the beam is incident on the second Faraday rotator 120 and exits the isolator 100 from the first Faraday rotator 120. As shown, the vertical component of the incoming unpolarized optical beam is rotated by 45 degrees in the clockwise direction by the second Faraday rotator 120. Since the rotated component is now aligned with the polarization axis of polarizer 130, it passes through the polarizer 130 and is incident upon the first Faraday rotator 110, which in turn further rotates the polarization state of the beam in the clockwise direction by an additional 45 degrees. Thus, a vertically polarized component of an optical beam is output from the bidirectional polarization isolator 100 in a horizontally polarized state

[0021] As further shown in FIG. 2b, the horizontal component of the incoming unpolarized optical beam is also rotated by 45 degrees in the clockwise direction by the second Faraday rotator 120. However, since the rotated component is now in a polarization state orthogonal to the polarization axis of the polarizer 130, the beam will be blocked and consequently no light will be output by the first Faraday rotator 110. Thus, the net result is that an unpolarized beam incident on the first Faraday rotator 110 produces a horizontally polarized beam at the output of the second Faraday rotator 120.

[0022] As FIGs. 2a and 2b illustrate, an unpolarized optical beam incident on the bidirectional polarization isolator 100 from either the left (so that it is first incident on

the first Faraday rotator 110) or the right (so that it is first incident on the second Faraday rotator 120) will output an optical beam in the horizontal polarization state.

[0023] The bidirectional polarization isolator 100 described herein may be used in a number of different applications. For example, as described below the bidirectional polarization isolator 100 may be used to facilitate mode-locking in a bidirectional mode-locked laser, which is used, among other things, to generate optical frequency combs. Such optical frequency combs may be employed in applications such as spectroscopy, precision range-finding and a wide variety of pump-probe experiments using asynchronous sampling.

[0024] In a mode-locked bidirectional laser, the various modes oscillate with fixed phases with respect to one another. In this way the laser modes will all periodically constructively interfere with one another, producing an intense burst or pulse of light. Such a laser is said to be mode-locked or phase-locked.

[0025] FIG. 3 shows one example of a bidirectional mode-locked laser 200. The laser 200 includes a polarization maintaining fiber 116 that defines a ring cavity. The laser also includes a rare-earth doped fiber 112 that serves as the gain element, a wavelength division multiplexer (WDM) or optical coupler 114 for injecting the pump power into the laser cavity, an 2x2 50/50 output coupler 222 for extracting bidirectional optical pulses, and the bidirectional polarization isolator 100. A saturable absorber 118 such as a carbon nanotube-based saturable absorber as the mode-locking element. By using a mode-locking element optical pulse trains traveling in opposite directions may be generated.

[0026] In one illustrative embodiment the rare-earth doped fiber 112 is an erbium doped fiber and the laser 200 operates at a wavelength of 1560nm. Of course, in other embodiments mode-locked lasers using other rare-earth elements and operating at other wavelengths may be employed as well.

[0027] In the example shown in FIG. 3 the bidirectional mode-locked laser 200 is mode locked by a passive mode-locking technique in which an element is placed in

laser cavity which causes self-modulation of the light. In the example of FIG. 3 the element is a saturable absorber, which has an intensity dependent transmission response. In general, passive mode-locking may be achieved using others suitable elements instead of a saturable absorber including, for instance, a semiconductor saturable absorber mirror (Sesam) or an arrangement that employs a nonlinear polarization evolution (NPE) mechanism. In other embodiments the bidirectional mode-locked laser may be mode-locked by an active mode-locking technique in which an external signal drives an optical modulator that modulates the light in the laser cavity. The optical modulator is typically located within the laser cavity itself.

[0028] In addition to different mode locking mechanisms, the bidirectional mode-locked laser may also employ various arrangements of fiber cavities that are different from the ring cavity shown in FIG. 3. For example, without limitation, linear cavities with Faraday rotator ends, figure-8 cavity arrangements and multiple ring arrangements may be employed. More generally, any laser cavity may be employed that can be mode-locked in a bidirectional manner.

[0029] Polarization effects can cause unwanted power and frequency modulation in laser systems generally. In particular, such effects can cause laser sources to become unstable when bidirectional lasing is desired. However, the deleterious impact of polarization on bidirectional lasing can be ameliorated by isolating the polarization states of the light within the bidirectional laser so that the light propagating in any given direction is in a single polarization state. For instance, in the laser cavity shown in FIG. 3 light propagating in a clockwise direction may be arranged to be in one polarization state and light propagating in the counterclockwise direction may be arranged to be in another polarization state. By arranging the polarization states in this way bidirectional mode-locked lasers may be self-starting without the need for control systems or technician input. Moreover, the light in each propagation direction may share common amplifier noise, making it possible to cancel a significant part of the timing instability that can arise in bidirectional mode-locked lasers.

[0030] The bidirectional polarization isolator 100 employed in the bidirectional mode-locking laser shown in FIG. 3 assigns a single linear polarization state to each

propagation direction in the laser cavity. In this way the light propagating in the clockwise and counterclockwise directions each can be in a single polarization state. FIG. 4 shows a segment of the bidirectional mode-locking laser shown in FIG. 3 with the bidirectional polarization isolator 100 of FIG. 1 inserted between two polarization maintaining optical fiber segments 160 and 170 of the laser cavity. In this example, collimating lens 165 and 175 are employed between the fiber segments 160 and 170 and the bidirectional optical isolator 100 in FIG. 4 in order to couple the light between the fiber segments and the bidirectional optical isolator.

[0031] For convenience, FIGs. 5a and 5b shows the forward and backward operation of the bidirectional polarization isolator 100 of FIG. 4, which was previously shown in FIGs. 2a and 2b.

[0032] In the example of FIG. 3 the polarization maintaining optical fiber segments are Polarization Maintaining and Absorption Reducing (PANDA) fibers, which as shown, use stress rods 180 that are nominally circular in cross section. Other examples of polarization maintaining fibers that may be employed include, without limitation, "bow-tie" polarization maintaining fiber, in which the stress rods take the form of annular wedges, and elliptical clad polarization maintaining fiber, in which an elliptically shaped cladding generates the required stress field.

[0033] As shown, the two optical fiber segments 160 and 170 in FIG. 4 are rotationally oriented with respect to one another so that linearly polarized light propagating in them are orthogonal to one another. That is, the two optical fiber segments are rotated by 90° with respect to one another so that if the left-most fiber segment 160 supports, for example, vertically polarized light the right-most fiber segment 170 will support horizontally polarized light. The bidirectional optical isolator 100 serves to ensure that linearly polarized light is injected to each fiber segment of the laser cavity.

[0034] The length of each of the optical fiber segments in the laser cavity generally will depend on the application for which the bidirectional mode-locked laser is to be employed. For instance, for applications that require two opposite-going optical pulse

trains to be generated which have similar but not identical repetition rates, the two segments may be approximately equal in length. In other applications that require the optical pulse trains to have significantly different repetition rates, the difference in the lengths of the two segments may be greater.

[0035] The example of the bidirectional polarization isolator described above outputs an optical beam in each of the two directions that are in the same polarization state. This is accomplished by using two 45° Faraday rotators that rotate the polarization state of light in the same direction. In one alternative embodiment, illustrated in FIG. 6, the bidirectional polarization isolator 200 includes two 45° Faraday rotators that rotate the polarization state of light in the opposite directions. For instance, in this example the first 45° Faraday rotator 210 rotates the polarization state in the clockwise direction and the second 45° Faraday rotator 220 rotates the polarization state in the counter-clockwise direction. Fig. 7a shows the polarization state of an initially unpolarized optical beam as it propagates from right to left through the bidirectional polarization isolator 200. Likewise, FIG. 7b shows the polarization state of an initially unpolarized optical beam as it propagates from right to left through the bidirectional polarization isolator 200. As shown, the bidirectional polarization isolator 200 outputs an optical beam in each of the two directions that are in opposite polarization states.

[0036] In some embodiments, the bidirectional polarization isolator may include additional optical components in addition to those shown in the figures above. For instance, in some cases a 45° half-wave plate may be employed. By way of illustration, the 45° half-wave plate may be inserted before the first 45° Faraday rotator 110 shown in FIG. 1 or the first 45° Faraday rotator 210 shown in FIG. 5. Alternatively, the 45° half-wave plate may be inserted after the second 45° Faraday rotator 120 shown in FIG. 1 or the second 45° Faraday rotator 220 shown in FIG. 5. The 45° half-wave plate will reflect a linear polarization state about a 45° axis and rotate a horizontally polarized state to a vertically polarized state and vice versa. As a consequence, when a bidirectional polarization isolator incorporating a 45° half-wave plate is employed in a bidirectional mode-locked layer, it is not necessary to rotate the

different fiber segments with respect to one another so that linearly polarized light propagating in them are orthogonal to one another. That is, the different fiber segments do not need to use a 90° splice, but rather may be spliced so that they support the same linear polarization state.

[0037] The bidirectional polarization isolators described herein may be produced in a variety of different configurations or types, including, for instance, in bulk, free space configurations, integrated optical configuration that allow for monolithic integration with other optical components (e.g., solid state ring lasers), and all fiber configurations. FIG. 8 shows one example of the bidirectional polarization isolator of FIG. 1 having an all fiber configuration, which may be particularly suitable for use in a bidirectional mode-locked fiber laser such as shown in FIG. 3. In this configuration the Faraday rotator that is employed is a single-mode fiber or a multi-mode fiber that is doped with rare-earth material(s). As shown, optical isolator 300 includes a fiber-optic based polarizer 315, a first Faraday rotator 310 and a second Faraday rotator 320. Each Faraday rotator 310 and 320 includes a fiber optic component 306 disposed within a magnetic cell 308 (shaped, for example, as a tube). The magnetic flux density of the magnetic cell 308 should be strong enough to produce a 45 degree polarization rotation when the light passes through the Faraday rotator. The ends of the fiber-optic components 306 are fusion-spliced with corresponding ends of the fiber polarizer 315 (as shown schematically by fiber-fusion splicing joints 332 and 334), thereby creating an all-fiber-optic based device. The fiber optic components 306 used in the first and second Faraday rotators 310 and 320, may be doped with a rare-earth oxide such, for example, as at least one of Pr_2O_3 , Nd_2O_3 , P_2O_3 , Sm_2O_3 , Eu_2O_3 , Gd_2O_3 , Tb_2O_3 , Dy_2O_3 , Ho_2O_3 , Er_2O_3 , Tm_2O_3 , Yb_2O_3 , La_2O_3 , Ga_2O_3 , Ce_2O_3 , and Lu_2O_3 .

[0038] As previously mentioned, the bidirectional polarization isolator described herein may be employed in a wide variety of different laser configurations in which polarization multiplexed, dual optical frequency combs are desired. Illustrative laser topologies in which the bidirectional polarization isolator may be employed are found the following references: Michael Kolano, Benedict Gräf, Stefan Weber, Daniel

Molter, and Georg von Freymann, "Single-laser polarization-controlled optical sampling system for THz-TDS," *Opt. Lett.* 43, 1351-1354 (2018); Xin Zhao, Ting Li, Ya Liu, Qian Li, and Zheng Zheng, "Polarization-multiplexed, dual-comb all-fiber mode-locked laser," *Photon. Res.* 6, 853-857 (2018); Karol Krzempek, Dorota Tomaszewska, and Krzysztof M. Abramski, "Dissipative soliton resonance mode-locked all-polarization-maintaining double clad Er:Yb fiber laser," *Opt. Express* 25, 24853-24860 (2017); and Takuro Ideguchi, Tasuku Nakamura, Yohei Kobayashi, and Keisuke Goda, "Kerr-lens mode-locked bidirectional dual-comb ring laser for broadband dual-comb spectroscopy," *Optica* 3, 748-753 (2016).

[0039] What has been described and illustrated herein are embodiments of the invention along with some of their variations. The terms, descriptions and figures used herein are set forth by way of illustration only and are not meant as limitations. Those skilled in the art will recognize that many variations are possible within the spirit and scope of the embodiments of the invention.

Claims

1. An optical device, comprising:
first and second 45° Faraday rotators; and
a 45° polarizer located between the first and second Faraday rotators
such that light in a prescribed polarization state that is incident on the first 45°
Faraday rotator traverses the first 45° Faraday rotator as well as the 45° polarizer and
the second 45° Faraday rotator.
2. The optical device of claim 1, wherein the first and second 45° Faraday
rotators are arranged to rotate a polarization state of light passing therethrough in a
common direction.
3. The optical device of claim 1, wherein the first and second 45° Faraday
rotators are arranged to rotate a polarization state of light passing therethrough in
opposite directions.
4. The optical device of claim 1, wherein the prescribed polarization state
is a linear polarization state.
5. The optical device of claim 1, wherein the first and second 45° Faraday
rotators are arranged so that the light in the prescribed polarization state is output
from the second 45° Faraday rotator in a second state orthogonal to the prescribed
polarization state.
6. The optical device of claim 1, wherein the first and second 45° Faraday
rotators are arranged so that the light in the prescribed polarization state output from
the second Faraday rotator is in in the prescribed polarization state.
7. An optical device, comprising:
first and second 45° Faraday rotators; and

a 45° polarizer located between the first and second Faraday rotators, the first and second 45° Faraday rotators being arranged with respect to one another so that only optical energy that is in a first polarization state is able to propagate through the optical device when the optical energy is incident upon the optical device from either first or second directions that are opposite to one another.

8. An optical device, comprising:

first and second 45° Faraday rotators; and

a 45° polarizer located between the first and second Faraday rotators, the first and second 45° Faraday rotators being arranged with respect to one another so that only optical energy that is in a first polarization state is able to propagate through the optical device when the optical energy is incident upon the optical device from a first direction and only optical energy that is in a second polarization state is able to propagate through the optical device when the optical energy is incident upon the optical device from a second direction opposite to the first direction, the first and second polarization states being orthogonal to one another

9. A bidirectional mode-locked laser, comprising:

an optical fiber cavity that includes polarization-maintaining optical fiber;

a gain element located in the optical fiber cavity for amplifying optical signals propagating in the optical fiber cavity;

a mode-locking element located in the optical fiber cavity for mode-locking the laser cavity to thereby generate first and second optical pulse trains traveling in opposite directions in the optical fiber cavity; and

a bidirectional polarization element located in the optical fiber cavity, the bidirectional polarization element being configured to only allow optical energy that is in a first polarization state to propagate therethrough in first and second directions, the first and second directions being opposite to one another and the first and second polarization states being orthogonal to one another, the bidirectional polarization element being located between two polarization-maintaining optical fiber segments in

the optical fiber cavity that are oriented with respect to one another so that optical energy propagating in the respective optical fiber segments are in orthogonal polarization states with respect to one another.

10. The bidirectional mode-locked laser of claim 9, wherein the first and second polarization states are linear polarization states.

11. The bidirectional mode-locked laser of claim 9, wherein the bidirectional polarization element outputs the optical energy in a second polarization state orthogonal to the first polarization state.

12. The bidirectional mode-locked laser of claim 9, wherein the two polarization-maintaining optical fiber segments are equal in length.

13. The bidirectional mode-locked laser of claim 9, wherein the two polarization-maintaining optical fiber segments are unequal in length.

14. The bidirectional mode-locked laser of claim 9, wherein the mode-locking element is configured for use with a passive mode-locking technique.

15. The bidirectional mode-locked laser of claim 14, wherein the mode-element includes a saturable-absorber.

16. The bidirectional mode-locked laser of claim 9, wherein the mode-locking element is configured for use with an active mode-locking technique.

17. The bidirectional mode-locked laser of claim 16, wherein the mode-element includes an optical modulator.

18. The bidirectional mode-locked laser of claim 9, wherein the gain element includes a rare-earth doped optical fiber.

19. The bidirectional mode-locked laser of claim 18, wherein the rare-earth doped optical fiber is an erbium-doped optical fiber.

20. The bidirectional mode-locked laser of claim 9, wherein the bidirectional polarization element includes first and second 45° Faraday rotators and a 45° polarizer located between the first and second 45° Faraday rotators.

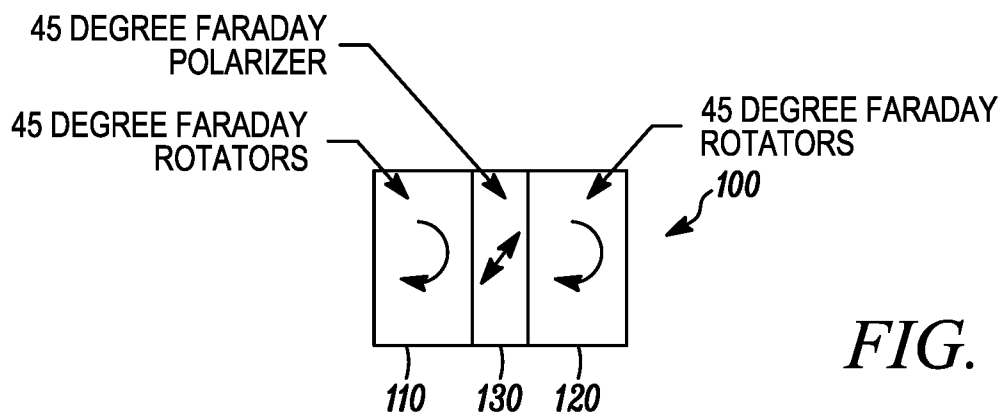


FIG. 1

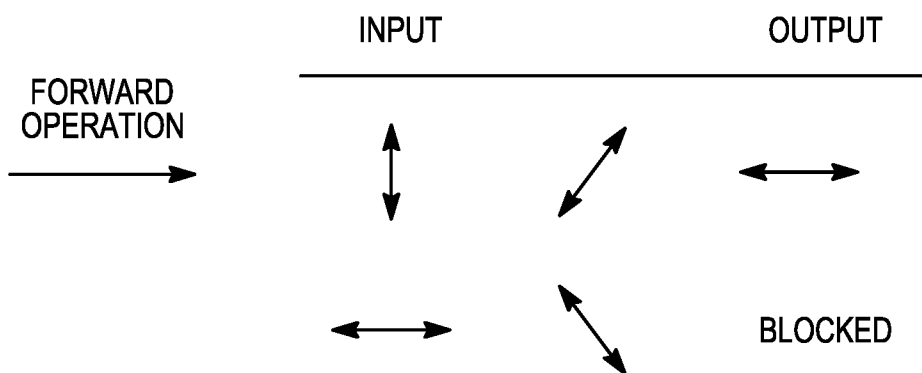
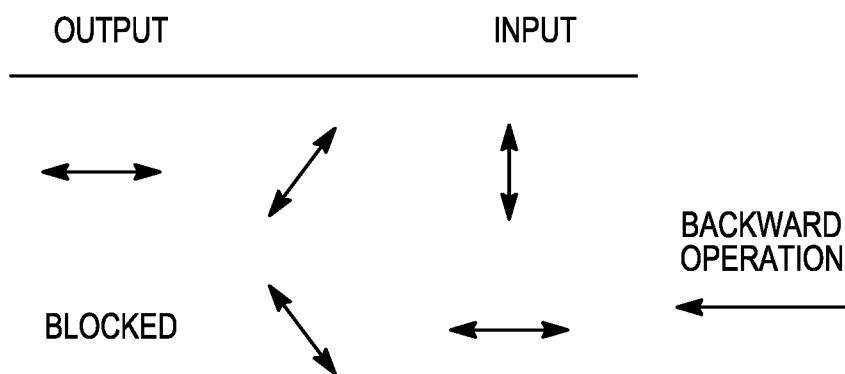


FIG. 2A

FIG. 2B



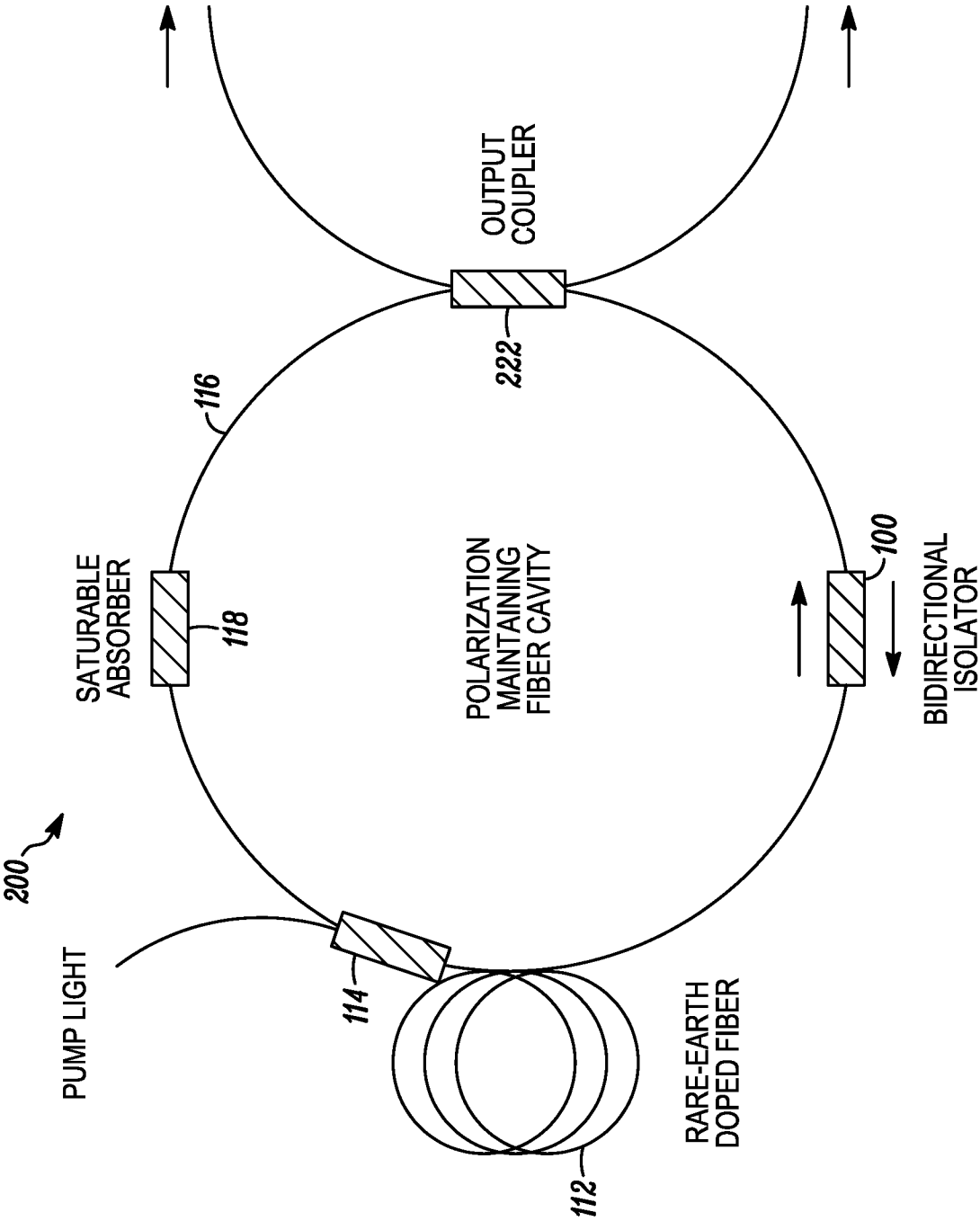


FIG. 3

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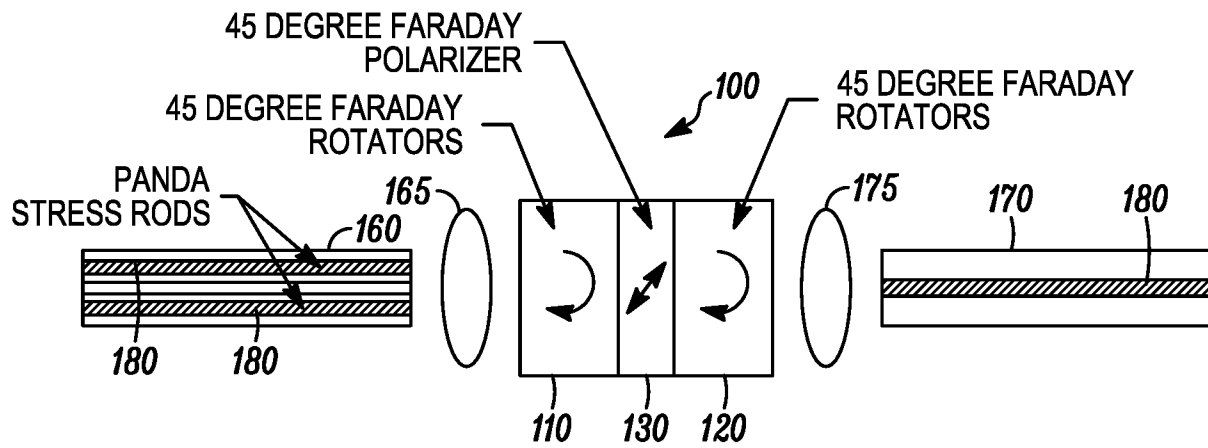


FIG. 4

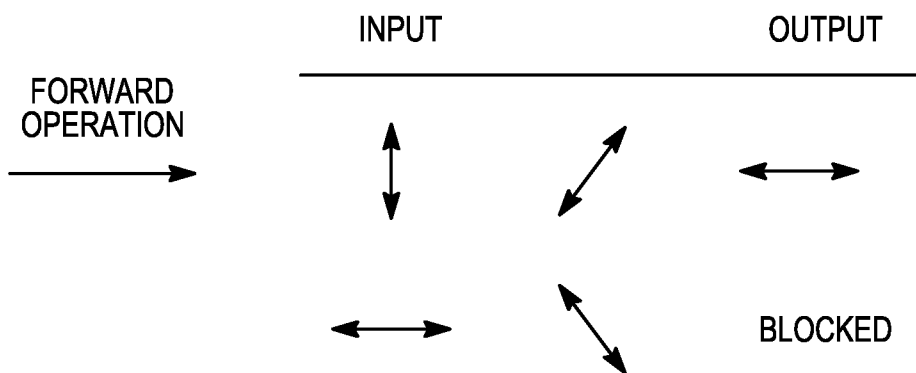
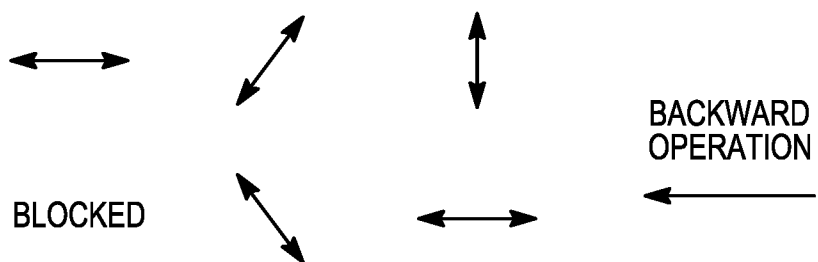


FIG. 5A

FIG. 5B



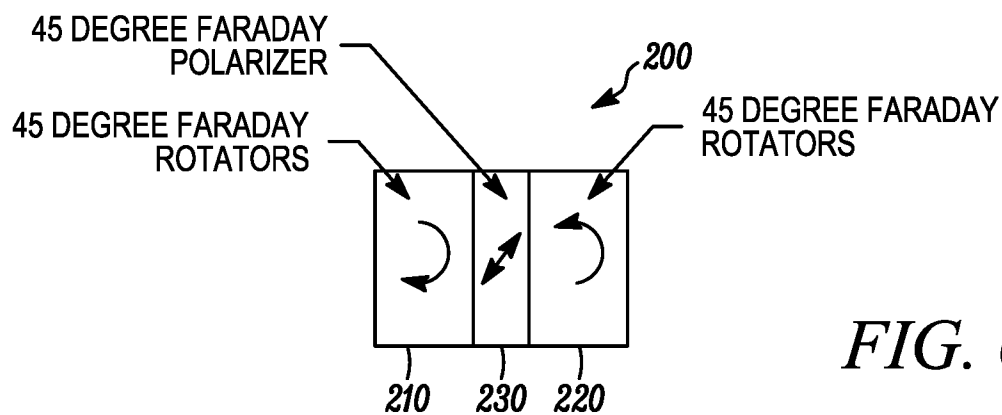


FIG. 6

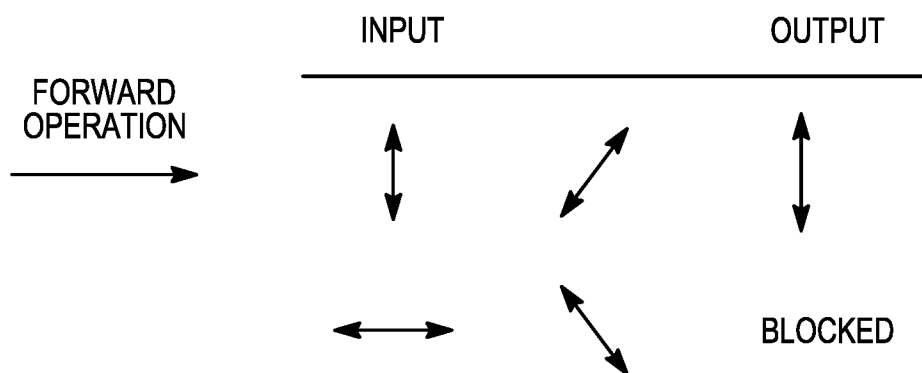
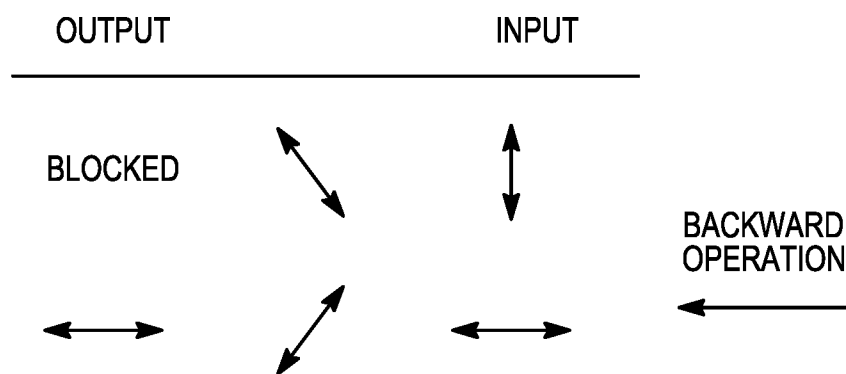


FIG. 7A

FIG. 7B



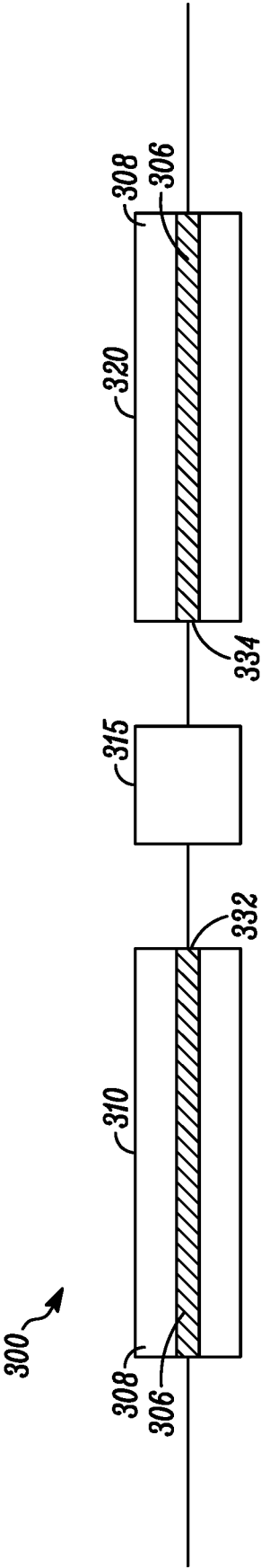


FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2019/018702

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - G02F 1/01; G02B 5/30; G02B 6/024; G02B 6/26; H01P 1/165 (2019.01)

CPC - G02F 1/01; G02B 5/30; G02B 6/024; G02B 6/26; H01P 1/165 (2019.05)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

USPC - 359/483.01; 359/484.03; 359/484.01; 359/484.02 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X ---	US 3,436,678 A (SHARP et al) 01 April 1969 (01.04.1969) entire document	1, 3, 4 ---
Y		3
X ---	JP 2004226599 A (PHOTONIC LATTICE INC) 12 August 2004 (12.08.2004) entire document	1, 7 ---
Y		2-6, 8
Y	US 4,756,607 A (WATANABE et al) 12 July 1988 (12.07.1988) entire document	2
Y	US 2007/0211252 A1 (FUTAMI et al) 13 September 2007 (13.09.2007) entire document	4
Y	US 5,448,579 A (CHANG et al) 05 September 1995 (05.09.1995) entire document	5, 6, 8
A	US 2009/0122397 A1 (KUBO et al) 14 May 2009 (14.05.2009) entire document	1-8
A	EP 0851266 A2 (NEC CORPORATION et al) 01 July 1998 (01.07.1998) entire document	1-8

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

30 May 2019

Date of mailing of the international search report

19 JUL 2019

Name and mailing address of the ISA/US

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Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:
See extra sheet(s).

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-8

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

Continued from Box No. III Observations where unity of invention is lacking

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I, claims 1-8, are drawn to an optical device, comprising: first and second 45° Faraday rotators; and a 45° polarizer located between the first and second Faraday rotators.

Group II, claims 9-20, are drawn to a bidirectional mode-locked laser, comprising: an optical fiber cavity that includes polarization-maintaining optical fiber; a gain element located in the optical fiber cavity for amplifying optical signals propagating in the optical fiber cavity.

The inventions listed as Groups I-II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: the special technical feature of the Group I invention: first and second 45° Faraday rotators; and a 45° polarizer located between the first and second Faraday rotators such that light in a prescribed polarization state that is incident on the first 45° Faraday rotator traverses the first 45° Faraday rotator as well as the 45° polarizer and the second 45° Faraday rotator as claimed therein is not present in the invention of Group II. The special technical feature of the Group II invention: an optical fiber cavity that includes polarization-maintaining optical fiber; a gain element located in the optical fiber cavity for amplifying optical signals propagating in the optical fiber cavity; a mode-locking element located in the optical fiber cavity for mode locking the laser cavity to thereby generate first and second optical pulse trains traveling in opposite directions in the optical fiber cavity; and a bidirectional polarization element located in the optical fiber cavity, the bidirectional polarization element being located between two polarization-maintaining optical fiber segments in the optical fiber cavity that are oriented with respect to one another so that optical energy propagating in the respective optical fiber segments are in orthogonal polarization states with respect to one another as claimed therein is not present in the invention of Group I.

Groups I and II lack unity of invention because even though the inventions of these groups require the technical feature of an optical device comprising a polarization element, this technical feature is not a special technical feature as it does not make a contribution over the prior art.

Specifically, US 2009/0122397 to Kubo et al. teaches an optical device comprising a polarization element (Para. [0007]).

Since none of the special technical features of the Group I or II inventions are found in more than one of the inventions, unity of invention is lacking.