(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
02 November 2017 (02.11.2017)

WIPO | PCT

(10) International Publication Number
WO 2017/190063 A2

(51) International Patent Classification:
G02B 6/124 (2006.01) ***G02B 6/13*** (2006.01)
G02B 6/126 (2006.01) ***G01R 15/24*** (2006.01)

(21) International Application Number:
PCT/US2017/030224

(22) International Filing Date:
28 April 2017 (28.04.2017)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:

62/328,726	28 April 2016 (28.04.2016)	US
62/365,553	22 July 2016 (22.07.2016)	US

(71) Applicant: GENERAL ELECTRIC COMPANY [US/US]; 1 River Road, Schenectady, New York 12345 (US).

(72) Inventors; and

(71) Applicants: KOSTE, Glen Peter [US/US]; General Electric Company Global Research, One Research Circle, Bldg. K1-3A59, Niskayuna, New York 12309 (US). **PALIT, Sabarni** [IN/US]; General Electric Company Global Research, One Research Circle, Bldg. K1-3A59, Niskayuna, New York 12309 (US). **DEKATE, Sachin Narahari** [US/US]; General Electric Company Global Research, One Research Circle, Bldg. K1-3A59, Niskayuna, New York 12309 (US).

(74) Agent: MANWARE, Robert A. et al.; P.O. Box 692289, Houston, Texas 77269 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(54) Title: PHOTONIC INTEGRATED CIRCUITS AND DEVICES FOR PHOTONIC SENSING

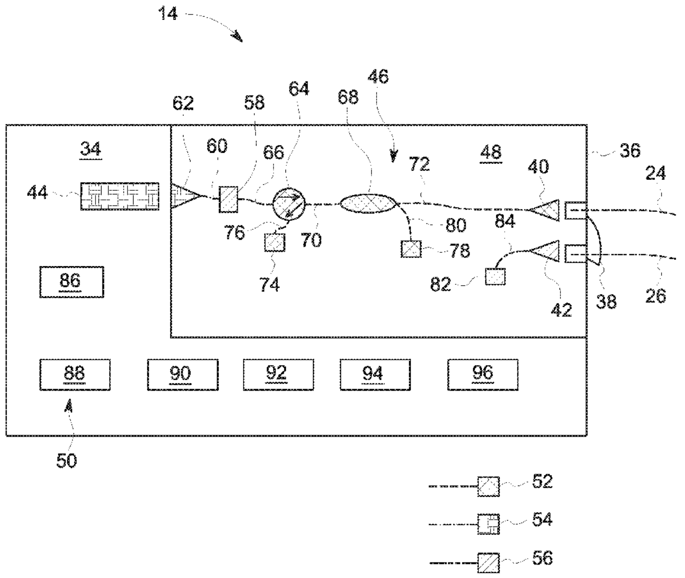

FIG. 2

(57) Abstract: A photonic sensing system includes an interrogator coupled to a sensing fiber. The interrogator includes a light source configured to emit light, and a photonic integrated circuit (PIC) comprising a plurality of photonic components. The PIC is configured to transmit the light emitted by the light source and to receive reflected light from the sensing fiber. The interrogator also includes a plurality of integrated circuit (IC) components configured to process and analyze signals from the interrogator to determine one or more measurands.

WO 2017/190063 A2

[Continued on next page]

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

PHOTONIC INTEGRATED CIRCUITS AND DEVICES FOR PHOTONIC SENSING

BACKGROUND

[0001] The subject matter disclosed herein relates to photonic sensing, and more specifically to integrated photonic polarization and wavelength sensing systems.

[0002] Photonic sensing, measurement based on photonic principles, is desirable in many applications. For example, a photonic sensing system may be used for measuring electrical current, temperature, strain, pressure, and many other measurands based on shifts in polarization or wavelength. A photonic sensing system may include a sensor interrogator coupled to a sensing fiber. In operation, the sensor interrogator may launch light into the sensing fiber and then analyze the backscattered or reflected (e.g., back-reflected) signals to make measurements, during which it may be desirable to isolate the optical source from the back-reflected or back-scattered light. For example, the sensor interrogator may include an isolator (e.g., a two port device to isolate the reflected light) or a circulator (e.g., a three-port device to direct the reflected light away from the light source) disposed between the light source and the sensing fiber to block back-reflected light from interfering with the light emitted by the light source. The sensor interrogator may selectively include discrete components, such as waveguide, reflector, isolator or circulator, distributed Bragg reflector (e.g., fiber Bragg grating or FBG), optical (de)multiplexer (e.g., arrayed waveguide grating or AWG), etc. The robustness (e.g., sensing integrity and/or mechanical integrity of the device) and/or functionalities (e.g., current sensing, wavelength sensing, etc.) of the photonic sensing system may vary or may be limited by ways of fabricating, coupling, and/or assembling of these discrete components. Accordingly, there is a need for systems and methods for more efficient architectures of various components of the photonic sensing system to provide improved robustness and functionalities.

BRIEF DESCRIPTION

[0003] Certain embodiments commensurate in scope with the originally claimed subject matter are summarized below. These embodiments are not intended to limit the scope of the disclosure. Indeed, the present disclosure may encompass a variety of forms that may be similar to or different from the embodiments set forth below.

[0004] In one embodiment, a photonic sensing system includes an interrogator coupled to a sensing fiber. The interrogator includes a light source configured to emit light, and a photonic integrated circuit (PIC) comprising a plurality of photonic components. The PIC is configured to transmit the light emitted by the light source and to receive reflected light from the sensing fiber. The interrogator also includes a plurality of integrated circuit (IC) components configured to process and analyze signals from the interrogator to determine one or more measurands.

[0005] In another embodiment, a system includes an integrated circuit (IC) includes a light source configured to emit light. The IC includes an interrogator configured to be coupled to a sensing fiber to transmit the light emitted by the light source and interrogate reflected light from the sensing fiber. The IC also includes a plurality of IC components configured to process and analyze signals from the interrogator to determine one or more measurands comprising electrical current or power. The interrogator includes a plurality of photonic components disposed on a single silicon-on-insulator (SOI) chip.

[0006] In another embodiment, an integrated circuit (IC) includes a light source configured to emit light. The IC includes an interrogator configured to be coupled to a sensing fiber to transmit the light emitted by the light source to the sensing fiber and to interrogate reflected light from the sensing fiber, wherein the sensing fiber comprising fiber Bragg gratings (FBG). The IC also includes a plurality of IC components configured to process and analyze signals from the interrogator to determine one or more measurand comprising wavelength, wherein the interrogator comprises a plurality of photonic components disposed on a single silicon-on-insulator (SOI) chip

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] These and other features, aspects, and advantages of the present disclosure will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

[0008] FIG. 1 is a schematic of a photonic sensing system with a remote rotator and a remote beam splitter, in accordance with an aspect of the present disclosure;

[0009] FIG. 2 is a schematic of a current sensor interrogator of the photonic sensing system of FIG. 1, in accordance with an aspect of the present disclosure;

[0010] FIG. 3 is a schematic of a photonic sensing system with a fully integrated sensor architecture, in accordance with an aspect of the present disclosure;

[0011] FIG. 4 is a schematic of a current sensor interrogator of the photonic sensing system of FIG. 3, in accordance with an aspect of the present disclosure;

[0012] FIG. 5 is a schematic of a photonic sensing system with a remote rotator, in accordance with an aspect of the present disclosure;

[0013] FIG. 6 is a schematic of a current sensor interrogator of the photonic sensing system of FIG. 5, in accordance with an aspect of the present disclosure;

[0014] FIG. 7 is a schematic of a photonic sensing system for wavelength measurements, in accordance with an aspect of the present disclosure;

[0015] FIG. 8 is a schematic of a wavelength sensor interrogator of the photonic sensing system of FIG. 7 with tunable narrowband source and polarization maintaining fibers, in accordance with an aspect of the present disclosure;

[0016] FIG. 9 is a schematic of a wavelength sensor interrogator of the photonic sensing system of FIG. 7 with tunable narrowband source and arbitrary fibers, in accordance with an aspect of the present disclosure;

[0017] FIG. 10 is a schematic of a wavelength sensor interrogator of the photonic sensing system of FIG. 7 with broadband source and polarization maintaining fibers, in accordance with an aspect of the present disclosure;

[0018] FIG. 11 is a schematic of a wavelength sensor interrogator of the photonic sensing system of FIG. 7 with broadband source and arbitrary fibers, in accordance with an aspect of the present disclosure;

[0019] FIGS. 12A and 12B show a top view partial schematic and a side view partial schematic, respectively, of a circulator of a photonic sensing system, and FIG. 12C show a side view partial schematic of another embodiment of the circulator of the photonic sensing system, in accordance with an aspect of the present disclosure;

[0020] FIG. 13 is a side view schematic of a Mach-Zehnder structure of the circulator of FIGS. 12A and 12B illustrating a butt-coupled architecture, in accordance with an aspect of the present disclosure;

[0021] FIGS. 14A-D are cross-sectional schematics illustrating a fabrication process of the butt-coupled architecture of FIG. 13 at various stages, in accordance with an aspect of the present disclosure;

[0022] FIGS. 15A-D are cross-sectional schematics illustrating another fabrication process of the butt-coupled architecture of FIG. 13 at various stages, in accordance with an aspect of the present disclosure;

[0023] FIGS. 16A and 16B show a top view partial schematic and a side view partial schematic, respectively, of a circulator of a photonic sensing system illustrating non-reciprocal phase shift controllable via heater lines, in accordance with an aspect of the present disclosure;

[0024] FIG. 17 is cross-sectional view schematic of a magneto-optic material of the circulator illustrating an example of a cerium doped yttrium iron garnet (Ce-YIG) on silicon-on-insulator (SOI) structure, in accordance with an aspect of the present disclosure;

[0025] FIG. 18 is cross-sectional view schematic of a magneto-optic material of the circulator illustrating another example of a Ce-YIG on SOI, in accordance with an aspect of the present disclosure;

[0026] FIG. 19 is a flow chart illustrating a method of fabricating the Ce-YIG on SOI of FIG. 17, in accordance with an aspect of the present disclosure; and

[0027] FIG. 20 is a flow chart illustrating a method of fabricating the Ce-YIG on SOI of FIG. 17, in accordance with an aspect of the present disclosure.

DETAILED DESCRIPTION

[0028] One or more specific embodiments will be described below. In an effort to provide a concise description of these embodiments, all features of an actual implementation may not be described in the specification. It should be appreciated that in the development of any such actual implementation, as in any engineering or design project, numerous implementation-specific decisions must be made to achieve the developers' specific goals, such as compliance with system-related and business-related constraints, which may vary from one implementation to another. Moreover, it should be appreciated that such a development effort might be complex and time consuming, but would nevertheless be a routine undertaking of design, fabrication, and manufacture for those of ordinary skill having the benefit of this disclosure.

[0029] When introducing elements of various embodiments of the present invention, the articles "a," "an," "the," and "said" are intended to mean that there are one or more of the elements. The terms "comprising," "including," and "having" are intended to be inclusive and mean that there may be additional elements other than the listed elements. Furthermore, any numerical examples in the following discussion are intended to be non-limiting, and thus additional numerical values, ranges, and percentages are within the scope of the disclosed embodiments.

[0030] As set forth above, a sensor interrogator may include various discrete components, and their fabrication, coupling, and/or assembling may influence the sensing system's robustness (e.g., sensing integrity and/or mechanical integrity) and/or functionalities (e.g., current sensing, wavelength sensing, etc.). In one aspect, the discrete components may be spread out and may occupy a large footprint. As such, one embodiment of the present disclosure is directed to architecting an integrated photonic sensor. In particular, combinations of discrete components are replaced by integrating all functionality onto a photonic integrated circuit (PIC), resulting in an integrated photonic sensor having reduced size, weight, and/or fabrication cost while at the same time improving robustness.

[0031] In another aspect, even within a component, the architecture of the component may influence the robustness of the overall sensing quality. For example, while a circulator has been demonstrated using a silicon-on-insulator (SOI) Mach Zehnder Interferometer (MZI), such technology may have several deficiencies. For example, a MZI may have strong wavelength dependence and narrow-band wavelength performance, and thus may require wavelength tuning or restriction to a functionality over a narrow wavelength range. As such, one embodiment of the present disclosure is directed to fabricating the MZI with improved architectures, including nearly equal MZI arm lengths, active phase tuning, patterning and bonding a magneto-optic material on a carrier substrate, coupling the carrier substrate on silicon waveguide chip, and aligning the coupled chips on an interposer.

[0032] Further, a circulator (e.g., MZI circulator) is fabricated by growing a cerium doped yttrium iron garnet (Ce-YIG) on a substrate which is then flip-chip bonded onto the SOI waveguide, and good direct bonding may benefit the performance of the circulator. In certain situations, upon respective surface treatments, Ce-YIG and SOI may be bonded by pressing them together without the use of an adhesive. However, even the state-of-the-art surface treatment may leave the surface depleted of oxygen, which may have negative impacts on the magnetic-properties of the Ce-YIG near the interface with the SOI waveguides. For example, the treated surfaces at the Ce-YIG and SOI interfaces may lead to reduced magneto-optic effect that may reduce the non-reciprocal phase-shift of the MZI. As such, one embodiment of the present disclosure is directed to methods for resetting the oxygen content near the surface of the Ce-YIG (e.g., after the respective surface treatment). Such methods may include a low-energy plasma-treatment, a high-energy plasma-treatment, an ozone treatment, or any other suitable oxidizing processes.

[0033] Turning now to the drawings, FIG. 1 shows a schematic of a photonic sensing system 10 coupled to a current (e.g., electrical current) carrying conductor 12. The photonic sensing system 10 may include a current sensor interrogator 14 coupled to one or more optical fibers 16 that are coupled to the current carrying conductor 12. The photonic sensing system 10 may include a polarization beam splitter 18 coupled to a polarization rotator 20 (e.g., a Faraday rotator). The photonic sensing system 10 may include a reflector 22 (e.g., light reflector such as a mirror) disposed at a terminal end of the one or more optical fibers 16. In the illustrated embodiment, the one or more optical fibers 16 include a polarization maintaining (PM) fiber 24 and a single-mode (SM) fiber 26, adjacent to one another, and configured to couple the current sensor interrogator 14 to the polarization beam splitter 18 and the polarization rotator 20. As may be appreciated, the PM fiber 24 maintains the polarization of the light passing through the fiber while the SM fiber 26 does not maintain the polarization of the light. The one or more optical fibers 16 also includes a sensing fiber 28 configured to couple the polarization rotator 20 to the reflector 22. For example, the polarization rotator 20 is on one terminal end of the sensing fiber 28, and the reflector 22 is on the other terminal end of the sensing fiber 28. The sensing fiber 28 may be a SM fiber and may wrap around the current carrying conductor 12 in one or more turns. Various components of the current sensor interrogator 14 will be discussed in detail in FIG. 2.

[0034] In operation, photonic polarization rotation measurement by the photonic sensing system 10 is accomplished by first launching light into the polarization maintaining PM fiber 24 along a known primary axis. The light then passes through the polarization beam splitter 18 that is aligned with the primary axis. The polarization rotator 20 then rotates the light polarization by a suitable degree with respect to the primary axis (e.g., the rotated light polarization is the secondary polarization). In the present embodiment, the polarization rotator 20 rotates the light polarization by about 22.5 degrees; however, in other embodiments, the polarization rotator 20 may rotate the light polarization by any suitable degree. This light is then launched into the sensing fiber 28. As an example, the sensing fiber 28 may be a fiber that is modified or configured to increase the verdet constant (i.e., an optical constant that describes the strength of the Faraday effect for a particular material).

[0035] As an electrical current flows through the current carrying conductor 12, a magnetic field is generated around the current carrying conductor 12 that may change the polarization of light propagating in the sensing fiber 28 that wraps around the current carrying conductor 12. The reflector 22 (e.g., light reflector such as a mirror) at the terminal end of the sensing fiber 28 reflects the light back into the sensing fiber 28. As the reflected or back-reflected light propagates through the polarization rotator 20 that rotates the light polarization by about 22.5 degrees, a total rotational bias adds up to be about 45 degrees. As may be appreciated, any deviations from this value (e.g., about 45 degrees) are expected to be attributed by rotations of polarization induced through the sensing region (e.g., through the sensing fiber 28). The reflected light then impinges on the polarization beam splitter 18 that splits the two light polarization components into two different paths that propagate to two different photodetectors disposed within the current sensor interrogator 14. For example, the primary polarization component may propagate to a first photodetector through the PM fiber 24 while the secondary polarization component may propagate to a second photodetector through the SM fiber 26.

[0036] Subsequently, the measurement of polarization is performed by a ratiometric measurement of the light intensity on the two photodetectors. For example, the measurement of any deviations from the designed value (e.g., about 45 degrees in this embodiment) may indicate the polarization induced by an electrical current passing through the current carrying conductor 12 and may be used to calculate a value of the corresponding electrical current. As such, the photonic sensing system 10 may measure the current and/or power for a suitable object of interest. It should be noted that the one or more optical fibers 16 may have any suitable lengths to facilitate measurement(s) on the suitable object of interest. In certain embodiments, each of the PM fiber 24 and the SM fiber 26 may be up to about 10 kilometers. In certain embodiments, the sensing fiber 28 may be up to about 1 meter or tens of meters (e.g., 10 meters, 20 meters, 30 meters, etc.). As set forth above, the sensing fiber 28 may wrap around the current carrying conductor 12 in one or more turns. As may be appreciated, the deviation from the designed value (e.g., about 45 degrees in this embodiment) may increase with the number of turns that the sensing fiber 28 wraps around the current carrying conductor 12 due to the amplified magnetic field. Accordingly, in certain embodiments, the sensing fibers 28 may be configured to wrap around the current carrying conductor 12 in more turns when the measurand (e.g., current) is expected to be small.

[0037] FIG. 2 shows a schematic of the current sensor interrogator 14 of the photonic sensing system 10 of FIG. 1. In the illustrated embodiment, a photonic integrated circuit (PIC) 48 is disposed on an interposer 34 of the current sensor interrogator 14 such that the PM fiber 24 and the SM fiber 26 may be coupled to the current sensor interrogator 14 in proximity to an edge 36 of the PIC 48. For example, the PM fiber 24 and the SM fiber 26 may each be fitted in a fiber trench 38, and the PM fiber 24 and the SM fiber 26 may be coupled to the PIC 48 via edge couplers 40 and 42, respectively. The current sensor interrogator 14 may include a light source 44, such as a laser, a plurality of optical components 46 disposed on the PIC 48, and a plurality of electrical integrated circuit (IC) components 50 disposed on the interposer 34, configured for the operation of the current sensor interrogator 14.

[0038] It should also be noted that the light source 44 and the plurality of photonic components 46 are each shaded or hatched differently to depict different modes of transmission or propagation of electromagnetic wave (e.g., light wave) within the components or devices. In particular, a first shade 52 represents a transverse magnetic (TM) mode with no magnetic field in the direction of propagation; a second shade 54 represents a transverse electric (TE) mode with no electric filed in the direction of propagation; and a third shade 56 represents a mixed TM and TE mode.

[0039] In the illustrated embodiments, the PIC 48 includes a polarization rotator 58, coupled to the light source 44 via a waveguide 60 and an edge coupler 62. The PIC 48 includes a circulator 64 coupled to the polarization rotator 58 via a waveguide 66, a splitter 68 coupled to the circulator 64 via a waveguide 70, and a waveguide 72 that couples the splitter 68 to the PM fiber 24 at the edge coupler 40. The PIC 48 also includes a sensor photodiode 74 coupled to the circulator 64 via a waveguide 76, a monitor photodiode 78 coupled to the splitter 68 via a waveguide 80, and a sensor photodiode 82 coupled to the SM fiber 26 via a waveguide 84 and the edge coupler 42.

[0040] The plurality of IC components 50 may include, but are not limited to, a light source driver 86, a processor or microprocessor 88, a digitizer 90, one or more filters 92, an operational amplifier or op-amp 94, and one or more trans-impedance amplifiers or TIAs 96. The light source driver 86 may provide power or current to the light source 44 (e.g., a laser) upon receiving instructions from the processor 88, to drive operation of the light source 44. The processor 88 may include one or more application specific integrated circuits (ASICs), one or more general purpose processors, one or more programmable logic controllers or circuits, or any combination thereof. The processor 88 may include or may be communicatively coupled to a memory (e.g., non-transitory computer-readable medium/memory circuitry) that may store one or more sets of instructions (e.g., processor-executable instructions) and algorithms implemented to perform operations related to function or operation of various components of the current sensor interrogator 14.

[0041] The digitizer 90, such as an analog-to-digital or A/D converter, may take analog signals and convert them to digital signals. The one or more filters 92 may filter noise from the signals (e.g., analog signals) and the filtered signals may be digitized by the digitizer 90. For example, the one or more filters 92 may be remove signals that have frequencies greater than a certain threshold value. The threshold value may be any suitable value, and in certain embodiments, the threshold value may be about 1000 Hertz. The one or more op-amps 94 may provide a signal boost to one or more light sensors/monitors or photodiodes, such as the sensor photodiodes 74 and 82 and the monitor photodiode 78. For example, the sensor photodiodes 74 and 82 and the monitor photodiode 78 may each couple to a respective op-amp 94 to receive a signal boost. The one or more TIAs 96 may convert current (e.g., converted from light) to voltage for one or more light sensors/monitors or photodiodes, such as the sensor photodiodes 74 and 82 and the monitor photodiode 78. For example, the sensor photodiodes 74 and 82 and the monitor photodiode 78 may each couple to a respective TIA 96 to convert current to voltage. In certain embodiments, the TIAs 96 may also provide gain or signal boost. The processor 88 is communicatively and/or operatively coupled to various components (e.g., the plurality of photonic components 46 and the plurality of IC components 50) of the current sensor interrogator 14. As such, the processor 88 may drive the light source 44 (e.g., a laser), read one or more light sensors/monitors or photodiodes, such as the sensor photodiodes 74 and 82 and the monitor photodiode 78, process the digitized signals into useful formation, and analyze the useful information to determine the measured current or power.

[0042] In operation, the light source 44 emits light that propagates in the waveguide 60 in TE mode. The polarization rotator 58 changes the light propagation from TE mode to TM mode, such that the light comes out of the polarization rotator 58 in TM mode and maintains in TM mode throughout propagation into the PM fiber 24. The circulator 64 induces non-reciprocal behavior on the TM-polarized light such that the TM-polarized light can only propagate in one direction (e.g., toward the PM fiber 24) but not in the reverse direction (e.g., toward the light source 44). Furthermore, as the light is reflected by the reflector 22 and enters the circulator 64, the reflected light is directed to the sensor photodiode 74, instead of toward the light source 44.

[0043] As the TM-polarized light propagates through the splitter 68, the splitter 68 may split or direct one portion (e.g., a first portion) of the TM-polarized light to continue propagation toward the PM Fiber 24 and split or direct the other portion (e.g., a second portion) of the TM-polarized light to continue propagation to the monitor photodiode 78. It should be noted that the splitter 68 may be configured to split light in any suitable proportion (e.g., 90/10, 80/20, 70/30, etc.). For example, a 90/10 split as illustrated herein, indicates that about 90% of the TM-polarized light is directed to propagate toward the PM fiber 24 and about 10% of the TM-polarized light is directed to propagate to the monitor photodiode 78.

[0044] The monitor photodiode 78 coupled to the processor 88 and/or one or more of the plurality of IC components 50, may monitor a portion (e.g., about 10% in the illustrated embodiment) of the TM-polarized light to determine the power of the light source 44 (e.g., corresponding to the intensity and/or power of the emitted light). Accordingly, the processor 88 may change (e.g., increase or decrease) the current provided to the light source 44. In certain embodiments, the processor 88 may change the operation of the circulator 64 based on feedback (e.g., monitored results corresponding to power of the light source 44) provided by the monitor photodiode 78.

[0045] As discussed in FIG. 1, the light (e.g., the first portion of the TM-polarized light) propagates through the PM fiber 24, the sensing fiber 28, and reflected by the reflector 22. The reflected light is rotated (e.g., about 22.5 degree-polarization) by the polarization rotator 20 and then split by the polarization beam splitter 18 based on the polarization. As such, a portion (e.g., first portion) of the reflected light maintains the TM-polarization and propagates through the PM fiber 24, the waveguides 72, 70, and 76, to the sensor photodiode 74, and the other portion (e.g., second portion) of the reflected light has a mixed TM and TE polarization and propagates through the SM fiber 26 and the waveguide 84, to the sensor photodiode 82.

[0046] The sensor photodiodes 74 and 82 coupled to the one or more of the plurality of IC components 50 and the processor 88 then perform suitable measurement and analysis, such as a ratiometric measurement of the light intensity, to determine the degree of polarization measured for the first portion and second portion of the reflected light. As set forth above, the total rotational bias of the first and second portions of the reflected is expected to be about 45 degrees. Any deviations from this value are caused by rotations of polarization caused in the sensing region (e.g., the sensing fiber 28). Accordingly, any deviation from this value may be used to calculate the measurand, such as current. The total rotational bias of about 45 degrees is discussed herein as a non-limiting example. In other embodiments, the total rotational bias may be any suitable values depending on the primary polarization and secondary polarization induced by the polarization rotator 18.

[0047] It should be noted that the photonic sensing system 10 discussed in FIGS. 1-2 has a sensor architecture with a remote rotator (e.g., the polarization rotator 20) and a remote polarization beam splitter (e.g., the polarization beam splitter 18). Specifically, the polarization rotator 20 and the polarization beam splitter 18 are disposed remotely and not integrated with the current sensor interrogator 14. As discussed below in FIGS. 3-6, the photonic sensing system 10 may include different architectures. Unless otherwise specified, various components or devices of the photonic system 10 discussed in FIGS. 3-6 perform or operate in the same manner as discussed in FIGS. 1-2.

[0048] FIG. 3 and FIG. 4 show schematics of one embodiment of the photonic sensing system 10 and the corresponding architecture of the current sensor interrogator 14, respectively. In the illustrated embodiment, the photonic sensing system 10 is a fully integrated system that a rotator and a polarization beam splitter that are both fully integrated with the current sensor interrogator 14. As shown in FIG. 3, the photonic sensing system 10 includes the current sensor interrogator 14 coupled to the sensing fiber 28 that wraps around the current carrying conductor 12 in any suitable number of turns. The reflector 22 is disposed at a terminal end of the sensing fiber 28 opposite to the current sensor interrogator 14.

[0049] As shown in FIG. 4, both the polarization beam splitter 18 and the polarization rotator 20 are fully integrated within the current sensor interrogator 14. In particular, the polarization beam splitter 18 is disposed on the PIC 48 as part of the current sensor interrogator 14. The polarization beam splitter 18 is coupled to the splitter 68 via a waveguide 73 (e.g., a TM-polarized waveguide) and coupled to the sensor photodiode 82 via a waveguide 85 (e.g., a TE-polarized waveguide). The polarization rotator 20 is disposed on the interposer 34. The polarization rotator 20 is coupled to the polarization beam splitter 18 via a waveguide 41 (e.g., a TM-polarized waveguide) and an edge coupler 43 disposed in proximity to an edge 45 of the SOI 48, and coupled to the sensing fiber 28. In the illustrated embodiment, a first component of the polarized reflected light is in TM-polarized mode and propagates following a first path to the sensor photodiode 74, and a second component of the polarized reflected light is in TE-polarized mode and propagates following a second path to the sensor photodiode 82. Subsequently, the sensor photodiodes 74 and 82 coupled to one or more of the plurality of IC components 50 and the processor 88 may process and analyze the signals/information in the same manner as set forth above.

[0050] FIG. 5 and FIG. 6 show schematics of one embodiment of the photonic sensing system 10 and the corresponding architecture of the current sensor interrogator 14, respectively. In the illustrated embodiment, the photonic sensing system 10 includes a remote rotator but an integrated polarization beam splitter. Specifically, the polarization rotator 20 is disposed remotely and not integrated with the PIC 48 of the current sensor interrogator 14 while the polarization beam splitter 18 is integrated with the PIC 48. As shown in FIG. 5, the photonic sensing system 10 includes the current sensor interrogator 14 coupled to the PM fiber 24 that couples to the polarization rotator 20. The sensing fiber 28 couples to the polarization rotator 20 and wraps around the current carrying conductor 12 in any suitable number of turns. The reflector 22 is disposed at a terminal end of the sensing fiber 28 opposite to the polarization rotator 20.

[0051] As shown in FIG. 6, the polarization beam splitter 18 is integrated within the PIC 48. In particular, the polarization beam splitter 18 is disposed on the PIC 48 as part of the current sensor interrogator 14. The polarization beam splitter 18 is coupled to the splitter 68 via the waveguide 73 (e.g., a TM-polarized waveguide) and coupled to the sensor photodiode 82 via the waveguide 85 (e.g., a TE-polarized waveguide). Further, the polarization beam splitter 18 is coupled to the PM fiber 24 via the waveguide 41 (e.g., a TM-polarized waveguide) and the edge coupler 43 is disposed in proximity to the edge 45 of the SOI 48 as well as the edge 36 of the PIC 48. The light reflected by the reflector 22 propagates through the polarization rotator 20 and then the polarization beam splitter 18 that splits the polarized (e.g., about 22.5 degrees) reflected light into two components based on polarization. In the illustrated embodiment, a first component of the polarized reflected light is in TM-polarized mode and propagates following a first path to the sensor photodiode 74, and a second component of the polarized reflected light is in TE-polarized mode and propagates following a second path to the sensor photodiode 82. Subsequently, the sensor photodiodes 74 and 82 coupled to one or more of the plurality of IC components 50 and the processor 88 may process and analyze the signals/information in the same manner as set forth above.

[0052] While the photonic sensing system 10 discussed in FIGS. 1-6 is directed to current sensing, the sensing system 10 may be configured for other measurands. As discussed in FIGS. 7-11, the photonic sensing system 10 includes a sensor architecture for wavelength measurement, which may be used for determining temperature, strain, pressure, etc. FIG. 7 shows a schematic of the photonic sensing system 10 configured for wavelength measurements. In the illustrated embodiment, the photonic sensing system 10 includes a wavelength sensor interrogator 15 coupled to fiber Bragg gratings (FBGs) 17 via an optical fiber 19. In particular, the FBGs 17 may be coupled to a specimen to be measured, and the wavelength sensor interrogator 15 may interrogate (e.g., process and analyze) data or information collected via the FBGs 17. In certain embodiments, the FBGs 17 may be used in combination with or may be replaced by other suitable wavelength sensors, such as Fabry-Perot interferometers. The optical fiber 19 may be a PM fiber or a SM fiber depending on the respective architecture of the wavelength sensor interrogator 15. Various components and different architectures of the photonic sensing system 10 are discussed in FIGS. 8-11 below. Because many of the components or devices in FIGS. 8-11 overlap with that in FIGS. 2, 4, and 6, unless otherwise specified, the same descriptions may be applied here, including the different shades 52, 54, and 56 that represent different modes (e.g., TM, TE, and mixed TM and TE modes) of propagation of electromagnetic wave (e.g., light wave).

[0053] FIG. 8 shows a schematic of one embodiment of the wavelength sensor interrogator 15 of FIG. 7. In the illustrated embodiment, the wavelength sensor interrogator 15 is coupled to the optical fiber 19, which is a PM fiber coupled to the FBG 17 via an edge coupler 39. The wavelength sensor interrogator 15 includes the plurality of photonic components 46 disposed on the PIC 48 that is disposed on the interposer 34 of the wavelength sensor interrogator 15. The wavelength sensor interrogator 15 also includes the light source 44 and the plurality of IC components 50. In the illustrated embodiment, the architecture of the wavelength sensor interrogator 15 is different than the current sensor interrogator 14 in that the plurality of the photonic components 46 includes a tunable micro-ring filter 47 coupled to the light source 44 via a waveguide 49 that couples to the light source 44 via the edge coupler 62. The plurality of the photonic components 46 include a reflector 51 that is coupled to the tunable micro-ring filter 47 via a waveguide 53 and is coupled to the polarization rotator 58 via the waveguide 60. The plurality of the photonic components 46 includes a reference filter or grating 81 that is coupled to the splitter 68 via the waveguide 80 and is coupled to the monitor photodiode 78 via a waveguide 83. Further, the plurality of IC components 50 includes a ring modulator driver 89 to drive operation of the tunable micro-ring filter 47. It should be noted that the set of components discussed above are contained in a small area (e.g., a few square centimeters) on the wavelength sensor interrogator 15 and provide all of the functions for measuring the wavelength spectrum of the interconnected FBGs 17. As such, the photonic sensing system 10 may significantly reduce footprint of the sensor.

[0054] In operation, the photonic sensing system 10 launches light into the optical fiber 19 (e.g., a PM fiber), and the light is reflected back by the FBGs 17 and propagates to the sensor photodiode 74 and the monitor photodiode 78. The signals collected by the sensor photodiode 74 and the monitor photodiode 78 are processed and/or analyzed by the processor 88 and/or one or more of the IC components 50, and the spectrum of the reflected light is analyzed to determine wavelength and/or corresponding temperature, strain, and pressure, etc. In particular, the light source 44, tunable micro-ring filter 47, and the reflector 51 form an external cavity laser which generates laser sweeping over a few nanometers of wavelength range. As such, the wavelength sensor interrogator 15 sweeps a tunable narrow-band laser over a range of wavelengths and records the resulting back-reflected light amplitude to construct the spectrum of the FBGs 17. In certain embodiments, the light source 44, tunable micro-ring filter 47, and the reflector 51 may be replaced by a tunable laser mounted on the interposer 34 to generate a tunable narrow-band laser. The splitter 68, the reference grating 81, and the monitor photodiode 78 provide on-chip wavelength calibration. The circulator 64 directs the reflected light (e.g., reflected by the FBG 17) to the sensor photodiode 74 which is then amplified and digitized to provide the spectral response.

[0055] The architecture of the wavelength sensor interrogator 15 discussed in FIG. 8 enables the photonic sensing system 10 to interrogate the FBG 17 using a PM fiber (e.g., the optical fiber 19 being a PM-fiber). However, a different architecture of the wavelength sensor interrogator 15 may be employed to enable the photonic sensing system 10 to interrogate the FBG 17 using a SM fiber (e.g., the optical fiber 19 being a SM-fiber), as will be discussed in FIG. 9. FIG. 9 shows a schematic of another embodiment of the wavelength sensor interrogator 15 of FIG. 7. In the illustrated embodiment, the architecture of the wavelength sensor interrogator 15 is different from the wavelength sensor interrogator 15 discussed in FIG. 8 in that the plurality of the photonic components 46 includes the polarization beam splitter 18 that is coupled to the splitter 68 via the waveguide 72, coupled to the sensor photodiode 82 via the waveguide 85, and coupled to the optical fiber 19 via the waveguide 41 and the edge coupler 43.

[0056] Because of the added polarization beam splitter 18 and the sensor photodiode 82, the wavelength sensor interrogator 15 may function with a SM fiber (e.g., the optical fiber 19 being a SM fiber) with arbitrary received polarization. For example, the reflected light from the FBG 17 may be in an arbitrary mode (e.g., mixed TM and TE mode), and the polarization beam splitter 18 splits the polarized reflected light into two components based on polarization. In the illustrated embodiment, a first component of the polarized reflected light is in TM-polarized mode and propagates following a first path to the sensor photodiode 74, and a second component of the polarized reflected light is in TE-polarized mode and propagates following a second path to the sensor photodiode 82. Subsequently, the signals from the sensor photodiodes 74 and 82 are added to map out the spectrum of the FBG 17 across all polarizations.

[0057] In other embodiments, instead of using the tunable micro-ring filter 47 to transmit a certain wavelength band as shown in FIGS. 8-9, the photonic sensing system 10 may perform filtering based on arrayed waveguide grating (AWG) as shown in FIGS. 10-11. FIG. 10 shows a schematic of another embodiment of the wavelength sensor interrogator 15 of FIG. 7. As shown, the architecture of the wavelength sensor interrogator 15 is different from the wavelength sensor interrogator 15 discussed in FIG. 8 in that the polarization rotator 58 is coupled to the light source 44, instead of having the tunable micro-ring filter 47 and the reflector 51 disposed in between. Accordingly, the plurality of IC components 50 does not include the ring modulator driver 89. In addition, instead of the sensor photodiode 74, an AWG 98 including an integrated photodiode array 100 is coupled to the circulator 64 via a waveguide 102. Further, the monitor photodiode 78 is coupled to the splitter 68 via the waveguide 80, instead of having the reference filter or grating 81 disposed in between. In operation, the photonic sensing system 10 transmits a range of wavelengths to the FBGs 17 and then records the wavelength spectrum of the reflected light. In particular, the circulator 64 directs the reflected light from the FBG 17 to the AWG 98, and isolates the light source 44 from reflections. The AWG 98 spatially separates the reflected light onto the integrated photodiode array 100 by wavelength. As such the optical fiber 19 used in the architecture discussed in FIG. 10 may be a PM-fiber instead of a SM-fiber.

[0058] In certain embodiments, an additional AWG 98 may be added to enable the wavelength sensor interrogator 15 to function with SM-fiber (e.g., the optical fiber 19 being a SM-fiber) with arbitrary received polarization as shown in FIG. 11. In comparison to the architecture shown in FIG. 10, the wavelength sensor interrogator 15 in FIG. 10 includes the polarization beam splitter 18 coupled to the splitter 68 via the waveguide 72, a second polarization rotator 104 coupled to the polarization beam splitter 18 via a waveguide 106, and a second AWG 108 including an integrated photodiode array 110 coupled to the polarization rotator 104 via a waveguide 112.

[0059] Because of the added polarization beam splitter 18 and the second AWG 108, the wavelength sensor interrogator 15 may function with SM fiber (e.g., the optical fiber 19 being a SM fiber) with arbitrary received polarization. For example, the reflected light from the FBG 17 may be in an arbitrary mode (e.g., mixed TM and TE mode), and the polarization beam splitter 18 splits the polarized reflected light into two components based on polarization. In the illustrated embodiment, a first component of the polarized reflected light is in TM-polarized mode and propagates following a first path to the AWG 98 (e.g., the first AWG). A second component of the polarized reflected light is in TE-polarized mode and propagates following a second path to the polarization rotator 104 that changes the light propagation from TE mode to TM mode, such that the light comes out of the polarization rotator 104 in TM mode and propagates in TM mode to the second AWG 98. Subsequently, the first AWG 98 and the second AWG 108 spatially separate the reflected light onto the integrated photodiode arrays 100 and 110 respectively by wavelength. The signals from the first AWG 98 and the second AWG 108 are added to map out the spectrum of the FBG across all polarizations.

[0060] Turning now to a specific component, the circulator 64 of the photonic sensing system 10 will be described. As set forth above, the circulator 64 may be used to isolate the light source 44 from the back-reflected or back-scattered light. In particular, the architecture of the circulator 64 may affect the stability of the light source

44 and/or signal power (e.g., reduction in optical output power). FIGS. 12A-B show partial schematics of an example of the circulator 64 in a top view (FIG. 12A) and a cross-sectional view (FIG. 12B), illustrating the construction and operation of the circulator 64. In the illustrated embodiment, the circulator 64 operates by the principle of non-reciprocal phase shifting of TM-polarized light in a Mach-Zehnder interferometer (MZI) 124 integrated with the SOI 48. For example, the MZI 124 includes a Mach-Zehnder structure 126 coupled to waveguides 128 (e.g., PIC-waveguides or SOI-waveguides, such as waveguides 66, 70, 76 and/or 102) integrated with the SOI 48. For example, the waveguides 128 may be coupled via one or more couplers 130 and disposed on top of an oxide layer 131 of the SOI 48. The one or more couplers 130 may be 3dB multi-mode interference (MMI) couplers, evanescent waveguide couplers, or any suitable waveguide couplers. Furthermore, each of the one or more couplers 130 is configured to split light, such that 50 % of the light propagates along a first path and the other 50% of the light propagates along a second path (e.g., a 50/50 split). The Mach-Zehnder structure 126 may include a magneto-optic material or waveguide 132 disposed on top or above the waveguides 128 and the SOI 48 (e.g., the waveguides 128 are integrated with the SOI 48) and may include one or more magnets 134 disposed on top of the magneto-optic material 132. In the illustrated architecture, light is coupled to and from the magneto-optic material 132 at the magneto-optic material 132.

[0061] In certain embodiments, the magneto-optic material 132 may include cerium-doped yttrium iron garnet (Ce-YIG). The Ce-YIG may be deposited via sputtering or via metal organic chemical vapor deposition (MOCVD). In certain embodiments, the magneto-optic material 132 may include conjugated polythiophenes, such as poly(3hexylthiophene-2, 5-diyl) regioregular (P3HT_RR) with a number average molecular weight of M_n about 17500 and poly(3-dodecylthiophene-2, 5-diyl) regioregular (P3DT_RR) with a M_n about 27000. In certain embodiments, the magneto-optic material 132 may be magnetite-polymethylmethacrylate core-shell nanocomposites. In certain embodiments, the magneto-optic material 132 may include cobalt ferrite ($CoFe_2O_4$) nanoparticles polymer composites. For example, the $CoFe_2O_4$ nanoparticles polymer composite may include about 5 wt% (e.g., weight percent)

$CoFe_2O_4$ nanoparticles having an average diameter about 20 nanometers and incorporated in a poly(3-benzyl-methacrylate) (PBzMA) host. In certain embodiments, the magneto-optic material 132 may include ionic liquid, such as Gd-DMIM-Cl, where Gd denotes the gadolinium cation, DMIM denotes the organic cation 1-decyl-3-methyl-imidazolium, and Cl denotes the chloride anion. The magneto-optic material 132 may be deposited by any suitable means.

[0062] In operation, the non-reciprocal MZI 124 directs light propagating through the waveguides 128 in a forward direction 138 from an input port 140 to a cross-port 142, and in a reverse direction 144, directs light from the cross-port 142 to a common port 146. The non-reciprocal phase shift (e.g., constructive and destructive interference and consequently isolation) is accomplished by directing an evanescent field 136 of the TM wave through the magneto-optic material 132 that is polarized by a permanent magnetic field exerted by the one or more magnets 134 coupled to the magneto-optic material 132. The one or more magnets 134 create opposing magnetic fields in two arms or paths of the Mach-Zehnder structure 126 (e.g., first arm or path 135 and a second arm or path 137). In particular, with the magnetic field exerted by the one or more magnets 134, a $\pi/2$ differential non-reciprocal phase shift between the first and second arms 135 and 137 of the MZI 124 is introduced in the forward direction 138 while a negative $\pi/2$ differential non-reciprocal phase shift between the first and second arms 135 and 137 arms the MZI 124 is introduced in the reverse direction 144. Alternatively, the forward differential non-reciprocal phase shift can be negative and the reverse positive. By introducing negative (or positive) $\pi/2$ differential reciprocal phase shift (e.g., same shift in both forward direction 138 and reverse direction 144), the overall differential phase shift (e.g., sum of the differential non-reciprocal and reciprocal phase shift) between the first and second arms 135 and 137 of the MZI 124 is zero in the forward direction 138 and the overall differential phase shift between the first and second arms 135 and 137 arms of the MZI 124 is equal to negative (or positive) π in the reverse direction 144. Under these conditions, all light entering the input port 140 in the forward direction 138 exits the cross-port 142 and light returning from the cross-port 142 propagating in the reverse direction 144 exits the common port 146. Due to the periodic behavior of MZIs, the same light routing is achieved if additional factors of positive or negative 2π differential reciprocal phase shift is introduced between the first and second arms 135 and 137 of the MZI 124.

[0063] However, it should be noted that reciprocal phase shift or phase bias may be induced if the path lengths of the two arms (e.g., the first and second arms 135 and 137) are different (e.g., intentionally induced or due to thermal or manufacturing variation effects). For example, if the differential reciprocal phase shift deviates from $\pi/2$, some portion of the light entering the input port 140 in the forward direction 138 may be lost to a terminal port coupled to the coupler 130 adjacent to the cross-port 142 and some portion of the reflected light returning from the cross-port 142 propagating in the reverse direction 144 may exit the input port 140 as opposed to the common port 146. Accordingly, one or more phase tuning elements, such as one or more phase modulators (PMs) 148 may be disposed along the two arms 135 and 137 to tune the MZI 124 to counter the phase bias (e.g., to calibrate the phase shift to be π). For example, the plurality of IC components 50 may include a phase modulator driver 150 operatively coupled to the one or more PMs 148, and upon receiving instructions from the processor 88, the phase modulator driver 150 may drive operation of the one or more PMs 148 to overcome thermal or manufacturing variation effects that tend to bias the MZI 124 away from the phase matched condition. In particular, the one or more PMs 148 may be used trim the reciprocal phase shift and/or tune the overall performance of the MZI 124.

[0064] Furthermore, the Mach-Zehnder structure 126 may include a feedback loop coupled to one or more of the plurality of IC components 50 and the processor 88, such that the one or more PMs 148 may be adjusted in real time or substantially real time. For example, the Mach-Zehnder structure 126 may include a coupler 129 (e.g., an optical tap) coupled to the waveguide 128 between the input port 140 and the coupler 130, and may include a monitor photodiode 75 coupled to the coupler 129 and one or more of the plurality of IC components 50. The coupler 129 is configured to split the light in any suitable portions, such that the reflected light propagating toward the input port 140, as opposed to the common port 146, may be directed to the monitor photo diode 75. Based on the signals detected by the monitor photodiode 75, the processor 88 may determine to adjust operation of the one or more PMs 148 to reduce or minimize the reflected light leaking toward the input port 140 (e.g., toward the light source 44).

In some embodiments, such feedback loop (e.g., the coupler 129 and the monitor photodiode 75) may be omitted.

[0065] In certain embodiments, the feedback loop set forth above may be coupled to the common port 146 as opposed to the input port 140. For example, the Mach-Zehnder structure 126 may include a coupler (e.g., a coupler functions in the same manner as the coupler 129) coupled to the waveguide 128 between the common port 146 and the coupler 130, and may include a monitor photodiode (e.g., a monitor photodiode functions in the same manner as the monitor photodiode 75) coupled to the coupler and one or more of the plurality of IC components 50. Based on the signals detected by the monitor photodiode, the processor 88 may determine to adjust operation of the one or more PMs 148 to reduce or minimize the reflected light leaking toward the input port 140 (e.g., toward the light source 44). In certain embodiments, the Mach-Zehnder structure 126 may include the feedback loop coupled to the input port 140 in combination with the feedback loop coupled to the common port 146.

[0066] In certain embodiments, the Mach-Zehnder structure 126 may include an optical passivation material 153 disposed on top of the waveguides 128, such that a gap 155 exists between the magneto-optic material 132 and the passivation material 153, as shown in FIG. 12C. The optical passivation material 153 may include silicon dioxide (SiO_2).

[0067] In certain embodiments, the Mach-Zehnder structure 126 may include the magneto-optic material 132 disposed adjacent to and in the same plane as the waveguides 128 in the same plane, as shown in FIG. 13. That is, in contrast with the embodiment illustrated in FIG. 12, wherein the magneto-optic material 132 is formed on top of the waveguides 128, these structures are formed in the same plane. FIG. 13 shows a side view schematic of an example of the Mach-Zehnder structure 126, illustrating a butt-coupled architecture 127. In this butt-coupled architecture 127, light is coupled between the magneto-optic material 132 and the waveguides 128 at their interfaces. However, as will be appreciated, the butt-coupled architecture 127 may include gaps 133 at the interfaces between the magneto-optic material 132 and the waveguides 128. As will be appreciated the gaps 133 in the light path may result in degradation of the light transmission, due to the changes in refractive indices through the gaps 133. In particular, changes in refractive indices in the material through which the evanescent field 136 travels due to transitions from the magneto-optic material 132 and surrounding air or other material(s) can result in degradation of light transmission. Accordingly, an index matching material, such as an optical polymer, may be disposed in the gaps 133 to reduce the degradation of the light. FIGS. 14A-D and FIGS. 15A-D show two example methods of fabricating the butt-coupled architecture of FIG. 13.

[0068] FIGS. 14A-D are cross-sectional schematic views illustrating the butt-coupled architecture 127 of FIG. 13 at various stages of an example fabrication process, in accordance with embodiments of the present disclosure. As illustrated in FIG. 14A, the magneto-optic material 132 is deposited and/or patterned on the SOI 48 (e.g., on the oxide layer 131) adjacent to and in the same plane as the waveguides 128, such that a gap 133 exists between the magneto-optic material 132 and the waveguides 128. As set forth above, the magneto-optic material 132 may be deposited via sputtering of Ce-YIG or via metal organic chemical vapor deposition (MOCVD) of Ce-YIG. As illustrated in FIG. 14B, next, an optically transparent material 154 is disposed (e.g., coated) on top to cover or substantially cover the magneto-optic material 132 and the waveguides 128, and to substantially fill the gaps 133. The optically transparent material 154 may be any suitable optically transparent materials. In certain embodiments, the optically transparent material 154 may include dielectric materials, such as silicon dioxide (SiO_2) and silicon nitride (Si_3N_4). In certain embodiments, the optically transparent material 154 may include optically transparent polymer, such as perfluorocyclobutane (PFCB), polymethyl methacrylate (PMMA), and polyimide. The optically transparent material 154 may be deposited by any suitable means.

[0069] In certain embodiments, prior to the deposition of the optically transparent material 154, a hydrophilic layer 156 may be optionally coated on top to cover or substantially cover the waveguides 128 and the magneto-optic material 132. Then, as illustrated in FIG. 14C, a photolithography process is applied to define location or distribution of the optically transparent material 154. In certain embodiments, after the photolithographic process which may result in the formation of a spacer, the optically transparent material 154 may be distributed directly adjacent and touching the magneto-optic material 132, but is not touching the waveguides 128. For example, a gap 158 between the waveguides 128 and the optically transparent material 154 is created (e.g., etched out) via the photolithography process. Subsequently, as illustrated in FIG. 14D, the optically transparent material 154 may be reflowed (e.g., via a heating process) to form lenses 160. For example, each of the lenses 160 may have a convex 162 substantially pointing toward the SOI-waveguide (e.g., in a direction substantially parallel to the lateral or planer direction of the SOI 48). It should be noted that the optically transparent material 154 or the lenses 160 may not touch the waveguides 128, such that the gaps 158 may be reduced but remain. The inclusion of the optically transparent material 154 and the formation of the lenses 160 may improve the transmission of light between the magneto-optic material 132 and the waveguides 128 by collimating the light and reducing losses through the gap 133.

[0070] FIGS. 15A-D are cross-sectional schematic views illustrating the butt-coupled architecture 127 of FIG. 13 at various stages of another example fabrication process, in accordance with embodiments of the pressure disclosure. As illustrated in FIG. 15A, the magneto-optic material 132 is deposited and/or patterned on the SOI 48 (e.g., on the oxide layer 131), adjacent to and in the same plane as the waveguides 128 following the same process discussed in FIG. 14A. As illustrated in FIG. 15B, next, the optically transparent material 154 is disposed (e.g., coated) on top to cover or substantially cover the magneto-optic material 132, the waveguides 128, and to fully fill the gaps 133. Then, as illustrated in FIG. 15C, a photolithography process is applied to define location or distribution of the optically transparent material 154. In particular, the optically transparent material 154 may be patterned and a portion of the optically transparent material 154 may be removed (e.g., etched) such that the optically transparent material 154 is only present between the magneto-optic material 132 and the waveguides 128, but in contact with each interface. Subsequently, as illustrated in FIG. 15D, the optically transparent material 154 may be reflowed or a planarization process may be applied to form fillers 164. It should be noted that the optically transparent material 154 or the fillers 164 touch both the magneto-optic material 132 and the waveguides 128 with no air gap in between (e.g., the gaps 133 of FIG. 15A are completely filled by the optically transparent material 154 or the fillers 164). It should also be noted that although each of the fillers 164 in the illustrated embodiment has a curved edge adjacent to the top surface of the magneto-optic material 132, in other embodiments, the fillers 164 may fully fill the gaps 133 and may be substantially flush with the top surface of the magneto-optic material 132.

[0071] It should be noted that the fabrication processes set forth above in FIGS. 14A-D and FIGS. 15A-D may be applied to fabricate the lenses 160 or the filler 164 within the gap 155 between the magneto-optic material 132 and the optical passivation material 153 of the Mach-Zehnder structure 126 shown in FIG. 12C. For example, the optically transparent material 154 may be applied on top of the optical passivation material 153 to substantially cover the optically passivation material 153 and the waveguides 128, and substantially fill the gap 155. In certain embodiments, the hydrophilic layer 156 may be optionally coated on top to cover or substantially cover the optical passivation material 153, the waveguides 128, and a portion of the the magneto-optic material 132, prior to the application of the optically transparent material 154. Subsequently, any suitable processes as discussed in FIGS. 14B-D and FIGS. 15B-D, or a combination thereof, may be applied to fabricate the lenses 160 or filler 164 within the gap 155 to reduce the degradation of the light.

[0072] As set forth in FIGS. 12A-B, the one or more PMs 148 may be used to trim the reciprocal phase shift and/or tune the overall performance of the MZI 124. In certain embodiments, the MZI 124 may include one or more phase tuning elements, such as heater lines to achieve controllable non-reciprocal phase shift, which may be implemented alone or in combination with the one or more PMs 148, as shown in FIGS. 16A-B. FIGS. 16A-B shows partial schematics of another example of the circulator 64 in a top view (FIG. 16A) and a cross-sectional view (FIG. 16B), illustrating the construction and operation of the circulator 64. Various components of the MZI 124 may perform or operate in the same manner as discussed in FIGS. 12A-B unless otherwise specified. In the illustrated embodiment, the Mach-Zehnder structure 126 includes heater lines 170 disposed within (e.g., embedded) the oxide layer 131 below the waveguides 128, such that a portion of the heater lines is in proximity of the first arm 135 and a portion of the heater lines is in proximity of the second arm 137. In other embodiments, the heater lines 170 may be disposed at any positions/locations suitable for heating the waveguides 128, the magneto-optic material 132, or both. For example, the heater lines 170 may be above, below, or adjacent to and in the same plane as the waveguides 128. The heater lines 170 may include indium tin oxide (ITO) based heater lines. Further, the heater lines 170 may be operatively coupled to the processor 88 such that upon receiving instructions from the processor 88, the heater lines 170 may heat suitable components and/or portions of the MZI 124 to change the magnitude of the magneto-optic effect and thereby change the magnitude of the differential non-reciprocal phase shift to adjust the phase bias due to manufacturing variation effects. For example, the heater lines 170 may be configured to introduce a temperature gradient across the first arm 135 and/or on the second arm 137 to trim the non-reciprocal phase shift and/or tune the overall performance of the MZI 124.

[0073] Configurations and processes for coupling the Ce-YIG based magneto-optic material 132 to the waveguides 128 integrated with the SOI 48 will now be described. As may be appreciated good bonding or coupling between the magneto-optic material 132 and the waveguides 128 may improve the performance of the MZI 124. In some embodiments, coupling between the two components (e.g., the magneto-optic material 132 and the waveguides 128) may be achieved via an adhesive disposed at the interface. In other embodiments, a good direct bonding between two components (e.g., the magneto-optic material 132 and the waveguides 128) may be formed by a process where the components are bonded upon pressing against one another without the use of an adhesive. Accordingly, it may be beneficial to apply a surface treatment process prior to the direct bonding process. However, a typical surface treatment process may leave the surface of the magneto-optic material 132 depleted of oxygen, which may affect the magneto-properties near the interface with the waveguides 128 and thus may affect the non-reciprocal phase-shift in the MZI 124. As will be discussed below, embodiments of the present disclosure are directed to structures and/or methods for coupling the magneto-optic material 132 on the waveguides 128 (e.g., integrated with the SOI 48), leading to improved modulator performance (e.g., less signal loss, higher phase-shift, etc.).

[0074] FIGS. 17 and 18 show schematics of examples of the magneto-optic material or waveguide 132 disposed or mounted on the waveguide 128 in a cross-sectional view, as similarly described with regard to FIGS. 12A-B. As shown in FIGS. 17 and 18, the waveguides 128 are integrated with the SOI 48. In particular, the waveguides 128 are disposed on the oxide layer 131 (e.g., silica) on a substrate 139 (e.g., silicon substrate) of the SOI 48. In the illustrated embodiments, the cross-sectional view is taken in a direction that traverses the longitudinal direction of the waveguides 128. Accordingly, one of the waveguides 128 may represent the first arm or path 135 while the other of the waveguides 128 may represent the second arm or path 137. A magneto-optic material on substrate chip (MO/substrate chip) 141 may be disposed on the SOI 48. In the illustrated embodiments, the MO/substrate chip 141 includes the magneto-optic material 132, such as Ce-YIG deposited on a substrate 145. The substrate 145 may be any suitable substrate, such as magnesium oxide (MgO), substituted-gadolinium gallium garnet (SGGG), sapphire, etc. Further, the substrate 145 may be removed (e.g., via a liftoff process) subsequent to coupling of the MO/substrate chip 141 to the SOI 48.

[0075] In the embodiment illustrated in FIG. 17, the MO/substrate chip 141 is directly coupled to or mounted on the waveguides 128 with the magneto-optic material 132 (e.g., Ce-YIG) contacting the waveguides 128 (e.g., contacting both waveguides 128 of the first and second arms 135 and 137). As such, the magneto-optic material 132 (e.g., Ce-YIG) may serve as an upper cladding and the oxide layer 131 may serve as a lower cladding for the waveguides 128 (e.g., cladding to cause light to be confined to the waveguides 128). In the embodiment illustrated in FIG. 18, the MO/substrate chip 141 is coupled to the waveguides 128 via an adhesive layer 147 disposed between the magneto-optic material 132 (e.g., Ce-YIG) and the oxide layer 131. As may be appreciated, the adhesive layer 147 may include any suitable adhesives, such as adhesive polymer, divinylsiloxane-bis-benzocyclobutene (DVS-bis-BCB), divinylsiloxane-bis-benzocyclobutene (DVS-BCB), etc. The adhesive layer 147 may have a varying thickness 149 across a lateral direction 151 of the SOI 48, such that the waveguides 128 may receive different non-reciprocal phase shifts (e.g., cladding from the magneto-optic material 132 (e.g., Ce-YIG) and the oxide layer 131) across the lateral direction 151. In particular, the non-reciprocal phase shift received by the waveguides 128 of the first arm 135 may be different from that received by the waveguides 128 of the second arm 137.

[0076] FIG. 19 is a flow chart illustrating a method of fabricating the Ce-YIG on SOI 48 of FIG. 17. As shown in FIG. 19, the method 180 may include depositing the magneto-optic film or thin film (e.g., film of the magneto-optic material 132, such as Ce-YIG film) on the substrate 145 to form the MO/substrate chip 141 (step 182). As set forth above, the the magneto-optic film (e.g., the magneto-optic material 132, such as Ce-YIG) may be deposited via any suitable processes, such as sputtering and MOCVD. The substrate 145 may be any suitable substrates, such as MgO, SGGG, or sapphire. In the illustrated embodiment, the substrate 145 is UV transparent (e.g., transparent with respect to ultraviolet light). In some embodiments, the substrate 145 comprising an amorphous material may be annealed together with the magneto-optic material 132, such as Ce-YIG, at a temperature about 800 degree Celsius (°C).

[0077] The method 180 may include cleaning the MO/substrate chip 141 surface and the SOI 48 surface (step 184). Herein, the surfaces refer to the surface of the magneto-optic material 132 and the surface of the SOI 48 that are in direct contact with one another when the MO/substrate chip 141 is coupled to (e.g., directly bonded to or mounted on) the SOI 48. The surfaces may be cleaned via any suitable surface treatment processes to facilitate improved coupling or bonding between the magneto-optic material 132 and the SOI 48. For example, step 184 may include treating the surfaces via nitrogen (N_2) plasma or argon (Ar) plasma to clean and/or create roughness on the surfaces. Upon completion of the cleaning or surface treatment process at step 184, the method 180 may include activating the surfaces of the MO/substrate chip 141 and the SOI 48 (step 186). In particular, while the cleaning or surface treatment process at step 182 may leave the treated surfaces depleted of oxygen, the activation process in step 186 may include any suitable oxidizing processes to restore or reset the oxygen content near the respective surfaces. For example, a suitable oxidizing process may include low-energy plasma and/or high energy plasma including oxygen (O_2) plasma or ozone plasma (O_3). Further, the plasma treatment may be performed in any suitable lengths, such as about 5 to 60 seconds. The method 180 may include disposing or placing the MO/substrate chip 141 on the SOI 48 (step 188). As set forth above, the

MO/substrate chip 141 may be placed on top of the SOI 48 such that the magneto-optic material 132 is in direct contact with the waveguides 128 integrated with the SOI 48 as shown in FIG. 17A.

[0078] The method 180 may include performing an annealing process under an applied uniform pressure (step 190). In particular, during the annealing process, a uniform pressure may be applied on the MO/substrate chip 141 and the SOI 48 to press and enforce bonding between the two components. As may be appreciated, the annealing process may be performed at nay suitable temperatures for any suitable lengths under any suitable uniform pressure. As a non-limiting example, a suitable annealing temperature may be about 100 °C to about 300 °C, a suitable annealing length or duration may be about 0.1 hours to about 8 hours, and a suitable uniform pressure may be about 10 megapascal (MPa) or about 1×10^7 Newton per square meter (N/m^2). As another non-limiting example, the annealing process (step 190) may be a rapid thermal annealing process at about 100 °C to about 600 °C for about 10 seconds to about 5 minutes under an applied uniformed pressure up to about 10 MPa or about 1×10^7 N/m^2 (e.g., between about 1 MPa or 1×10^6 N/m^2 and about 10 MPa or 1×10^7 N/m^2). In certain embodiments, different annealing temperatures may be applied to the MO/substrate chip 141 and the SOI 48. The method 180 may include performing a lift-off process to remove the substrate from the MO/substrate chip 141 (step 194). For example, the lift-off process may be achieved via applying a focused pulse ultraviolet light (UV) excimer laser beam to the interface between the substrate 145 and the magneto-optic material 132 to lift-off or remove the substrate 145.

[0079] FIG. 20 is a flow chart illustrating a method 200 of fabricating the MO/substrate chip 141 on SOI 48 of FIG. 18. As shown in FIG. 20, the method 200 may include depositing the magneto-optic film or thin film (e.g., film of magneto-optic material 132, such as Ce-YIG) on the substrate 145 to form the MO/substrate chip 141 (step 202). The method 200 may include cleaning the MO/substrate chip 141 surface and the SOI 48 surface (step 204). As may be appreciated, steps 202 and 204 may be essentially identical to steps 182 and 184, respectively. The method 200 may include disposing the adhesive 147 on the SOI 48 (step 206). As set forth above, the adhesive 147 may be include any suitable adhesives, such as adhesive polymer, DVS-bis-BCB, DVS-BCB, etc. Further, the adhesive 147 may be disposed via any suitable methods, such as spin-coating. The method 200 may include curing the SOI 48 (step 208). As may be appreciated, the curing process may be performed at any suitable temperatures for any suitable lengths or durations. For example, the SOI 48 may be cured or soft-cured at about 150 °C to about 250 °C for about 1 minute to about 5 minutes. In certain embodiments, the SOI 48 may be cured via a rapid thermal annealing process. The method 200 may include disposing or placing the MO/substrate chip 141 on the SOI 48 (step 210). In particular, the MO/substrate chip 141 may be placed on top of the adhesive layer 147 such that the MO/substrate chip 141 is adhere to the SOI 48 at a suitable location and/or orientation, as shown in FIG. 18.

[0080] The method 200 may include performing an annealing or curing process under an applied uniform pressure (step 212). In particular, during the annealing process, a uniform pressure may be applied on the MO/substrate chip 141 and the SOI 48 to press and enforce adhesion between the two components. As may be appreciated, the annealing or curing process may be performed at any suitable temperatures for any suitable lengths under any suitable uniform pressure. As a non-limiting example, step 212 may include a hard-curing process performed at temperatures between about 200 °C and about 300 °C, for about 0.1 hours to about 5 hours, and under a uniform pressure up to about 300 kilopascal (kPa) or about 3×10^5 Newton per square meter (N/m^2). As another non-limiting example, step 212 may include a rapid thermal annealing process performed at about 250 °C, for about 0.1 minutes to about 5 minutes, under an applied uniformed pressure up to about 300 kPa or about 3×10^5 N/m^2. The method 200 may include performing a lift-off process to remove the substrate from the MO/substrate chip 141 (step 214). For example, the lift-off process may be achieved via applying a focused pulse ultraviolet light (UV) excimer laser beam to the interface between the substrate 145 and the magneto-optic material 132 to lift-off or remove the substrate 145.

[0081] As may be appreciated, although the magneto-optic material 132 discussed in FIGS. 17-20 includes Ce-YIG, in certain embodiments, the magneto-optic material 132 may include any suitable magneto-optic materials, such as the magneto-optic polymers as set forth above. In the cases that the magneto-optic material 132 includes a magneto-optic polymer, the magneto-optic polymer may be disposed on the SOI 48 and the substrate 145 may be omitted. The methods 180 and 200 as discussed in FIGS. 19-20 may be modified accordingly at least based in part on the thermal and/or thermal mechanical properties of the magneto-optic polymer. However, it should be appreciated that although one or more steps may be omitted, any suitable oxidizing processes to restore or reset the oxygen content near the respective surfaces (step 186) may still be applied to restore or reset the oxygen content near the respective surfaces. It should also be noted that in case of materials, such as dielectrics, metals, and/or semiconductors are present above the waveguides 128, these materials may be cleared or removed prior to disposing the MO/substrate chip or the magneto-optic material 132 on the SOI 48 (e.g., step 188 or step 206) by suitable masking and etching (e.g., dry or wet etching) of trenches to expose the waveguides 128.

[0082] This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal language of the claims.

CLAIMS:

1. A photonic sensing system comprising:

an interrogator coupled to a sensing fiber, wherein the interrogator comprises:

a light source configured to emit light;

a photonic integrated circuit (PIC) comprising a plurality of photonic components, wherein the PIC is configured to transmit the light emitted by the light source and to receive reflected light from the sensing fiber; and

a plurality of integrated circuit (IC) components configured to process and analyze signals from the interrogator to determine one or more measurands.

2. The photonic sensing system of claim 1, wherein the PIC is implemented using silicon-on insulator (SOI) technology.

3. The photonic sensing system of claim 1, wherein the one or more measurands comprise electrical current.

4. The photonic sensing system of claim 3, comprising:

a polarization beam splitter and a polarization rotator disposed along one or more light paths between the interrogator and the sensing fiber, wherein the polarization beam splitter is coupled to the interrogator via a polarization maintaining (PM) fiber that transmits the emitted light toward the sensing fiber and via a single mode (SM) fiber that transmits the reflected light toward the interrogator, and wherein the polarization rotator is coupled to both the polarization beam splitter and the sensing fiber.

5. The photonic sensing system of claim 3, wherein the PIC comprises a polarization beam splitter and a polarization rotator disposed along one or more light paths between the interrogator and the sensing fiber.

6. The photonic sensing system of claim 3, comprising:

a polarization rotator disposed along a light path between the interrogator and the sensing fiber, wherein the light path is confined within a polarization maintaining (PM) fiber that transmits the emitted light toward the sensing fiber and subsequently transmits reflected light toward the interrogator; and

a polarization beam splitter disposed on the SOI chip and coupled to the PM fiber.

7. The photonic sensing system of claim 1, wherein the sensing fiber comprises fiber Bragg gratings (FBG) and the one or more measurands comprise wavelength.

8. The photonic sensing system of claim 7, wherein the plurality of photonic components comprise a tunable micro-ring filter coupled to the light source, and the sensing fiber comprises a polarization maintaining (PM) fiber.

9. The photonic sensing system of claim 7, wherein the plurality of photonic components comprise a tunable micro-ring filter coupled to the light source and a polarization beam splitter coupled to the sensing fiber, and the sensing fiber comprises a single mode (SM) fiber.

10. The photonic sensing system of claim 7, wherein the sensing fiber comprises a polarization maintaining (PM) fiber, and the plurality of photonic components comprise a first arrayed waveguide grating (AWG) coupled to a first photodiode array to interrogate the reflected light.

11. The photonic sensing system of claim 7, wherein the plurality of photonic components comprise:

a first arrayed waveguide grating (AWG) coupled to a first photodiode array to interrogate the reflected light; and

a second AWG coupled to a second photodiode array;

a polarization rotator coupled to the second arrayed waveguide grating; and a polarization beam splitter coupled to the polarization rotator and the sensing fiber comprising a single mode (SM) fiber.

12. An integrated circuit (IC), comprising:

a light source configured to emit light;

an interrogator configured to be coupled to a sensing fiber to transmit the light emitted by the light source and interrogate reflected light from the sensing fiber; and

a plurality of IC components configured to process and analyze signals from the interrogator to determine one or more measurands comprising electrical current or power, wherein the interrogator comprises a plurality of photonic components disposed on a single silicon-on-insulator (SOI) chip.

13. The IC of claim 12, comprising:

a polarization beam splitter and a first polarization rotator disposed along one or more light paths between the interrogator and the sensing fiber, wherein the polarization beam splitter is coupled to the interrogator via a polarization maintaining (PM) fiber that transmits the emitted light toward the sensing fiber and via a single mode (SM) fiber that transmits the reflected light toward the interrogator, and wherein the polarization beam splitter is coupled to a polarization rotator that is coupled to the sensing fiber.

14. The IC of claim 13, the plurality of photonic components comprising:

a second polarization rotator coupled to the light source;

a light circulator coupled to the second polarization rotator and a first light sensor;

a splitter coupled to the light circulator, a second light sensor, and the PM fiber; and

a third light sensor coupled to the SM fiber.

15. The IC of claim 12, the plurality of photonic components comprising:

a first polarization rotator coupled to the light source;

a light circulator coupled to the second polarization rotator and a first light sensor;

a splitter coupled to the light circulator and a second light sensor; and

a second polarization beam splitter coupled to the splitter and a third light sensor, wherein the polarization beam splitter is coupled to a second polarization rotator that is disposed on an interposer of the PIC and coupled to the sensing fiber.

16. The IC of claim 12, comprising

a first polarization rotator disposed along a light path between the interrogator and the sensing fiber, wherein the light path is confined within a polarization maintaining (PM) fiber that transmits the emitted light toward the sensing fiber and subsequently transmits reflected light toward the interrogator; and

a polarization beam splitter disposed on the SOI chip and coupled to the PM fiber.

17. The IC of claim 16, the plurality of photonic components comprising:

a first polarization rotator coupled to the light source;

a light circulator coupled to the second polarization rotator and a first light sensor;

a splitter coupled to the light circulator and a second light sensor; and

a polarization beam splitter coupled to the splitter and a third light sensor, wherein the polarization beam splitter is coupled to the PM fiber.

18. An integrated circuit (IC), comprising:

a light source configured to emit light;

an interrogator configured to be coupled to a sensing fiber to transmit the light emitted by the light source to the sensing fiber and to interrogate reflected light from the sensing fiber, wherein the sensing fiber comprising fiber Bragg gratings (FBG); and

a plurality of IC components configured to process and analyze signals from the interrogator to determine one or more measurand comprising wavelength, wherein the interrogator comprises a plurality of photonic components disposed on a single silicon-on-insulator (SOI) chip.

19. The IC of claim 18, the plurality of photonic components comprising:

a tunable micro-ring filter coupled to the light source;

a reflector coupled to the tunable micro-ring filter;

a first polarization rotator coupled to the reflector;

a light circulator coupled to the first polarization rotator and a first light sensor;

a splitter coupled to the light circulator;

a reference filter coupled to the splitter; and

a second light sensor coupled to the reference filter, wherein the splitter is coupled to the sensing fiber comprising a polarization maintaining (PM) fiber.

20. The IC of claim 18, the plurality of photonic components comprising:

a tunable micro-ring filter coupled to the light source;

a reflector coupled to the tunable micro-ring filter;

a first polarization rotator coupled to the reflector;

a light circulator coupled to the first polarization rotator and a first light sensor;

a splitter coupled to the light circulator;

a reference filter coupled to the splitter;

a second light sensor coupled to the reference filter; and

a polarization beam splitter coupled to the splitter and a third light sensor, wherein the polarization beam splitter is coupled to the sensing fiber comprising a single mode (SM) fiber.

21. The IC of claim 18, the plurality of photonic components comprising:

a first polarization rotator coupled to the light source;

a light circulator coupled to the first polarization rotator and an arrayed waveguide grating (AWG) that couples to a first photodiode array; and a splitter coupled to the light circulator, a light sensor, and the sensing fiber, wherein the sensing fiber comprises a polarization maintaining (PM) fiber.

22. The IC of claim 18, the plurality of photonic components comprising:

a first polarization rotator coupled to the light source;

a light circulator coupled to the first polarization rotator and a first arrayed waveguide grating (AWG) that couples to a first photodiode array;

a splitter coupled to the light circulator, a light sensor, and a polarization beam splitter; and

a second polarization rotator coupled to the polarization beam splitter; and

a second AWG that couples to a second array of photodiodes, wherein the polarization beam splitter is coupled to the sensing fiber comprising a single mode (SM) fiber.

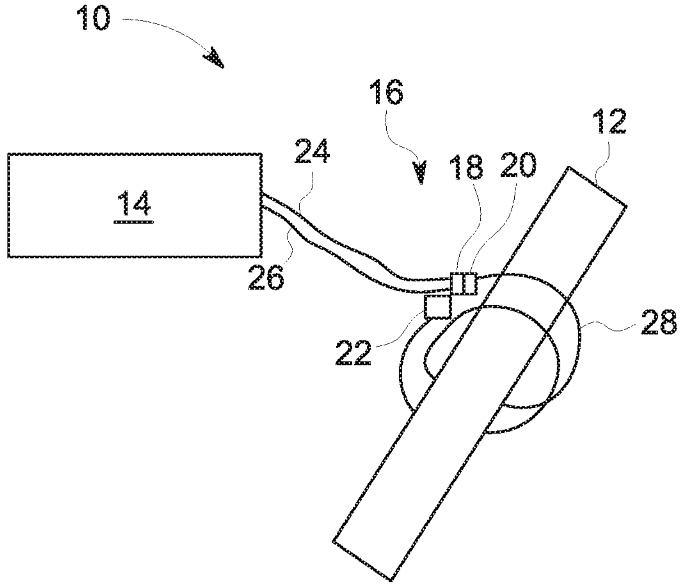
10
16
12
24
18
20
14
26
28
22

FIG. 1

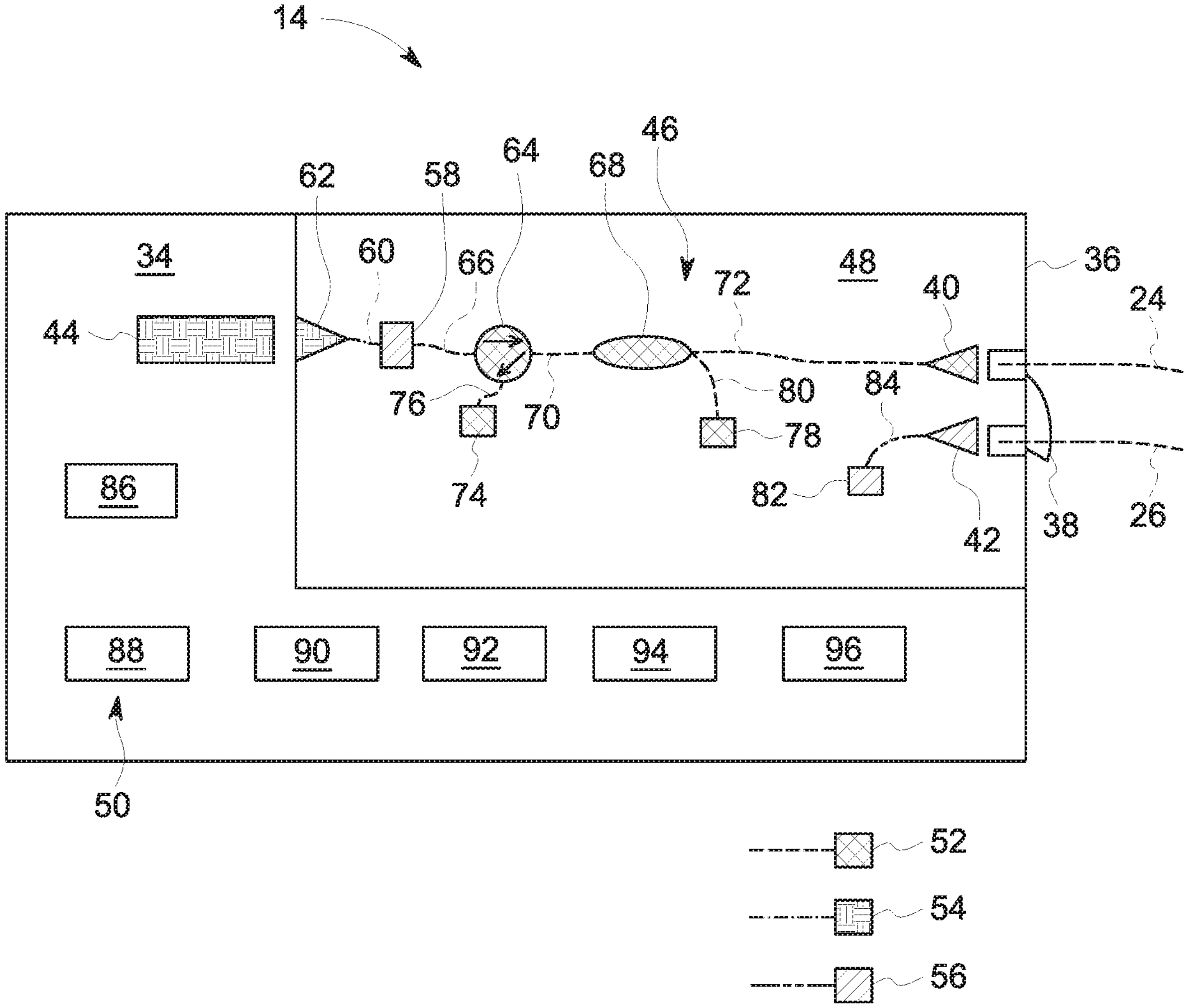
14
46
62
58
64
68
60
66
72
48
36
34
40
24
44
84
76
70
80
78
74
82
38
26
42
86
88
90
92
94
96
50
52
54
56

FIG. 2

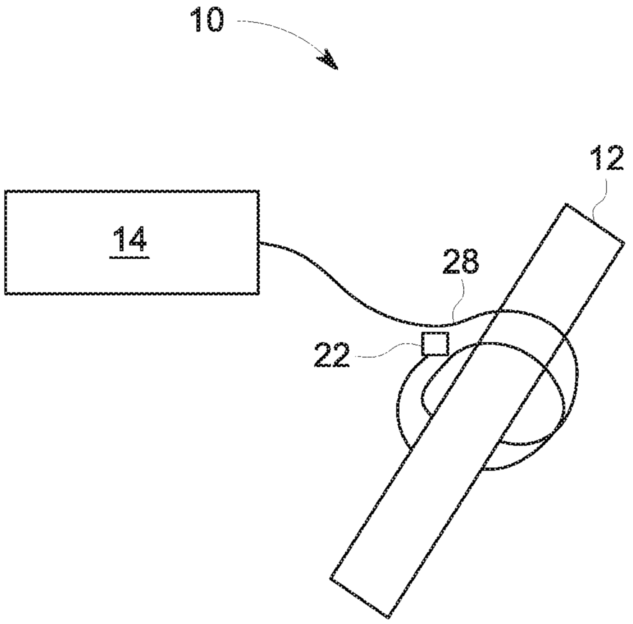

FIG. 3

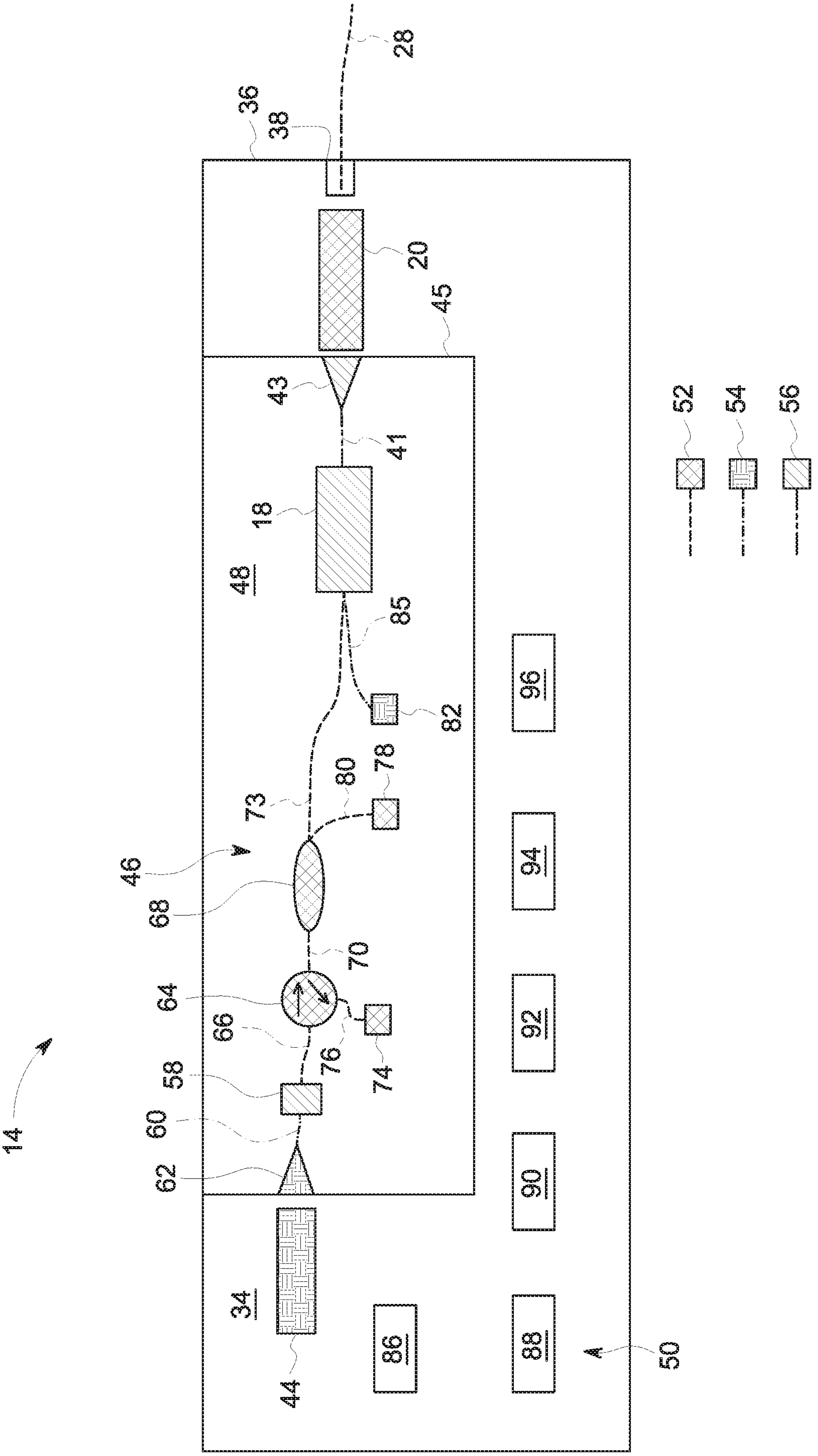
28
36
38
20
45
43
41
18
48
85
82
96
52
54
56
73
80
78
46
68
94
70
64
66
76
74
92
58
60
62
14
90
34
44
86
88
50

FIG. 4

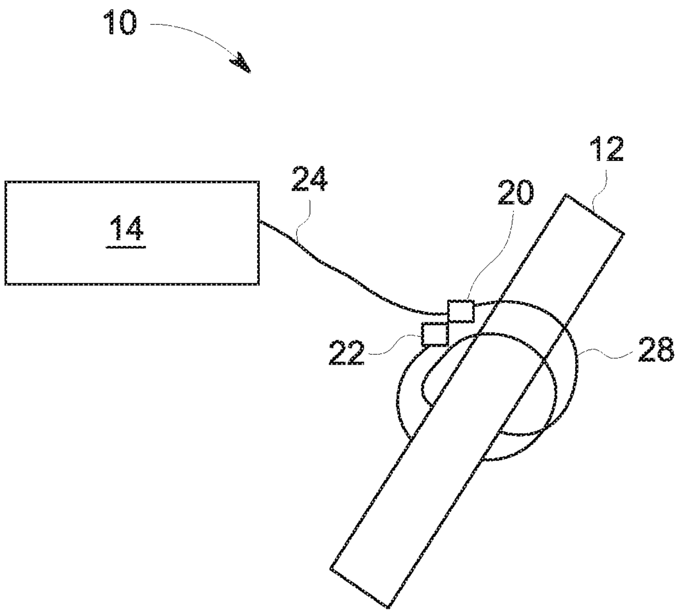

FIG. 5

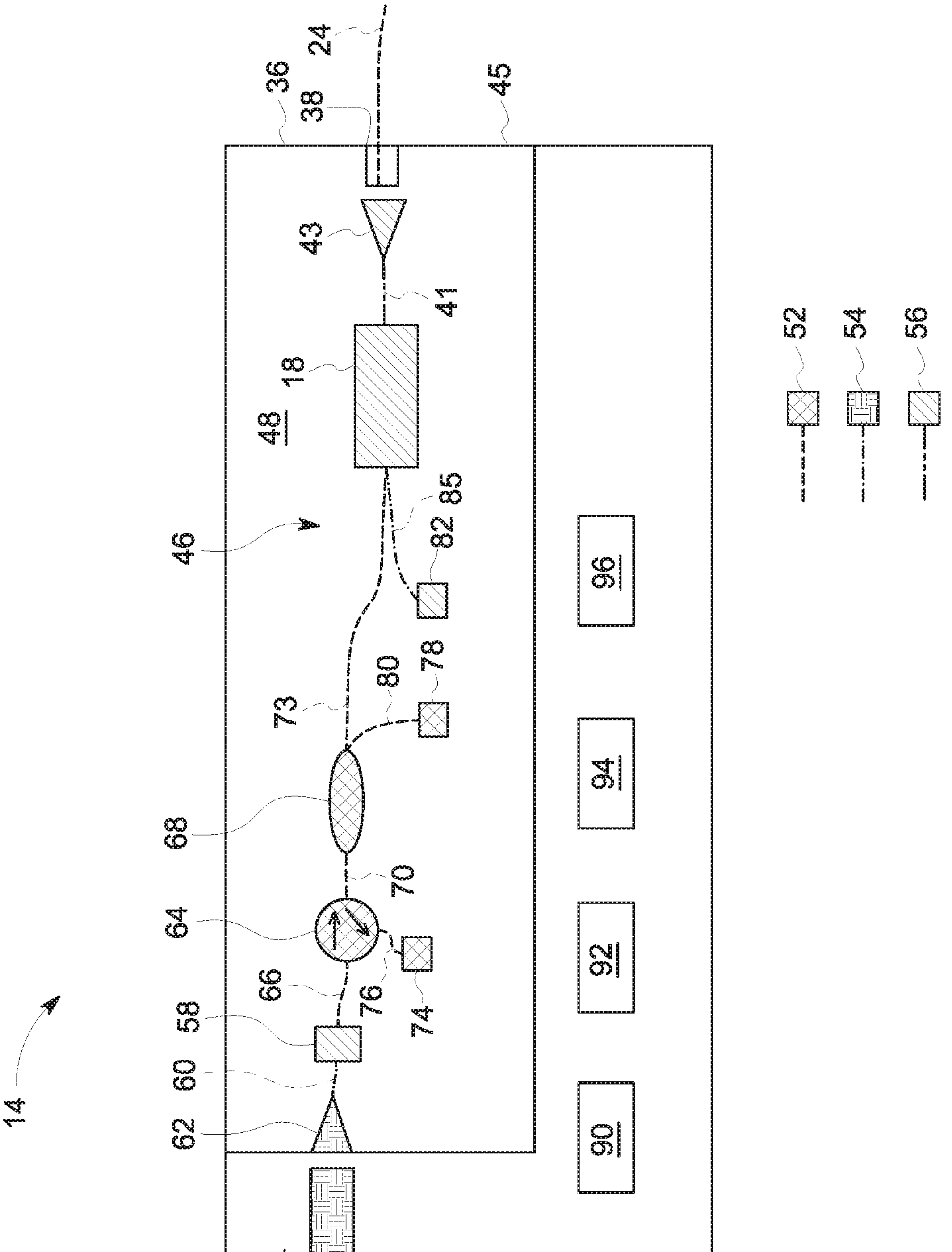
14
36
38
24
45
43
41
18
48
46
85
82
73
80
78
68
70
64
66
76
74
58
60
62
34
44
86
88
50
90
92
94
96
52
54
56

FIG. 6

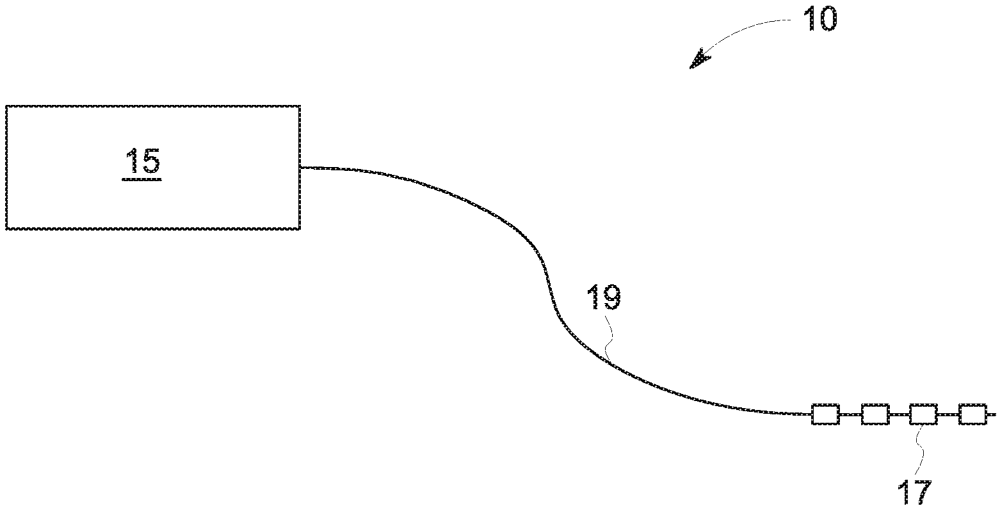

FIG. 7

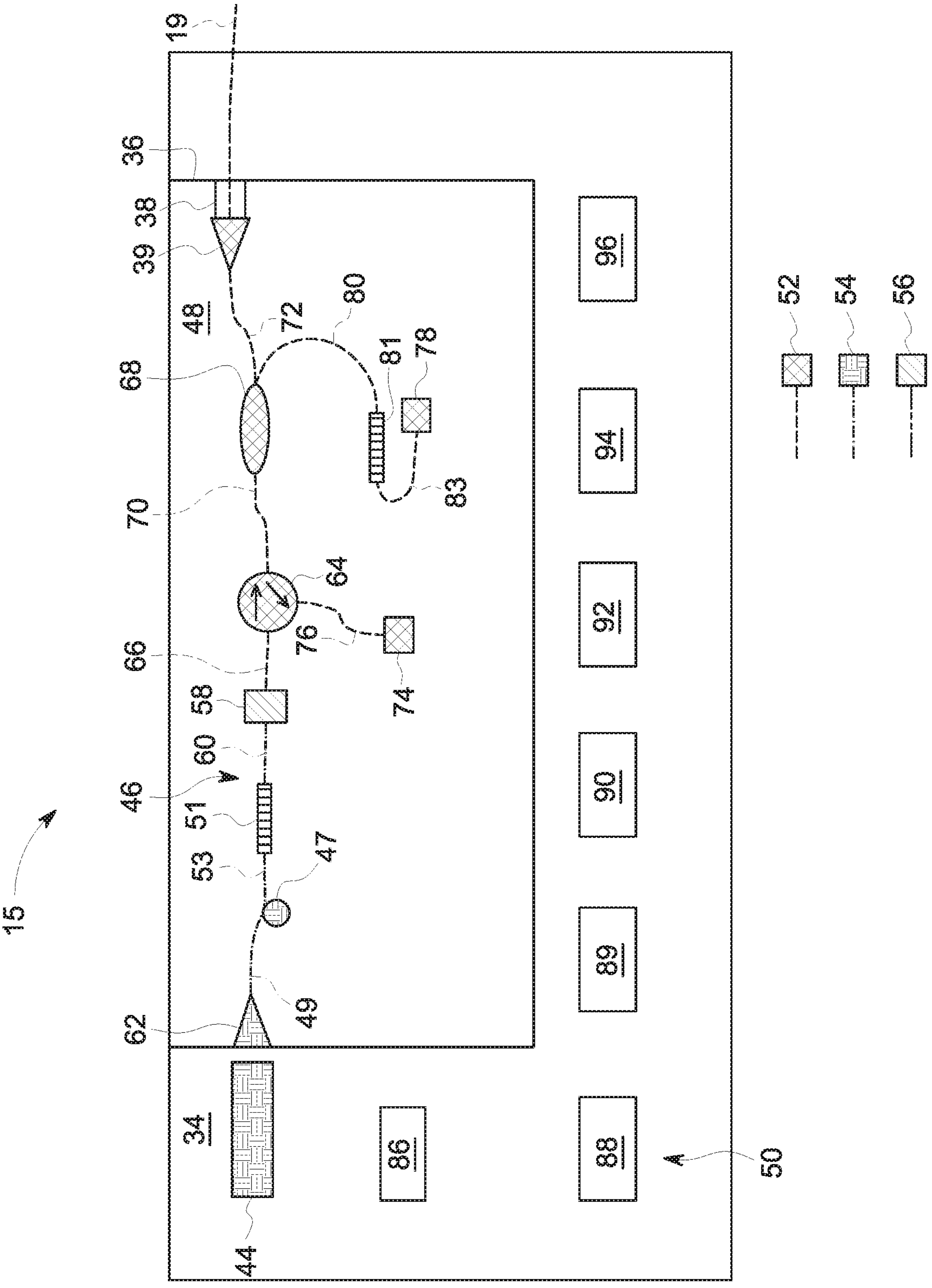
19
36
38
39
48
72
80
68
81
78
70
83
64
66
76
74
58
60
46
51
53
47
15
62
49
34
44
86
88
50
96
94
92
90
89
52
54
56

FIG. 8

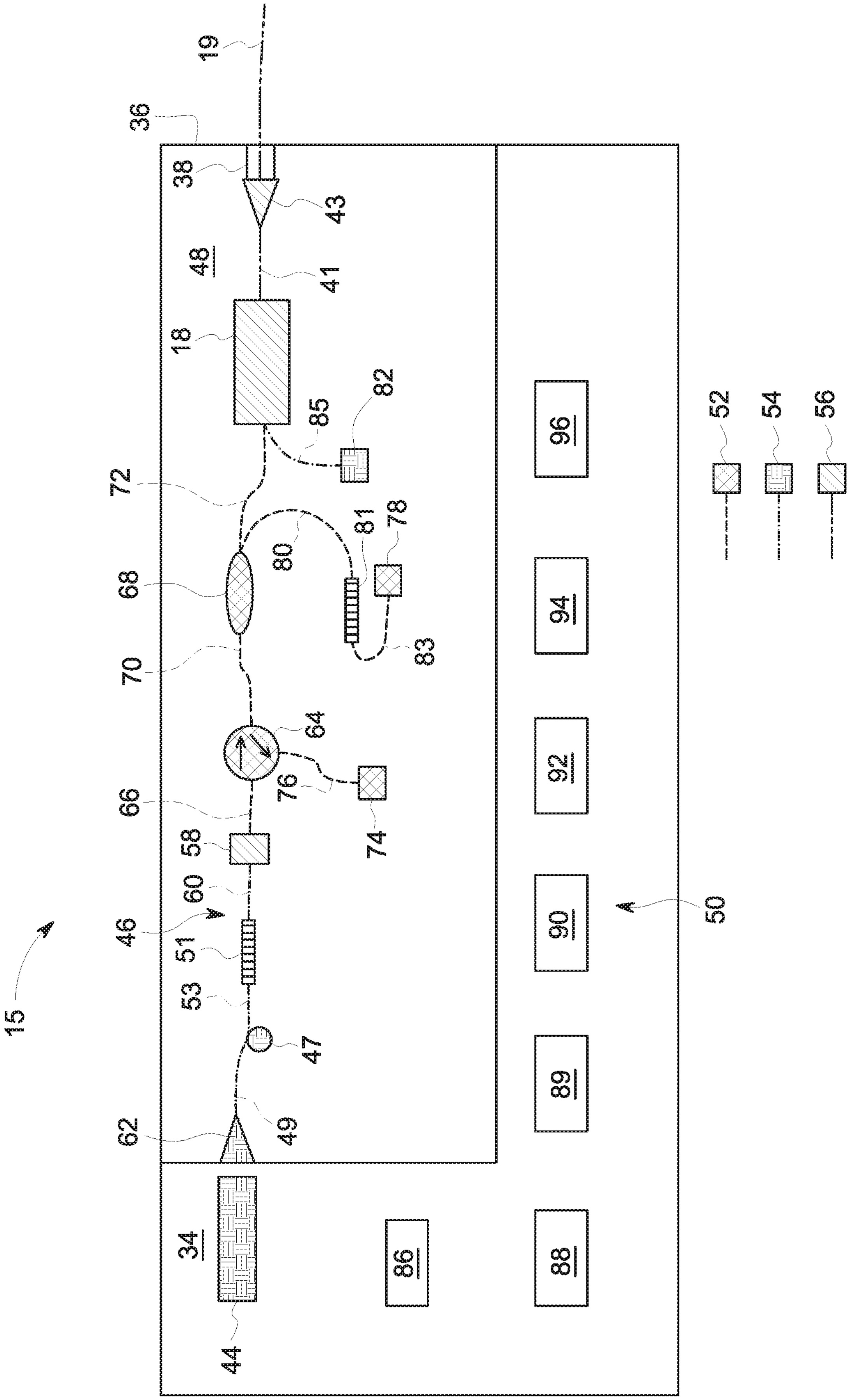
15
19
36
38
43
48
41
18
82
85
72
68
80
81
78
83
70
64
66
76
74
58
60
46
51
53
47
62
49
34
44
86
88
89
90
92
94
96
50
52
54
56

FIG. 9

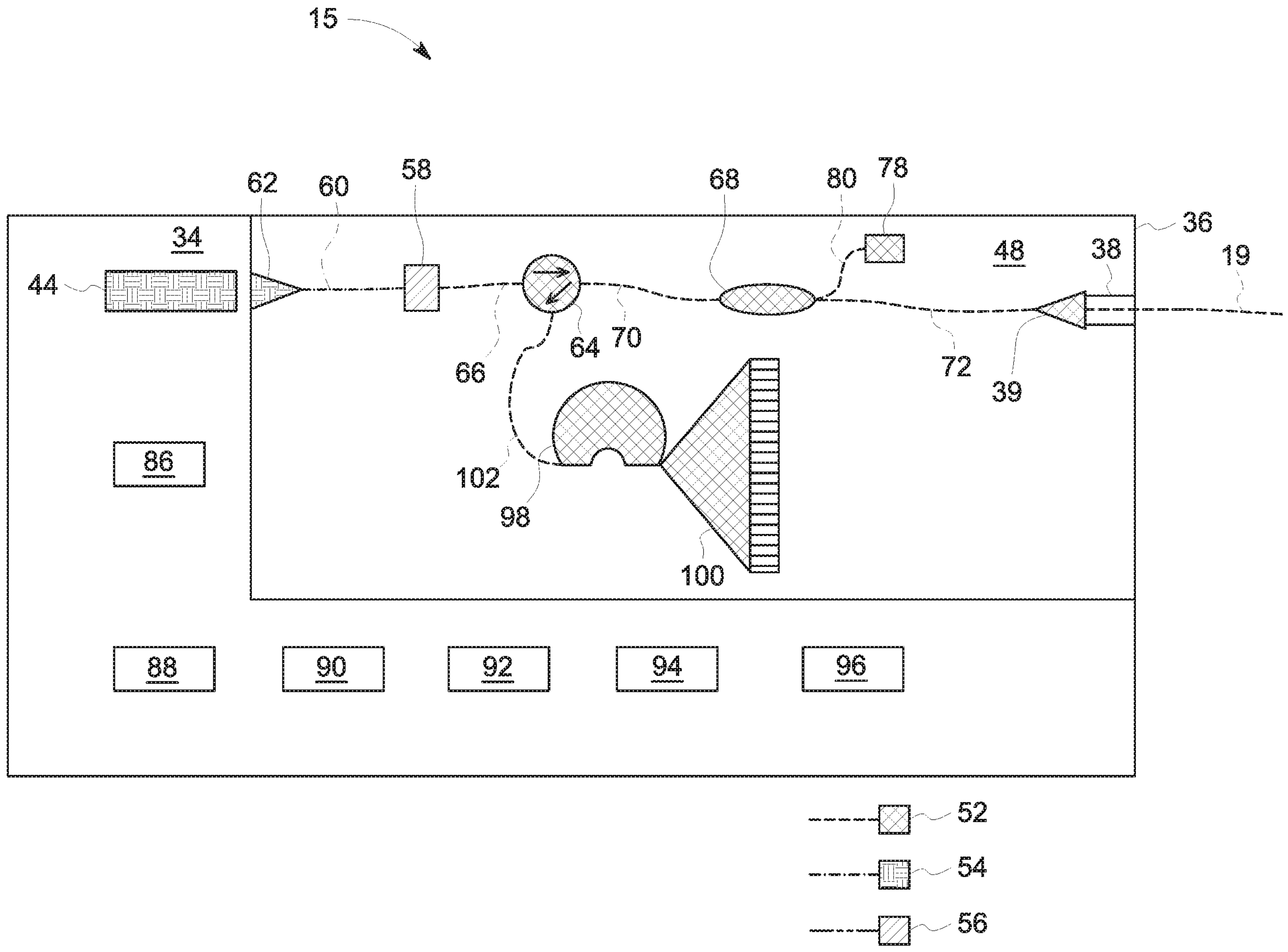
15
62
60
58
68
80
78
34
44
36
48
38
19
66
64
70
72
39
86
102
98
100
88
90
92
94
96
52
54
56

FIG. 10

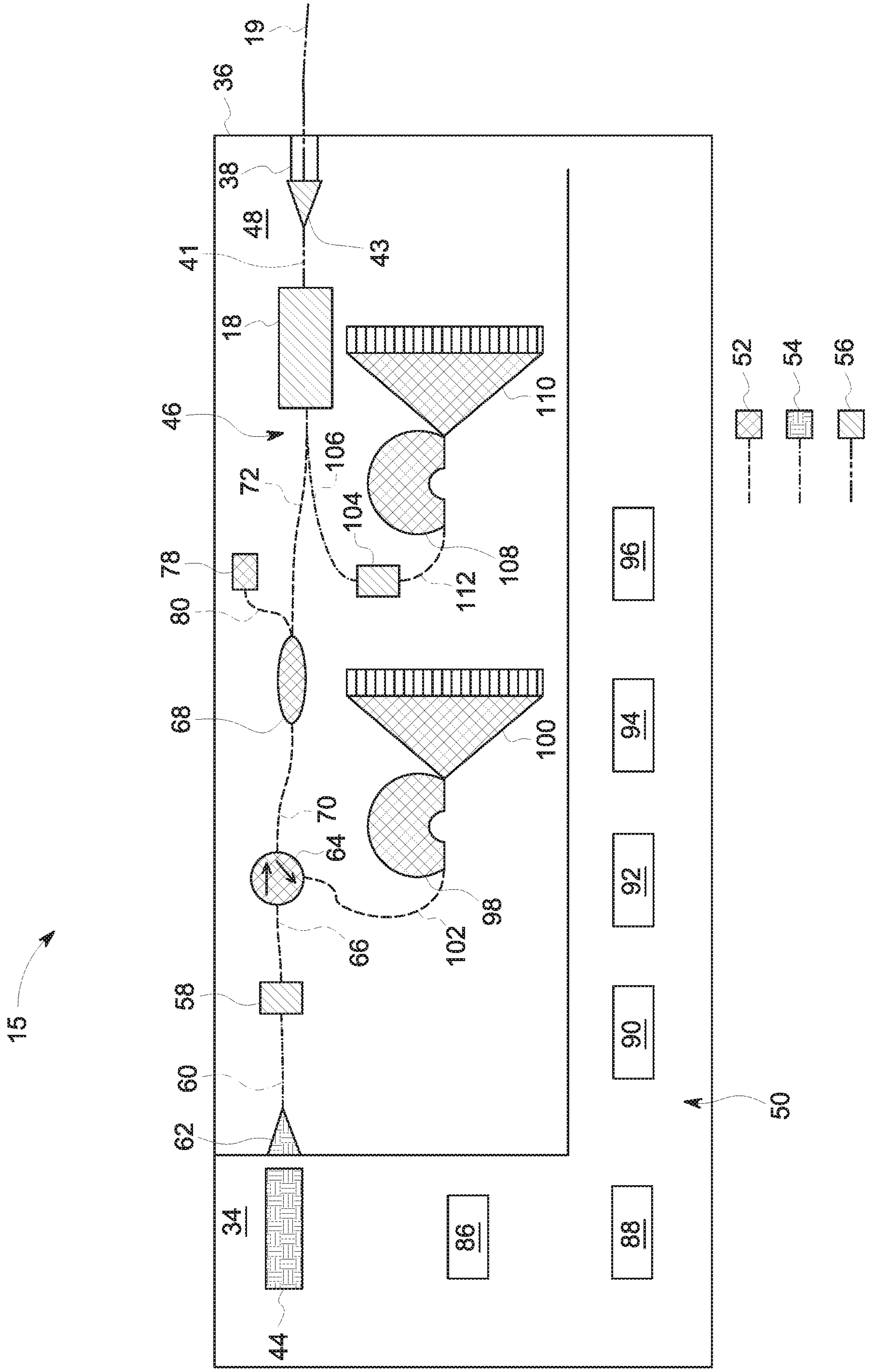
19
36
38
48
43
41
18
46
110
106
72
104
108
112
78
80
68
100
70
64
98
102
66
58
60
62
15
34
44
86
88
90
92
94
96
50
52
54
56

FIG. 11

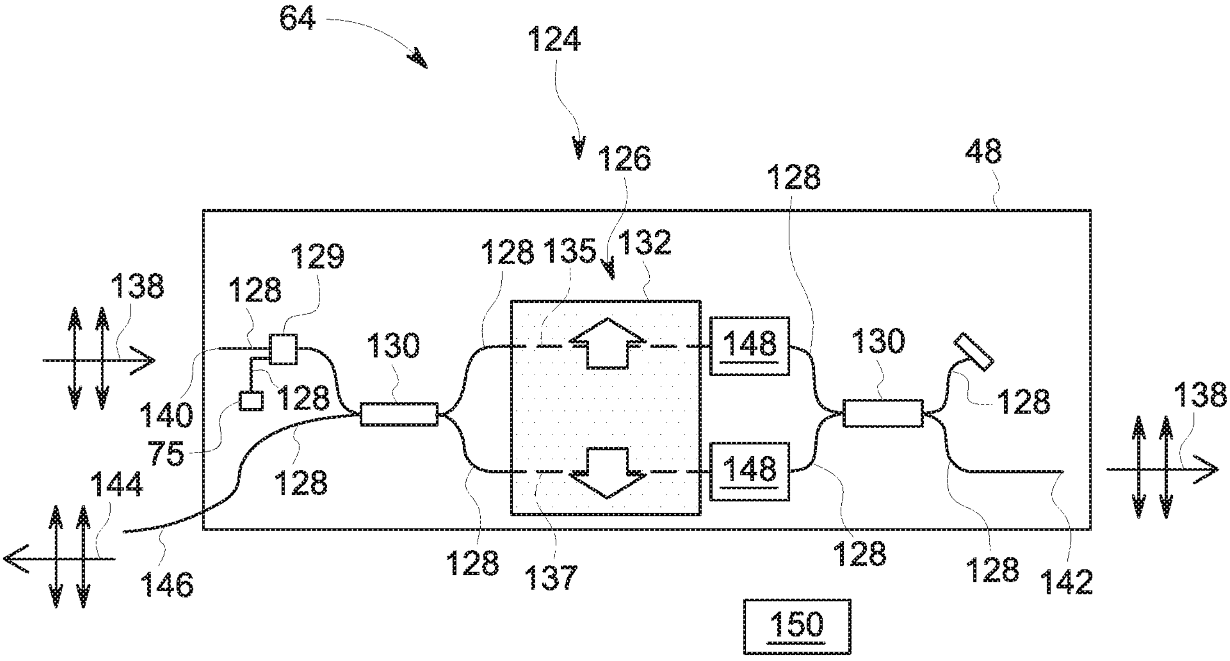

FIG. 12A

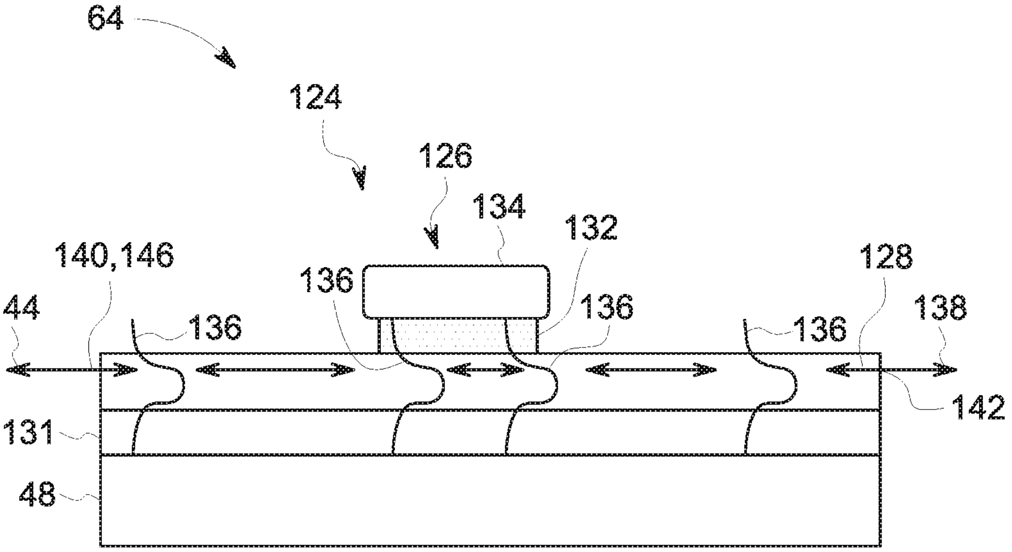

FIG. 12B

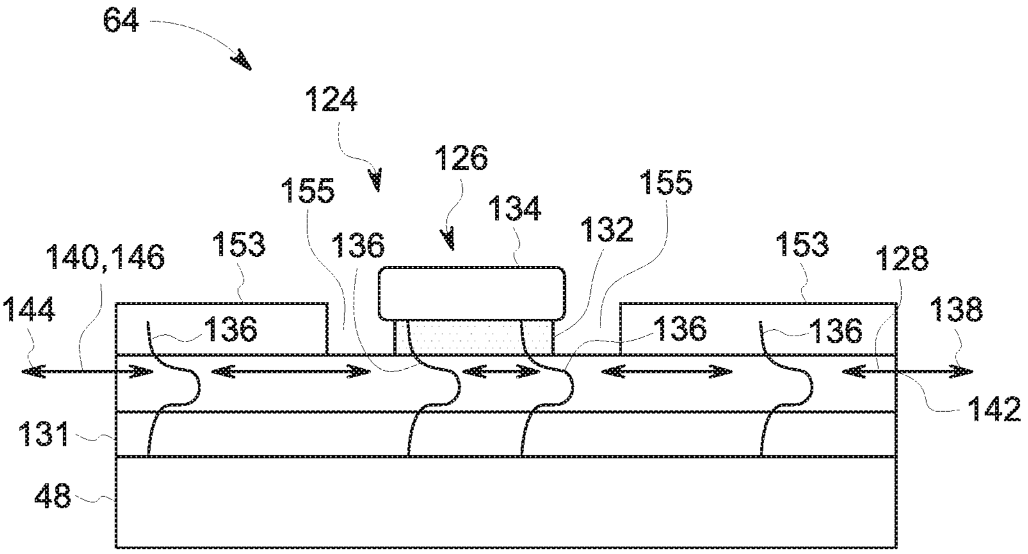

FIG. 12C

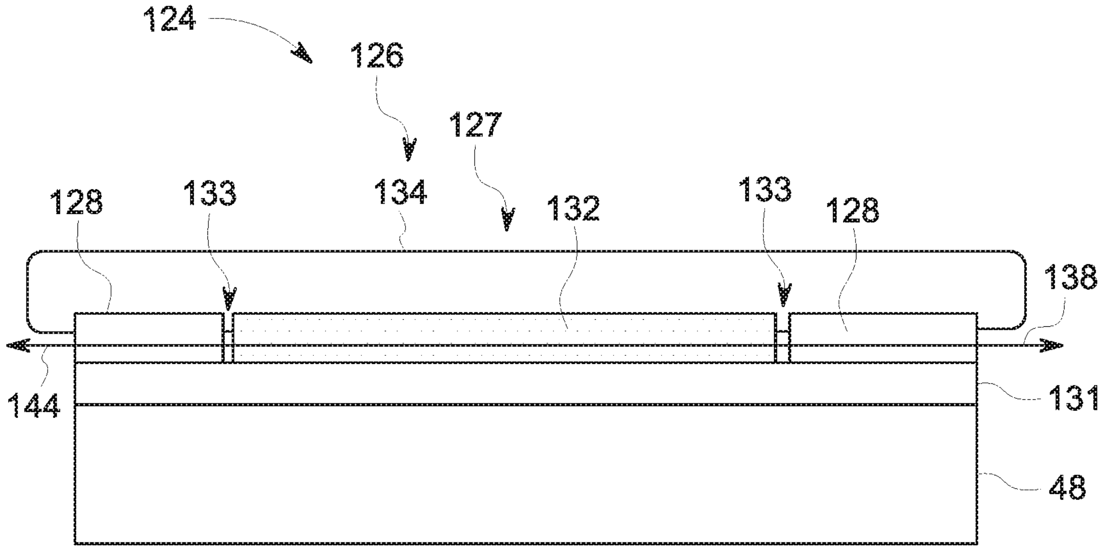

FIG. 13

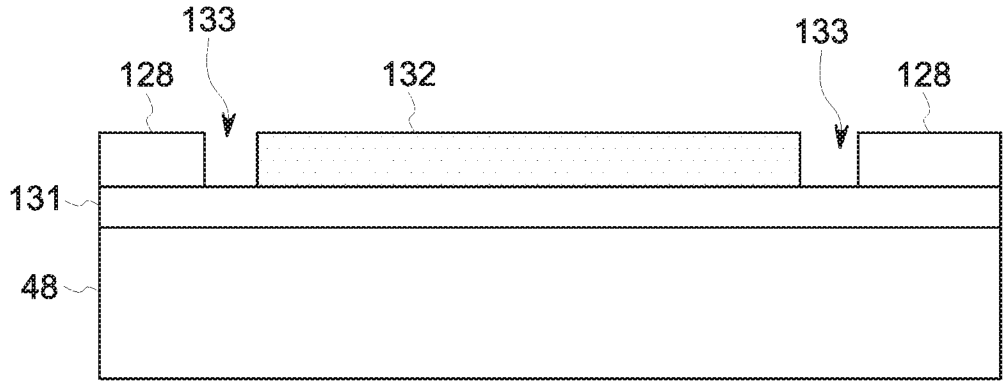

FIG. 14A

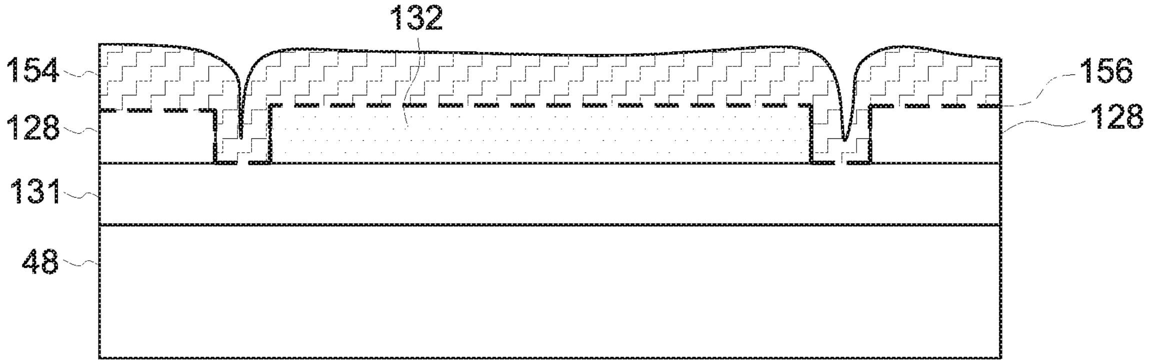

FIG. 14B

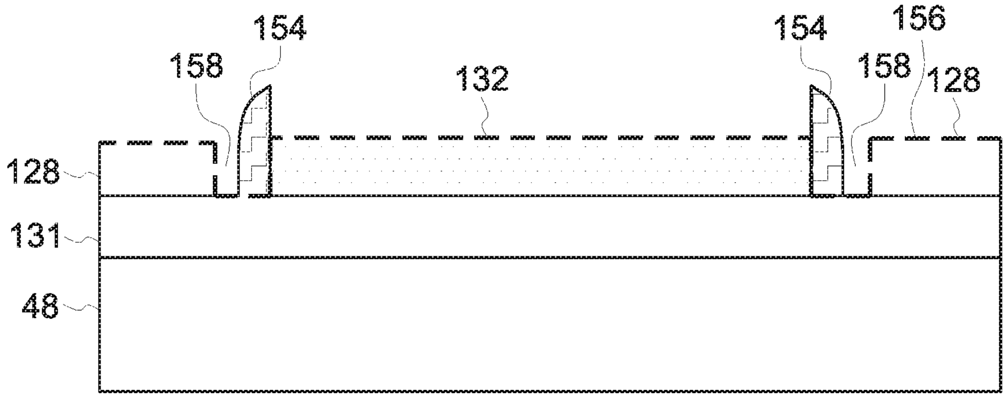

FIG. 14C

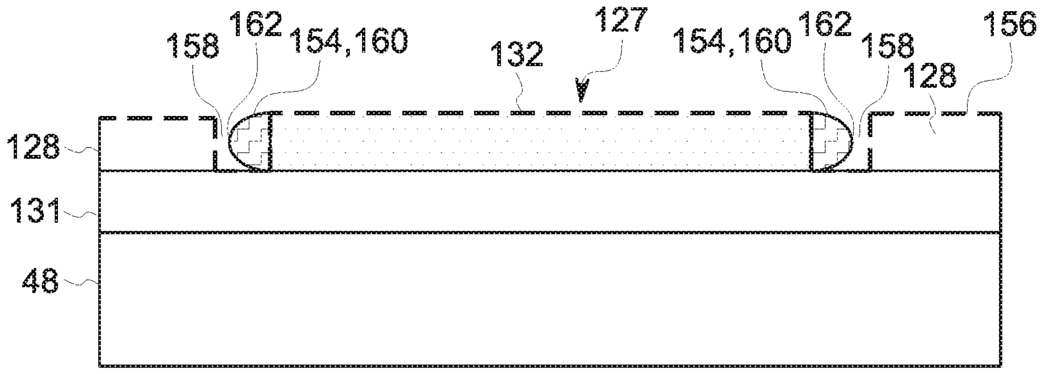

FIG. 14D

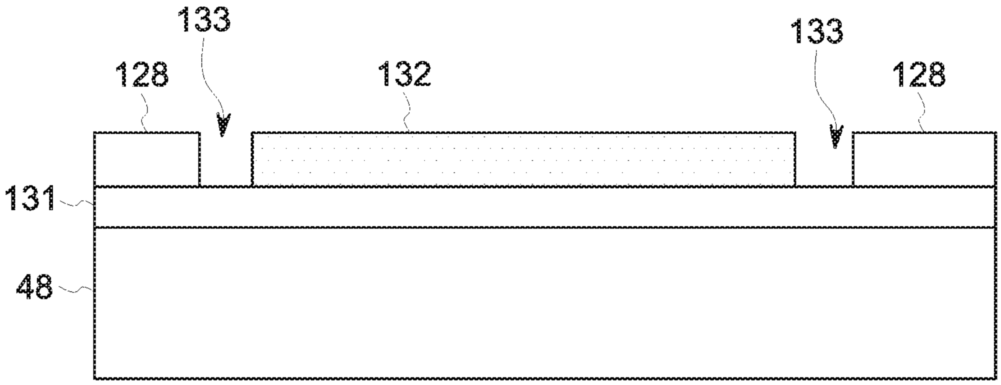

FIG. 15A

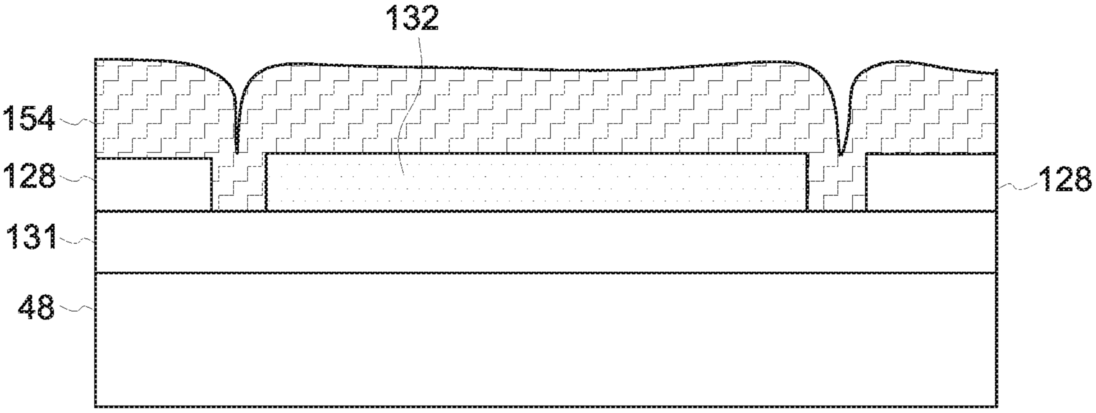

FIG. 15B

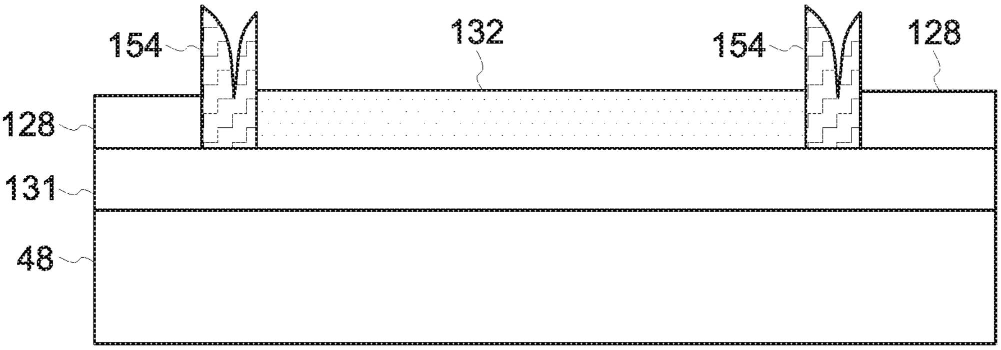

FIG. 15C

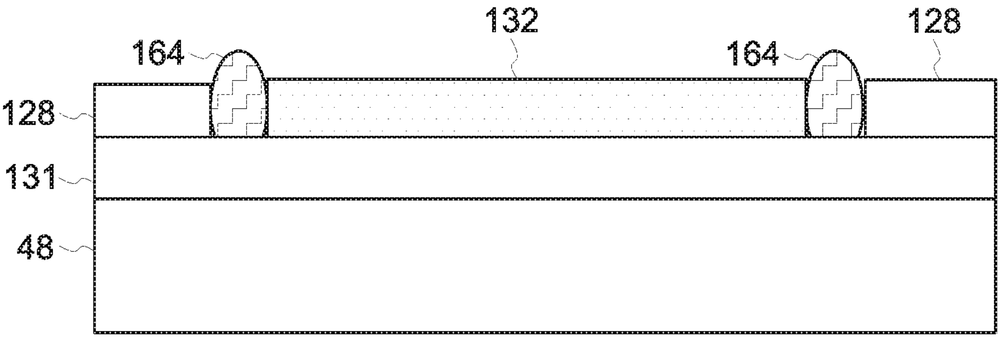

FIG. 15D

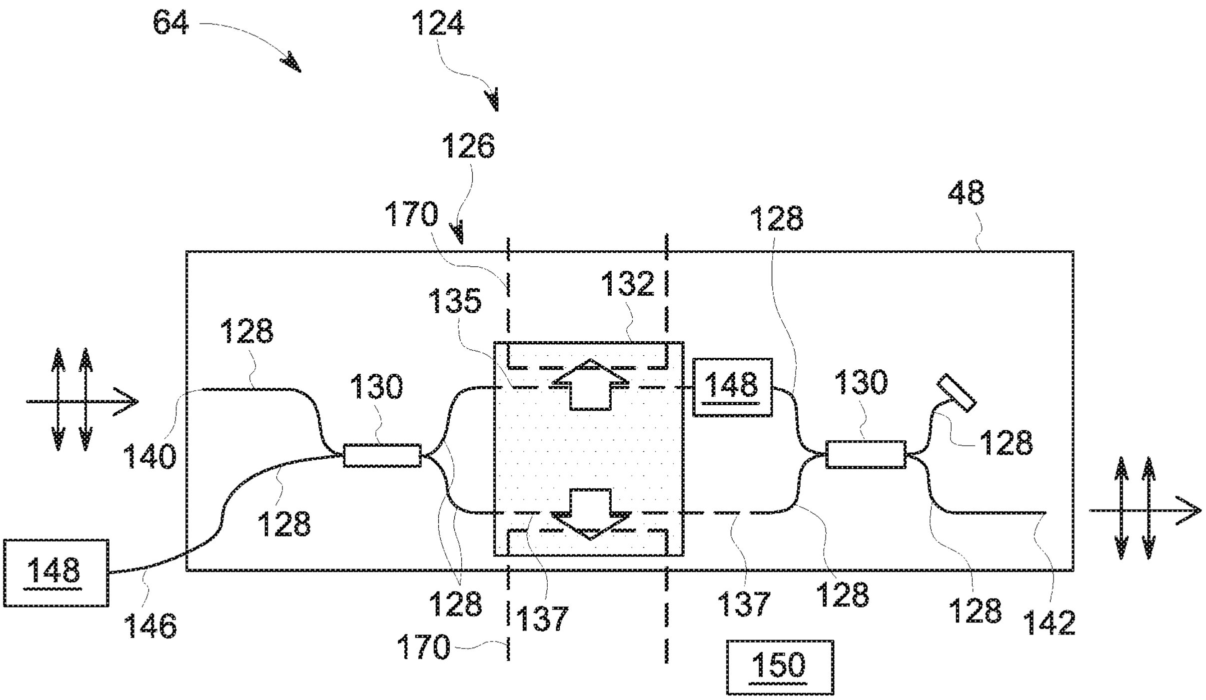

FIG. 16A

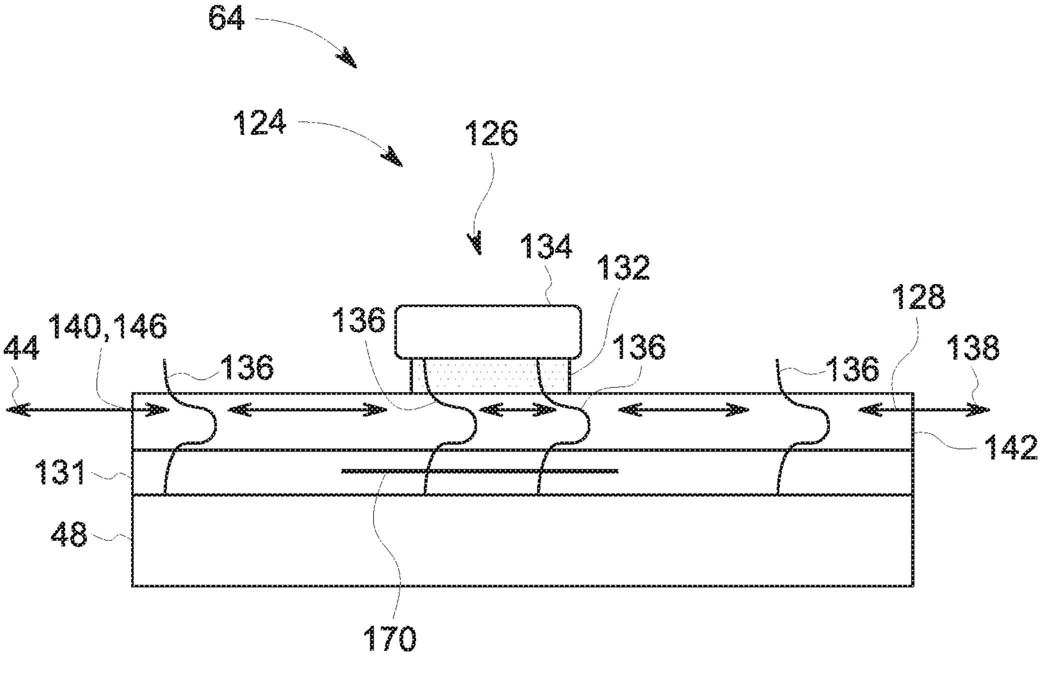

FIG. 16B

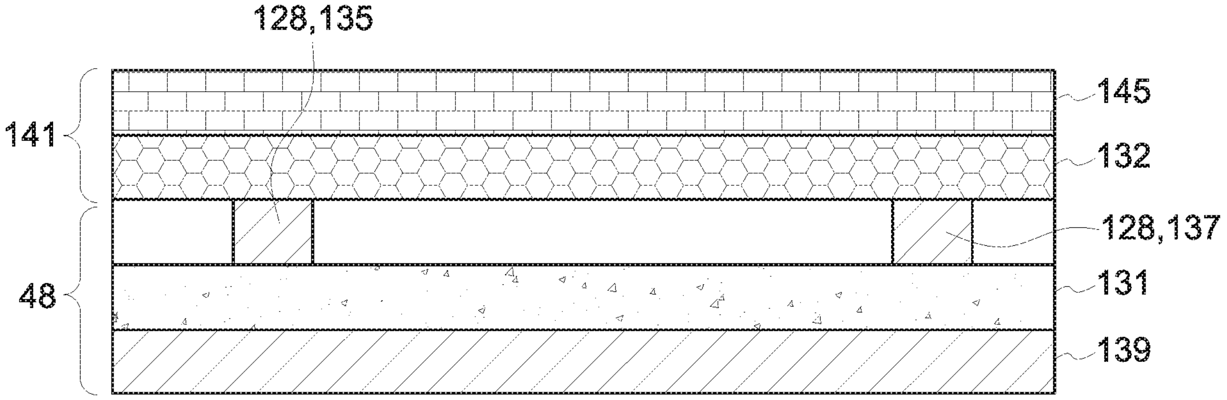
128,135
145
141
132
128,137
48
131
139

FIG. 17

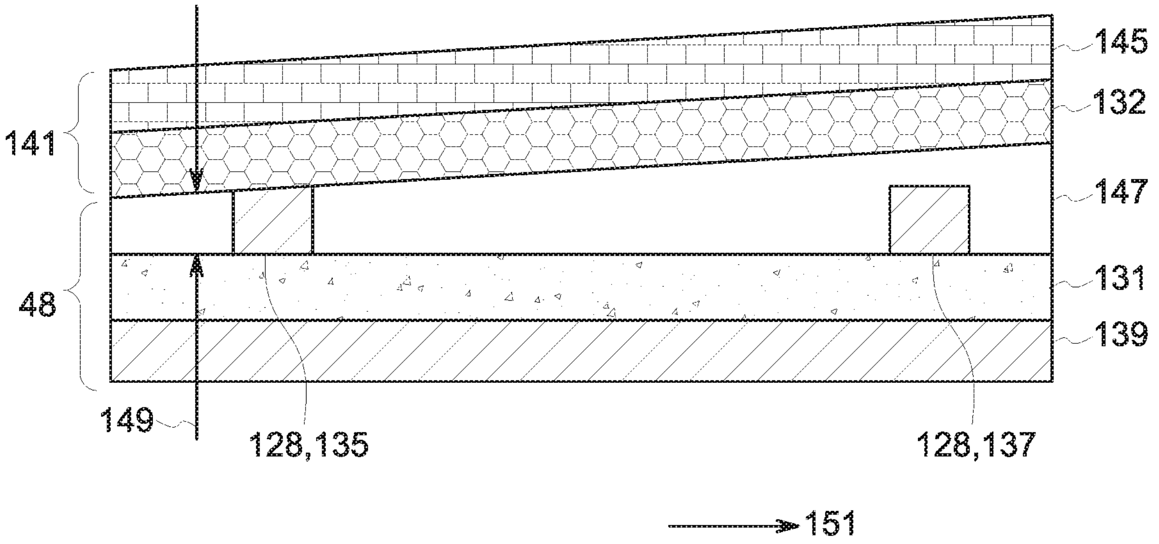
145
132
141
147
131
48
139
149
128,135
128,137
151

FIG. 18

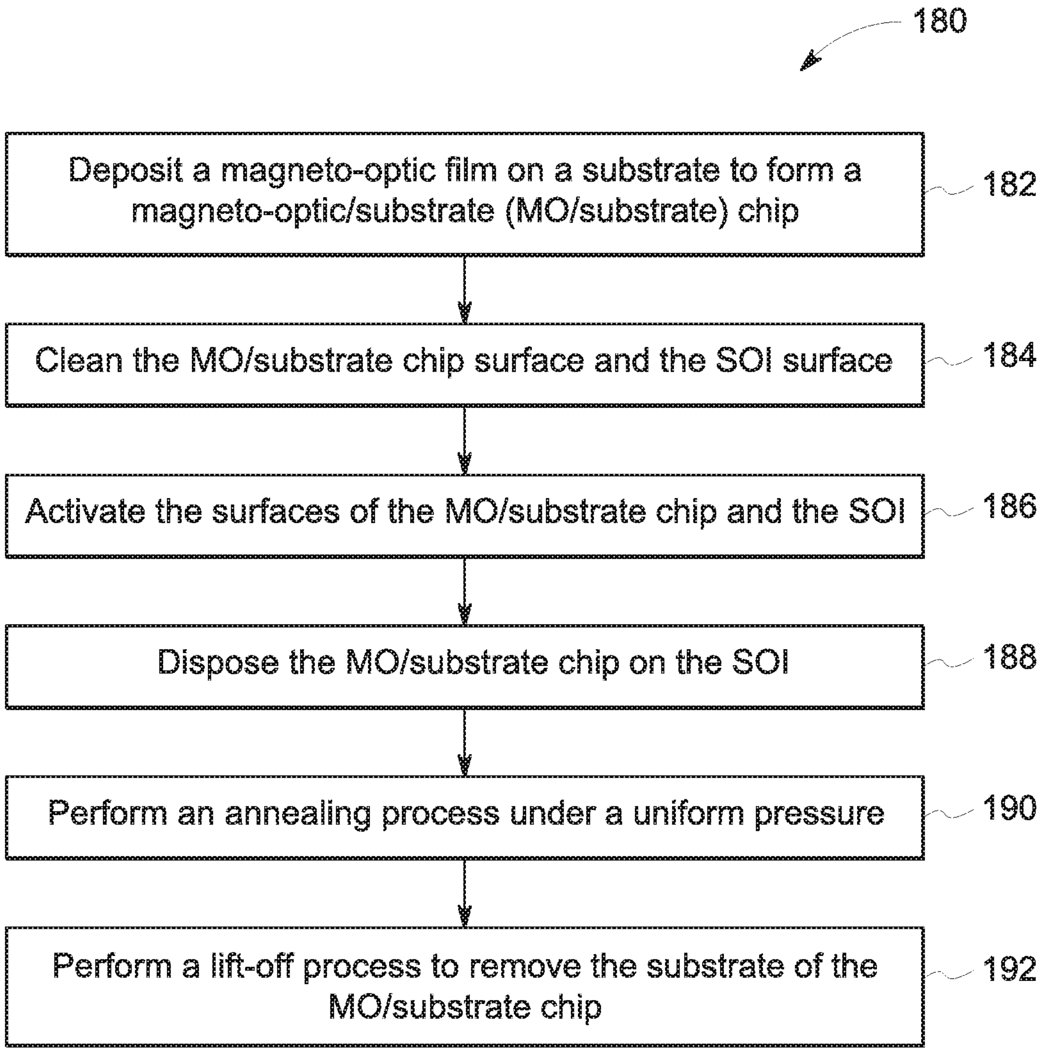
180
Deposit a magneto-optic film on a substrate to form a magneto-optic/substrate (MO/substrate) chip
182
Clean the MO/substrate chip surface and the SOI surface
184
Activate the surfaces of the MO/substrate chip and the SOI
186
Dispose the MO/substrate chip on the SOI
188
Perform an annealing process under a uniform pressure
190
Perform a lift-off process to remove the substrate of the MO/substrate chip
192

FIG. 19

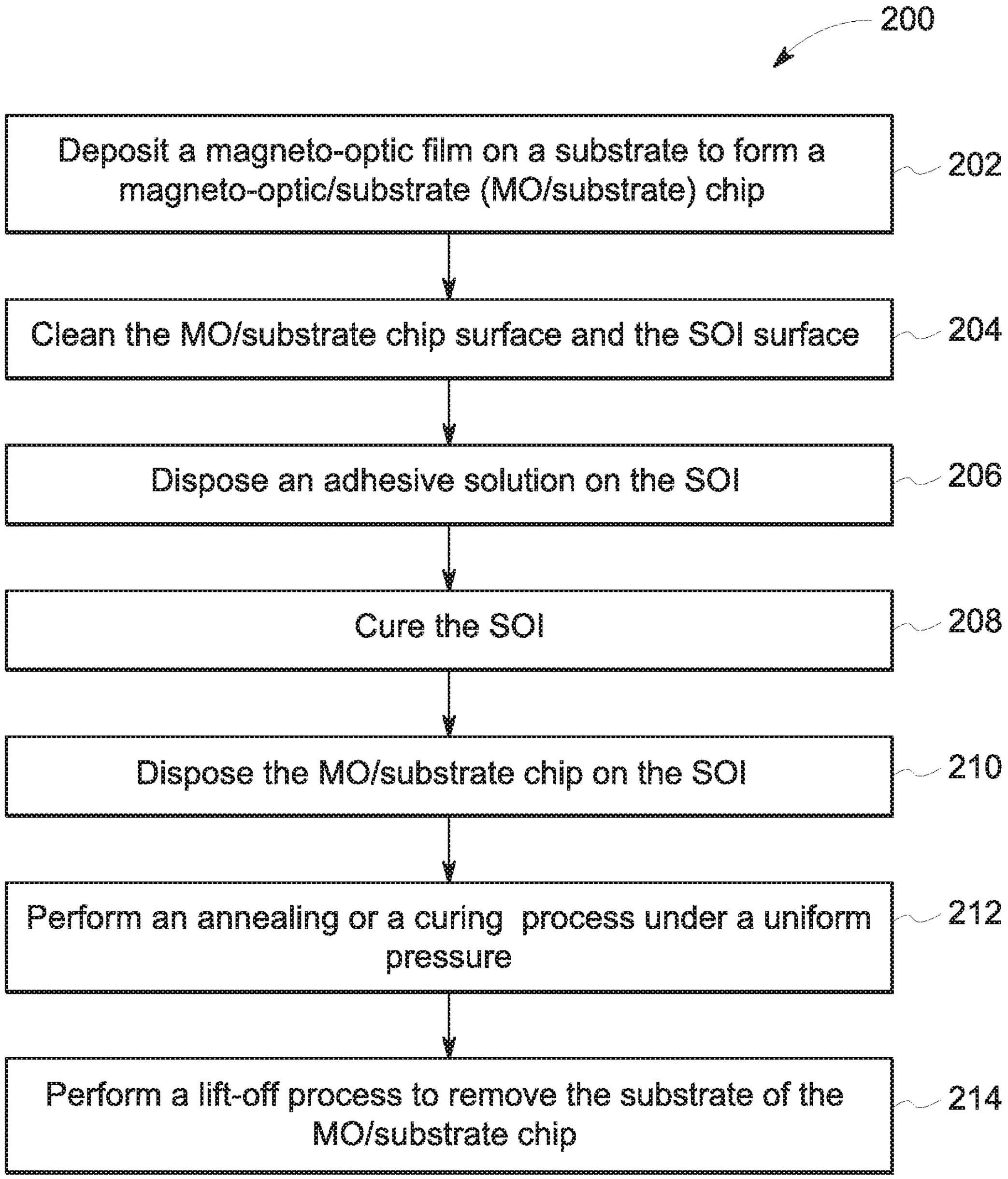
200
Deposit a magneto-optic film on a substrate to form a magneto-optic/substrate (MO/substrate) chip
202
Clean the MO/substrate chip surface and the SOI surface
204
Dispose an adhesive solution on the SOI
206
Cure the SOI
208
Dispose the MO/substrate chip on the SOI
210
Perform an annealing or a curing process under a uniform pressure
212
Perform a lift-off process to remove the substrate of the MO/substrate chip
214

FIG. 20