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(54) Title: OPTICAL LIGHT SOURCE AND OPTICAL TRANSMITTER

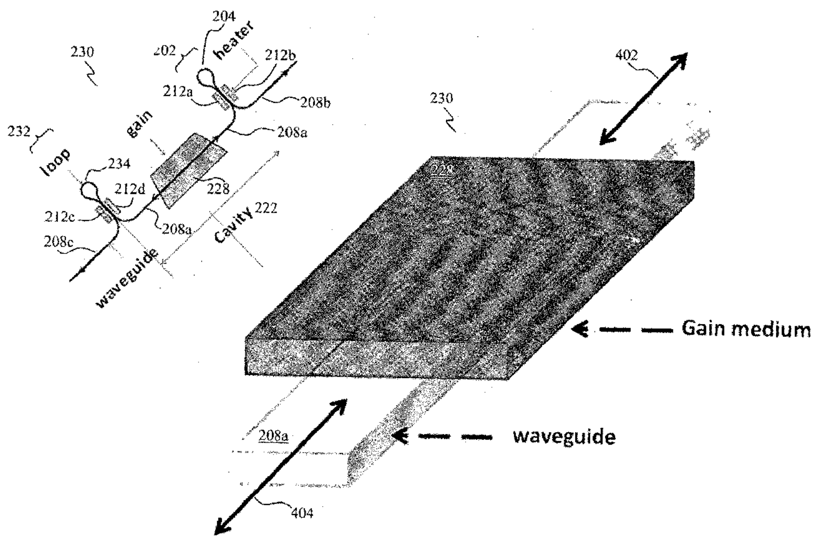

FIG. 4

(57) Abstract: According to embodiments of the present invention, an optical light source is provided. The optical light source includes at least two reflectors arranged spaced apart from each other, the at least two reflectors defining an optical cavity therebetween, wherein at least one reflector of the at least two reflectors includes an optical tuning element, and an optical gain medium positioned in the optical cavity and in an optical path between the at least two reflectors, wherein the optical tuning element is configured to allow tuning of light propagating in the optical cavity between the at least two reflectors and the optical gain medium in response to an applied voltage to the optical tuning element. According to further embodiments of the present invention, an optical transmitter is also provided.

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OPTICAL LIGHT SOURCE AND OPTICAL TRANSMITTER

Cross-Reference To Related Applications

[0001] This application claims the benefit of priority of Singapore patent application No. 201205695-8, filed 31 July 2012, and Singapore patent application No. 201209174-0, filed 13 December 2012, the contents of these being hereby incorporated by reference in their entirety for all purposes.

Technical Field

[0002] Various embodiments relate to an optical light source and an optical transmitter.

Background

[0003] An optical light source is a key component for applications such as long-haul and data-center optical communication and on-chip optical interconnection. Furthermore, for optical communications, wavelength division multiplexing (WDM) is a key enabling technology for optical transceivers.

[0004] Over the past decades, academic and industrial researchers worldwide have been feverishly exploring silicon (Si) photonics as a possible technology towards next-generation multi-channel optical communications and optical interconnects for computer communication (compcom). Thanks to the mature silicon Complementary Metal-Oxide-Semiconductor (CMOS) fabrication processes and foundry process platform, various micro- and nano-scale photonic structures can now be fabricated with high precision and repeatability on silicon and silicon-on-insulator (SOI) wafers. However, as being widely aware, silicon, as an indirect bandgap material, cannot emit light efficiently. While SOI is a promising material platform for low-cost low-power-consumption devices for on-chip interconnection and optical communications, yet it lacks of an efficient light source. This means that it is required to adopt off-chip optical light source for signal transmission.

[0005] In view of the above inefficiency, different approaches are employed, with various degree of success, e.g. hybrid silicon laser using wafer bonding, germanium (Ge)-based laser, doped silicon laser, and silicon Raman laser. Among these, hybrid optical light source using III-V bonding to silicon wafer is regarded as a promising technique.

[0006] Hybrid silicon laser using III/V-to-silicon bonding is widely accepted as the most promising solution for on-chip optical light source. Over the past years, hybrid lasers with different designs including Fabry-Perot cavity, distributed Bragg reflection cavity, micro-ring cavity, etc. have been employed. For example, coarse wavelength division multiplexing (CWDM) Si photonics link using integrated hybrid silicon lasers have been employed with 50 Gb/s data transmission.

[0007] Nevertheless, major problems for the hybrid lasers using conventional optical cavities, even for the III-V lasers, include the weak control of the quality factor (Q) of the laser cavities and the lack of tune-ability (tunability) of the resonance wavelength with a fixed laser cavity. Other problems include issues relating to light coupling between the III-V gain medium and the silicon waveguide, which may be poor or inefficient, difficulties in building the laser cavity, where conventional polished facet for III-V laser is less applicable, and difficulties in controlling the laser reflectivity and emission wavelength.

[0008] Furthermore, for conventional hybrid silicon laser for WDM applications, it is very difficult to align the laser wavelengths to the WDM multiplexer. For example, for conventional WDM transmitter, it is required to adjust the laser operation wavelengths to align with the WDM channels. This is relatively difficult to be realized, especially for large number of WDM channels, such as dense wavelength division multiplexing (DWDM).

Summary

[0009] According to an embodiment, an optical light source is provided. The optical light source may include at least two reflectors arranged spaced apart from each other, the at least two reflectors defining an optical cavity therebetween, wherein at least one reflector of the at least two reflectors includes an optical tuning element, and an optical gain medium positioned in the optical cavity and in an optical path between the at least two reflectors, wherein the optical tuning element is configured to allow tuning of light propagating in the optical cavity between the at least two reflectors and the optical gain medium in response to an applied voltage to the optical tuning element.

[0010] According to an embodiment, an optical transmitter is provided. The optical transmitter may include a first reflector, at least one second reflector arranged spaced apart from the first reflector, the first reflector and the at least one second reflector defining an optical cavity therebetween, a multiplexer element arranged in the optical cavity, the multiplexer element including a first port, and at least two second ports, wherein a respective second port of the at least two second ports is associated with a respective channel wavelength, wherein the multiplexer element is configured to receive light on each of the at least two second ports and to provide light at the respective channel wavelength to the first port based on the respective received light, and wherein the multiplexer element is further configured to transmit the light at the respective channel wavelengths from the first port, and at least two optical gain media positioned in the optical cavity, wherein a respective optical gain medium of the at least two optical gain media is in a respective optical path between the respective second port and the at least one second reflector, the respective optical gain medium configured to emit light to be received by the respective second port, the light including the respective channel wavelength, wherein the at least one second reflector is configured to reflect light from the at least two optical gain media, and wherein the first reflector is configured to reflect at least a portion of the light at the respective channel wavelengths transmitted from the first port to the at least two optical gain media, so as to cause lasing in the optical cavity at the channel wavelengths.

Brief Description of the Drawings

[0011] In the drawings, like reference characters generally refer to like parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

[0012] FIG. 1A shows a schematic block diagram of an optical light source, according to various embodiments.

[0013] FIG. 1B shows a schematic block diagram of an optical transmitter, according to various embodiments.

[0014] FIG. 2A shows schematic views of different designs of optical light sources incorporating at least one feedback loop with a directional coupler (DC), according to various embodiments.

[0015] FIG. 2B shows schematic views of different designs of optical light sources incorporating at least one feedback loop with a Mach-Zehnder interferometer (MZI), according to various embodiments.

[0016] FIG. 3 shows a schematic view of a loop mirror, according to various embodiments.

[0017] FIG. 4 shows a schematic partial perspective view of the optical light source of an embodiment of FIG. 2A.

[0018] FIG. 5A shows a schematic partial perspective view of the optical light source of an embodiment of FIG. 2A.

[0019] FIG. 5B shows a cross sectional view of the optical light source taken along the line A-A' shown in FIG. 5A.

[0020] FIG. 5C shows a cross sectional view of the optical light source taken along the line B-B' shown in FIG. 5A.

[0021] FIG. 5D shows a cross-sectional side view of the optical light source of the embodiment of FIG. 5A.

[0022] FIG. 5E shows a schematic partial perspective view of an optical light source, according to various embodiments.

[0023] FIG. 5F shows a cross sectional view of the optical light source taken along the line C-C' shown in FIG. 5E.

[0024] FIG. 5G shows as cross-sectional views, various processing stages of forming a reflector, according to various embodiments.

[0025] FIG. 6A shows optical microscope images of an indium phosphide (InP) wafer bonded to a silicon (Si) wafer.

[0026] FIG. 6B shows a C-mode scanning acoustic microscope (C-SAM) image of an indium phosphide (InP) wafer bonded to a silicon (Si) wafer.

[0027] FIG. 6C shows transmission electron microscope (TEM) images of a cross section of an indium phosphide (InP) wafer bonded to a silicon (Si) wafer.

[0028] FIG. 7A shows a set-up for measurements of a tunable reflector.

[0029] FIG. 7B shows a plot of measured transmission and reflection responses obtained based on the set-up of FIG. 7A.

[0030] FIG. 8A shows a set-up for measurements of light emission based on the tunable reflector of FIG. 7A.

[0031] FIG. 8B shows a plot of measured light emission obtained based on the set-up of FIG. 8A.

[0032] FIG. 8C shows a plot illustrating an enlarged view of a peak wavelength of the measured light emission of FIG. 8B.

[0033] FIG. 9 shows plots of measured light emission obtained based on the set-up of FIG. 8A, for different electrical power supplies.

[0034] FIG. 10A shows schematic views of different designs of optical light sources incorporating at least one microring-coupled Y-splitter, according to various embodiments.

[0035] FIG. 10B shows schematic views of different designs of optical light sources incorporating at least one microring-coupled Mach-Zehnder interferometer (MZI), according to various embodiments.

[0036] FIG. 11 shows a schematic block diagram of an optical transmitter, according to various embodiments.

[0037] FIG. 12 shows schematic views of different designs for a tunable reflector, according to various embodiments.

[0038] FIG. 13A shows schematic views of different designs for a microring resonator based multiplexer element, according to various embodiments.

[0039] FIG. 13B shows an operation of the dual-microring multiplexer element of the embodiment of FIG. 13A.

[0040] FIG. 13C shows schematic views of different designs for a multiplexer element, according to various embodiments.

[0041] FIGS. 14A to 14C show schematic views of optical transmitters, according to various embodiments.

[0042] FIG. 15A shows a set-up for measurements of light emission based on a tunable MZI-ring reflector, according to various embodiments.

[0043] FIG. 15B shows plots of measured light emission obtained based on the set-up of FIG. 15A.

[0044] FIG. 16A shows a set-up for measurements of an optical transmitter.

[0045] FIG 16B shows plots of WDM spectra obtained based on the set-up of FIG. 16A.

Detailed Description

[0046] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, optical and electrical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0047] Embodiments described in the context of one of the devices may be analogously valid for the other device.

[0048] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0049] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element includes a reference to one or more of the features or elements.

[0050] In the context of various embodiments, the phrase “at least substantially” may include “exactly” and a reasonable variance.

[0051] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance.

[0052] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0053] As used herein, the phrase of the form of “at least one of A or B” may include A or B or both A and B. Correspondingly, the phrase of the form of “at least one of A or B or C”, or including further listed items, may include any and all combinations of one or more of the associated listed items.

[0054] Various embodiments may relate to fields including silicon (Si) photonics (e.g. Si nano/micro-photonics), optical communication system, and data center/on-chip optical interconnect.

[0055] Various embodiments may provide an optical cavity or a laser cavity with tunable reflectivity. Various embodiments may provide tunable hybrid silicon (Si) lasers or light sources. Various embodiments may provide silicon passive laser cavity with tunability.

[0056] Various embodiments may relate to the design of hybrid optical light sources including a silicon waveguide for laser cavity and a III-V bonding layer which may serve as a gain medium for the laser cavity. The silicon waveguide structure may include one or more tunable loop reflectors or microring resonators that may serve as the laser cavity. In various embodiments, the tunable loop reflector may be made of a directional coupler, a Mach-Zehnder interferometer (MZI), or a microring structure, and with a control system or device. The control device may be a low-speed thermo-optical device or a high-speed optical-electrical device. In various embodiments, the tunable microring may serve as a resonance wavelength selector.

[0057] Various embodiments may address issues or disadvantages associated with conventional hybrid lasers by combining III-V material on silicon (Si) and with Si-photonic circuit to provide the needed reflectivity and tunablity. Various embodiments may provide designs for optical light sources with controllable cavity reflectivity, which may increase the quality factor value (Q-value) and/or tunable resonator resonances. The optical cavity or the laser cavity may be designed for hybrid optical light sources (e.g. hybrid silicon lasers) with tunable reflectivity and cavity resonances for easy control of on-chip hybrid laser properties (e.g. for at least one of laser threshold or lasing wavelength). Silicon-on-insulator (SOI) processes may be employed to implement or fabricate the optical light sources of various embodiments.

[0058] Various embodiments may provide an optical light source with at least two reflectors. In various embodiments, any one of or each of the reflectors may include a feedback loop or a loop mirror. Any one of or each of the loop mirrors may be coupled with a directional coupler (DC) or a Mach-Zehnder interferometer (MZI). At least one of the loop mirrors may be a tunable loop mirror. In various embodiments, any one of or each of the reflectors may include a microring-coupled Y-splitter or a microring-coupled Mach-Zehnder interferometer. By incorporating a tunable loop mirror, or a microring as a resonator, the optical light source may be provided with a tuning function, with easy extension to Q-switched laser, and mode-locked laser. The optical light source of various embodiments may be a hybrid, incorporating III-V material (e.g. indium phosphide (InP)) on silicon (Si).

[0059] As compared to conventional optical laser cavities without tunability or tuning function, e.g. the Fabry-Perot cavity formed by polishing, the Distributed Bragg reflectors (DBR) cavity, etc., the optical light source (e.g. hybrid laser) of various embodiments may have a tunable optical cavity which may allow tunability of optical properties of the optical light source. In addition, the tunable optical cavity of various embodiments may be directly applicable to advanced laser sources, e.g. Q-switched lasers, mode-locked lasers, etc.

[0060] Various embodiments of the optical light source may be provided with one or more output waveguides, from which light may be transmitted or outputted. The optical light source may allow easy coupling with fiber or other integrated waveguide(s). The optical light source may have a simple structure, with tuning function. The optical light source may have a small size.

[0061] The optical light source of various embodiments may be employed in various applications, for example as an optical communication light source, an optical communication transceiver, or an on-chip optical interconnect. The optical light source of various embodiments may also be employed in applications relating to green data center, Q-switched laser, mode-locked laser, and ultra-short pulse laser.

[0062] Various embodiments may also provide an optical transceiver or an optical transmitter, for example a hybrid optical transmitter. The optical transmitter may be a WDM transmitter, e.g. a hybrid silicon (Si) WDM self-aligned transmitter. Various embodiments may also provide a wavelength self-aligned WDM optical transceiver, e.g. a WDM transceiver in silicon chip.

[0063] Various embodiments of the optical transceiver or optical transmitter may include an optical light source having an optical cavity (e.g. laser cavity). The light source may include or may be formed by using hybrid integration of Si and III-V material. The III-V material may be bonded on top of the Si chip and may serve as a gain material. The optical cavity may be defined by one or more tunable reflectors and a WDM multiplexer element (MUX) may be arranged in the optical cavity. The tunable reflector(s) may serve as a tunable mirror for mirror reflection with tunable reflectivity. The WDM MUX may serve as a multiplexer as well as a cavity mode selector. Furthermore, the WDM MUX may also serve as a demultiplexer.

[0064] The optical transmitter of various embodiments may self-align the WDM laser wavelengths to the WDM MUX channels, which may address issues or disadvantages associated with conventional transmitters. For example, the optical transmitter of various embodiments may potentially address or solve the wavelength misalignment problem between the WDM light source and the WDM MUX associated with conventional transmitters. Furthermore, the optical transmitter of various embodiments may provide cost effective solutions for WDM optical transceivers.

[0065] Various embodiments may provide an optical transmitter (e.g. a hybrid WDM transmitter) with wavelength self-alignment. In various embodiments, by embedding a WDM multiplexer element (WDM MUX) into a laser cavity of the hybrid WDM transmitter for wavelength selection, the WDM laser wavelength and the WDM channel may be self-aligned. The WDM multiplexer may serve as a light combiner, as well as a lasing mode selector, such that only the wavelengths that at least substantially align with the WDM wavelengths may lase. Various embodiments of the optical transmitter may be widely used for WDM optical communication.

[0066] Various embodiments may provide one or more of the following : (1) a tunable reflector structure; (2) a simple structure for building an on-chip low-loss optical cavity; (3) easy control of cavity reflectivity and the control of cavity Q-values, and thus the threshold; (4) tunable resonance wavelength, for tunable emission wavelength; (5) a structure combining an optical light source (e.g. WDM light source) and a multiplexer element (e.g. WDM MUX); (6) simple fabrication process; (7) planar integration, with CMOS compatible fabrication; (8) structures that may be directly applicable for advanced laser sources, such as Q-switched laser, mode-locked laser, and so forth; (9) potential large-scale photonic integration with other optoelectronic devices; (10) cost effectiveness.

[0067] FIG. 1A shows a schematic block diagram of an optical light source 100, according to various embodiments. The optical light source 100 may include at least two reflectors 104 arranged spaced apart from each other, the at least two reflectors 104 defining an optical cavity 102 therebetween, wherein at least one reflector 104 of the at least two reflectors 104 includes an optical tuning element 106, and an optical gain medium 108 positioned in the optical cavity 102 and in an optical path between the at least two reflectors 104, wherein the optical tuning element 106 is configured to allow tuning of light propagating in the optical cavity 102 between the at least two reflectors 104 and the optical gain medium 108 in response to an applied voltage to the optical tuning element 106. The line represented as 110 is illustrated to show the relationship between the at least two reflectors 104, the optical tuning element 106 and the optical gain medium 108, which may include electrical coupling and/or mechanical coupling and/or optical coupling.

[0068] In other words, the optical light source 100 may include at least two reflectors 104, for example a first reflector and a second reflector, which may be arranged spaced apart from each other. The optical light source 100 may include an optical cavity 102 defined by the at least two reflectors 104. This may mean that each of the at least two reflectors 104 may define a respective boundary of the optical cavity 102. A light propagating within the optical cavity 102 may be reflected by the at least two reflectors 104. The optical light source 100 may further include an optical gain medium 108 arranged in the optical cavity 102 and in an optical path between the at least two reflectors 104. This may mean that the optical gain medium 108 may be provided or integrated on the same chip incorporating the optical light source 100, meaning an on-chip optical gain medium 108. The optical gain medium may provide optical gain for a light propagating within the optical cavity 102. This may mean that a light propagating within the optical cavity 102 may be reflected by the at least two reflectors 104 and may pass through the optical gain medium 108, one or more times, where the light may be amplified. The at least two reflectors 104 and the optical gain medium 108 may cooperate to cause lasing within the optical cavity 102. Therefore, the optical cavity 102 may act as a laser cavity or lasing cavity that may enable amplification of light within the optical cavity 102. The light, which may have been amplified, may exit or be transmitted via at least one of the at least two reflectors 104. In various embodiments, at least one reflector 104 of the at least two reflectors 104 may include an optical tuning element 106, where a voltage applied thereto may control the optical tuning element 106 to allow tuning of light propagating in the optical cavity 102 between the at least two reflectors 104 and the optical gain medium 108, for example, as a result of a change in the reflectivity of the reflector 104 incorporating the optical tuning element 106.

[0069] In various embodiments, the optical tuning element 106 may be integrated with the optical light source 100. In the context of various embodiments, the optical tuning element 106 may be integrated with the at least one reflector 104 of the at least two reflectors 104. This may mean that the optical tuning element 106 may be integrated on the same chip incorporating the optical light source 100, meaning an on-chip optical tuning element 106.

[0070] In various embodiments, each of the at least two reflectors 104 may include a respective optical tuning element 106. This may provide a higher degree of tunability for tuning of the light propagating in the optical cavity 102.

[0071] In various embodiments, any one of or each of the at least two reflectors 104 may include a feedback loop. The feedback loop may form part of the optical tuning element 106. The feedback loop may be in the form of a waveguide (e.g. a planar waveguide), for example a silicon (Si) waveguide.

[0072] In various embodiments, the optical tuning element 106 may be controlled by a thermo-optical device or an electro-optic device. The thermo-optical device or the electro-optic device may be part of the optical tuning element 106.

[0073] In various embodiments, the optical tuning element 106 may include a reflectivity tuning element or a cavity resonance tuning element.

[0074] In various embodiments, by incorporating a reflectivity tuning element, an optical light source 100 with tunable reflectivity may be provided, which may provide lasing threshold optimization. In various embodiments, the reflectivity tuning element may tune a reflectivity of the reflector 104 having the optical tuning element 106.

[0075] In various embodiments, by incorporating a cavity resonance tuning element, an optical light source 100 with tunable cavity resonances may be provided, which may provide controllable emission wavelength. This may mean that the wavelength of the light that is emitted by the optical light source 100 may be controlled. In various embodiments, the cavity resonance tuning element may act as a cavity selector or resonance wavelength selector for selecting the cavity resonance or cavity mode propagating in the optical cavity 102 and to be emitted.

[0076] In the context of various embodiments, the reflectivity tuning element may include a feedback loop, and a directional coupler (DC) or a Mach-Zehnder interferometer (MZI). In various embodiments, the directional coupler or the Mach-Zehnder interferometer may be coupled to the feedback loop, e.g. including optical coupling. In various embodiments, the directional coupler or the Mach-Zehnder interferometer, for example, may allow coupling of energy between two optical lines or waveguides arranged sufficiently close together. This may mean that energy passing through one line may be coupled to the other line. In various embodiments, the feedback loop may include silicon, silicon nitride, or silicon oxide. In various embodiments, the feedback loop may be in the form of a waveguide (e.g. a planar waveguide), for example a silicon (Si) waveguide.

[0077] In the context of various embodiments, the cavity resonance tuning element may include a microresonator-coupled Y-splitter or a microresonator-coupled Mach-Zehnder interferometer. The microresonator may be coupled between two arms of the Y-splitter or two arms of the Mach-Zehnder interferometer. In various embodiments, the microresonator may include a microring, a microdisk, or any other types of resonator.

[0078] In various embodiments, at least one reflector 104 of the at least two reflectors 104 may be configured to allow light to exit from the optical light source 100. In embodiments where one reflector 104 of the at least two reflectors 104 may be configured to allow light to exit, the optical light source 100 may be configured to provide uni-directional light emission. In embodiments where two reflectors 104 of the at least two reflectors 104 may be configured to allow light to exit, the optical light source 100 may be configured to provide bi-directional light emission.

[0079] In the context of various embodiments, the optical light source 100 may further include a waveguide (e.g. a planar waveguide), for example a silicon (Si) waveguide, optically coupled between the at least two reflectors 104. In this way, the waveguide may define the optical path between the at least two reflectors 104. In various embodiments, the optical gain medium 108 may be positioned over the waveguide. This may mean that the optical gain medium 108 may be arranged over or on the waveguide, for example bonded directly on the waveguide. The optical gain medium 108 may be arranged adjacent to the waveguide, or in a vicinity of the waveguide, sufficiently close so as to allow coupling of light between waveguide and the optical gain medium 108. In further embodiments, the optical gain medium 108 may be positioned at least substantially along the same plane as the waveguide.

[0080] In various embodiments, the optical gain medium 108 may be configured to receive energy from an external source (e.g. a pump source) so as to provide an initial light to the at least two reflectors 104 and to subsequently amplify a reflected light propagating there-between the at least two reflectors 104. The external source may include a voltage supplier as current injection light source or external photons as optical pumping light source.

[0081] In the context of various embodiments, the optical gain medium 108 may include a III-V bonding layer or a material configured to provide the gain.

[0082] In the context of various embodiments, the optical gain medium 108 may include a III-V material, for example in the form of a III-V bonding layer. In the context of various embodiments, the III-V material may include but not limited to aluminium gallium arsenide (AlGaAs), aluminium gallium indium phosphide (AlGaInP), aluminium gallium nitride (AlGaN), aluminium gallium phosphide (AlGaP), aluminium nitride (AlN), aluminium phosphide (AlP), boron nitride (BN), boron phosphide (BP), gallium arsenide (GaAs), gallium arsenide phosphide (GaAsP), gallium nitride (GaN), gallium phosphide (GaP), indium gallium arsenide (InGaAs), indium gallium nitride (InGaN), indium gallium phosphide (InGaP), indium nitride (InN), or indium phosphide (InP).

[0083] In the context of various embodiments, the optical gain medium 108 may include a multiple quantum well (MQW) region.

[0084] In the context of various embodiments, the optical light source 100 may be a hybrid optical light source, for example a hybrid laser. As a non-limiting example, the optical light source 100 may be a hybrid III-V/silicon optical light source or laser.

[0085] FIG. 1B shows a schematic block diagram of an optical transmitter (or an optical transceiver) 140, according to various embodiments. The optical transmitter 140 includes a first reflector 144, at least one second reflector 146 arranged spaced apart from the first reflector 144, the first reflector 144 and the at least one second reflector 146 defining an optical cavity 142 therebetween, a multiplexer element 148 arranged in the optical cavity 142, the multiplexer element 148 including a first port 150, and at least two second ports 152, wherein a respective second port 152 of the at least two second ports 152 is associated with a respective channel wavelength, wherein the multiplexer element 148 is configured to receive light on each of the at least two second ports 152 and to provide light at the respective channel wavelength to the first port 150 based on the respective received light, and wherein the multiplexer element 148 is further configured to transmit the light at the respective channel wavelengths from the first port 150, and at least two optical gain media 154 positioned in the optical cavity 142, wherein a respective optical gain medium 154 of the at least two optical gain media 154 is in a respective optical path between the respective second port 152 and the at least one second reflector 146, the respective optical gain medium 154 configured to emit light to be received by the respective second port 152, the light including the respective channel wavelength, wherein the at least one second reflector 146 is configured to reflect light from the at least two optical gain media 154, and wherein the first reflector 144 is configured to reflect at least a portion of the light at the respective channel wavelengths transmitted from the first port 150 to the at least two optical gain media 154, so as to cause lasing in the optical cavity 142 at the channel wavelengths. The line represented as 160 is illustrated to show the relationship between the first port 150 and the at least two second ports 152 of the multiplexer element 148, which may include mechanical coupling and/or optical coupling, while the line represented as 162 is illustrated to show the relationship between the first reflector 144, the at least one second reflector 146, the multiplexer element 148 and the at least two optical gain media 154, which may include electrical coupling and/or mechanical coupling and/or optical coupling.

[0086] In other words, the optical transmitter 140 may include a first reflector 144 and at least one second reflector 146, which may be arranged spaced apart from each other. The optical transmitter 140 may include an optical cavity 142 defined by the first reflector 144 and the at least one second reflector 146. This may mean that the first reflector 144 and the at least one second reflector 146 may define a respective boundary of the optical cavity 142. A light propagating within the optical cavity 142 may be reflected by the first reflector 144 and the at least one second reflector 146.

[0087] The optical transmitter 140 may further include a multiplexer element (MUX) 148 arranged or embedded in the optical cavity 142. The multiplexer element 148 may include a first port (e.g. output port) 150 and at least two second ports (e.g. input ports) 152. The first port 150 and the at least two second ports 152 may be provided on the same side or on different sides (e.g. opposite sides) of the multiplexer element 148. The multiplexer element 148 may have at least two channels or optical channels, where a respective channel may be associated with a respective second port 152. A respective channel may be associated with a respective channel wavelength.

[0088] The optical transmitter 140 may further include at least two optical gain media 154 positioned in the optical cavity 142, wherein a respective optical gain medium 154 may be arranged in a respective optical path between a respective second port 152 of the multiplexer element 148 and the at least one second reflector 146. This may mean that the at least two optical gain media 154 may be provided or integrated on the same chip incorporating the optical transmitter 140, meaning on-chip optical gain media 154. A respective optical gain medium 154 may emit light to be received by a respective second port 152, where the light may have or include a range of wavelengths including the channel wavelength associated with the respective second port 152, e.g. a light having a spectrum spanning across a plurality of wavelengths including the channel wavelength. In other words, the respective optical gain medium 154 may emit light across a range of wavelengths, where the light includes a portion thereof at or having the channel wavelength associated with the respective second port 152. A respective optical gain medium 154 may provide a respective optical gain within the optical cavity 142.

[0089] Each second port 152 of the multiplexer element 148 may receive light from the respective optical gain medium 154, where the multiplexer element 148 may then provide light at the respective channel wavelength to the first port 150 based on the respective received light, so that the multiplexer element 148 may transmit light at the respective channel wavelengths from the first port 150. This may mean that the multiplexer element 148 may be configured to filter the light including the respective channel wavelength, received on each of the at least two second ports 152, so as to provide light or filtered light at the respective channel wavelength to the first port 150 for transmission therefrom.

[0090] The at least one second reflector 146 may reflect light from the at least two optical gain media 154, for example back to the at least two optical gain media 154. The first reflector 144, which may be a partial reflector, may reflect at least a portion of the light at the respective channel wavelengths transmitted from the first port 150 to the at least two optical gain media 154, so as to cause lasing in the optical cavity 142 at the channel wavelengths. This may mean that light of a respective channel wavelength propagating within the optical cavity 142 may be reflected by the first reflector 144 and the at least one second reflector 146 and may pass through a respective optical gain medium 154, one or more times, where the light may be amplified. The first reflector 144 and the at least one second reflector 146 and the at least two optical gain media 154 may cooperate to cause lasing within the optical cavity 142. Therefore, the optical cavity 142 may act as a laser cavity or lasing cavity that may enable amplification of light within the optical cavity 142.

[0091] In various embodiments, the multiplexer element 148 may function as a cavity or lasing mode selector, meaning that the multiplexer element 148 may be configured for the selection of the cavity or lasing modes. This may mean that the multiplexer element 148 may select the lasing wavelengths, where the lasing wavelengths may be aligned or self-aligned to the channel wavelengths associated with the multiplexer element 148.

[0092] In various embodiment, the first reflector 144, the at least one second reflector 146 and the at least two optical gain media 154 may form an optical light source as part of the optical transmitter 140.

[0093] In various embodiments, the first reflector 144 may reflect at least a portion of light transmitted from the first port 150 through the multiplexer element 148 to the at least two optical gain media 154.

[0094] In various embodiments, each optical gain medium 154 may provide or emit light of wavelengths different from that of the other optical gain medium 154. In various embodiments, each optical gain medium 154 may provide or emit light of wavelengths, a portion of which may overlap with that of the other optical gain medium 154.

[0095] In various embodiments, the at least one second reflector 146 may mean two or more second reflectors 146. Therefore, the optical transmitter 140 may include a plurality of second reflectors 146 arranged spaced apart from the first reflector144, wherein the respective optical gain medium 154 may be arranged in a respective optical path between the respective second port 152 and a respective second reflector 146 of the plurality of second reflectors 146.

[0096] In various embodiments, at least one of the first reflector 144 or the at least one second reflector 146 may include an optical tuning element, wherein the optical tuning element may be configured to allow tuning of light propagating in the optical cavity 142 in response to an applied voltage to the optical tuning element. This may mean that a voltage applied to the optical tuning element may control the optical tuning element to allow tuning of light propagating in the optical cavity 142 between the the first reflector 144 and the at least one second reflector 146, for example as a result of a change in the reflectivity of the reflector incorporating the optical tuning element.

[0097] In various embodiments, the optical tuning element may be integrated with the optical transmitter 140. In the context of various embodiments, the optical tuning element may be integrated with at least one of the first reflector 144 or the at least one second reflector 146. This may mean that the optical tuning element may be integrated on the same chip incorporating the optical transmitter 140, meaning an on-chip optical tuning element.

[0098] In various embodiments, each of the first reflector 144 and the at least one second reflector 146 may include an optical tuning element. This may provide a higher degree of tunability for tuning of the light propagating in the optical cavity 142.

[0099] In embodiments having a plurality of second reflectors 146, any one of or each of the plurality of second reflectors 146 may include an optical tuning element.

[0100] In various embodiments, each second reflector 146 may include a feedback loop. The feedback loop may form part of an optical tuning element. The feedback loop may be in the form of a waveguide (e.g. a planar waveguide), for example a silicon (Si) waveguide.

[0101] In various embodiments, the optical tuning element may be controlled by a thermo-optical device or an electro-optic device. The thermo-optical device or the electro-optic device may be part of the optical tuning element.

[0102] In various embodiments, the optical tuning element may include at least one of a feedback loop and either a directional coupler (DC) or a Mach-Zehnder interferometer (MZI), a microresonator-coupled Y-splitter, or a microresonator-coupled Mach-Zehnder interferometer (MZI).

[0103] In various embodiments of the optical tuning element, the feedback loop may be coupled, including optical coupling, to the DC or the MZI, and which may collectively form a reflectivity tuning element. In this way, a tunable loop reflector/mirror or a tunable MZI loop reflector/mirror may be respectively provided. In various embodiments, by incorporating a reflectivity tuning element, an optical transmitter 140 with tunable reflectivity may be provided. In various embodiments, the reflectivity tuning element may tune a reflectivity of the reflector having the optical tuning element.

[0104] In various embodiments, the directional coupler or the Mach-Zehnder interferometer, for example, may allow coupling of energy between two optical lines or waveguides arranged sufficiently close together. This may mean that energy passing through one line may be coupled to the other line. In various embodiments, the feedback loop may include silicon, silicon nitride, or silicon oxide. In various embodiments, the feedback loop may be in the form of a waveguide (e.g. a planar waveguide), for example a silicon (Si) waveguide.

[0105] In various embodiments, the microresonator-coupled Y-splitter or the microresonator-coupled Mach-Zehnder interferometer (MZI) may be a cavity resonance tuning element. In this way, a tunable microresonator reflector/mirror may be provided. In various embodiment, the microresonator may be coupled between two arms of the Y-splitter or two arms of the Mach-Zehnder interferometer. In various embodiments, the microresonator may include a microring, a microdisk, or any other types of resonator. In various embodiments, by incorporating a cavity resonance tuning element, an optical transmitter 140 with tunable cavity resonances may be provided.

[0106] In various embodiments, the multiplexer element 148 may include at least one of a microresonator-based multiplexer arrangement, an arrayed waveguide grating (AWG) or a concave grating.

[0107] In various embodiments, the microresonator-based multiplexer arrangement may include at least one of a plurality of microrings, wherein a respective microring of the plurality of microrings may be optically coupled to the respective optical gain medium 154, or a plurality of pairs of microrings, wherein a respective pair of microrings of the plurality of pairs of microrings may be optically coupled to the respective optical gain medium 154.

[0108] In the context of various embodiments, the optical transmitter 140 may further include a plurality of waveguides (e.g. a plurality of planar waveguides), for example a plurality of silicon (Si) waveguides. A respective waveguide of the plurality of waveguides may be optically coupled between the respective second port 152 and the at least one second reflector 146. In this way, a respective waveguide may define a respective optical path between the respective second port 152 and the at least one second reflector 146. In various embodiments, a respective optical gain medium 154 may be positioned over a respective waveguide. This may mean that the respective optical gain medium 154 may be arranged over or on the respective waveguide, for example bonded directly on the respective waveguide. The respective optical gain medium 154 may be arranged adjacent to the waveguide, or in a vicinity of the waveguide, sufficiently close so as to allow coupling of light between the respective waveguide and the respective optical gain medium 154.

[0109] In various embodiments, the at least two optical gain media 154 may be configured to receive energy from an external source (e.g. a pump source) so as to provide an initial light propagating within the optical cavity 142. The external source may include a voltage supplier as current injection light source or external photons as optical pumping light source.

[0110] In the context of various embodiments, any one of or each of the at least two optical gain media 154 may include a III-V material, for example in the form of a III-V bonding layer, or a material configured to provide the gain.

[0111] In the context of various embodiments, the III-V material may include but not limited to aluminium gallium arsenide (AlGaAs), aluminium gallium indium phosphide (AlGaInP), aluminium gallium nitride (AlGaN), aluminium gallium phosphide (AlGaP), aluminium nitride (AlN), aluminium phosphide (AlP), boron nitride (BN), boron phosphide (BP), gallium arsenide (GaAs), gallium arsenide phosphide (GaAsP), gallium nitride (GaN), gallium phosphide (GaP), indium gallium arsenide (InGaAs), indium gallium nitride (InGaN), indium gallium phosphide (InGaP), indium nitride (InN), or indium phosphide (InP).

[0112] In the context of various embodiments, any one of or each of the at least two optical gain media 154 may include a multiple quantum well (MQW) region.

[0113] In the context of various embodiments, the mutiplexer element 148 may be a wavelength division multiplexing multiplexer element (WDM MUX).

[0114] In the context of various embodiments, the optical transmitter 140 may be a wavelength division multiplexing (WDM) transmitter, e.g. a hybrid WDM transmitter.

[0115] It should be appreciated that one or more features or components as described in the context of the optical transmitter 140 that may be similarly present in the optical light source 100 may be as described in the context of the similar or like features or components in the optical light source 100.

[0116] Various embodiments may provide optical light sources (e.g. hybrid lasers) with tunable mirror reflectivities, which may be formed by different combinations of one or more basic elements, which may act as a reflector, e.g. a feedback loop with a directional coupler (DC) and/or a feedback loop with a Mach-Zehnder interferometer. The optical cavities of the optical light sources of various embodiments may lay in a silicon layer and formed by different combinations of the basic elements. By integrating either a thermo-optical device or an electro-optical device into the DC or the MZI, the DC or the MZI may be thermo-optically tuned or electro-optically tuned, which may allow the reflection of the feedback loop and therefore the reflector to be changed and controlled. By using various configurations, either uni-directional emission optical light sources or lasers, or bi-directional emission optical light sources or lasers, may be obtained.

[0117] FIG. 2A shows schematic views of different designs of optical light sources (e.g. hybrid lasers) incorporating at least one feedback loop with a directional coupler (DC), according to various embodiments.

[0118] FIG. 2A shows an arrangement 200 for a feedback loop with a DC, which may form a reflector or loop mirror 202, or part of a reflector, for the optical light source of various embodiments. The reflector 202 may include a feedback loop 204 which may be formed into two arms (please refer to FIG. 3 for detailed view of a loop mirror) and coupled to a DC 206, which subsequently may be coupled with a first waveguide (e.g. input waveguide; silicon waveguide) 208a and a second waveguide (e.g. output waveguide; silicon waveguide) 208b. In various embodiments, the feedback loop 204 with the DC 206, the first waveguide 208a and the second waveguide 208b may be a continuous waveguide structure, e.g. formed from a single waveguide.

[0119] Light may be provided into the first waveguide 208a towards the reflector 202, where a portion of the light may be reflected by the reflector 202 back through the first waveguide 208a, and a portion of the light may be transmitted by the reflector 202 into the second waveguide 208b. The double-headed arrow 210a illustrates the propagation directions of light through the first waveguide 208a, which may be bi-directional, while the arrow 210b illustrates the propagation direction of light through the second waveguide 208b, which may be uni-directional.

[0120] In various embodiments, a thermo-optical device or electro-optical device, as an optical tuning element or as part of an optical tuning element, may be integrated with the DC 206, for controlling the reflection of the reflector 202 or the feedback loop 204. This may mean that the optical tuning element may function as a reflectivity tuning element.

As a non-limiting example based on a thermo-optical device, the thermo-optical device may include one or more heaters, e.g. a first heater 212a and a second heater 212b.

[0121] FIG. 2A also shows an arrangement for an optical light source 220. The optical light source 220 may include an optical cavity 222 defined by the reflector 202, which may be as described above in the context of the arrangement 200, and another reflector 224 arranged spaced apart from the reflector 202. The reflector 224 may include a feedback loop 226. The first waveguide 208a may be coupled to the reflector 224, or may be formed into the feedback loop 226. The optical light source 220 may further include an optical gain medium 228, for example in the form of a III-V bonding layer (e.g. InP), positioned in the optical cavity 222 and in an optical path between the reflectors 202, 224. The optical gain medium 228 may be arranged on or over the first waveguide 208a where light may be coupled between the first waveguide 208a and the optical gain medium 228.

[0122] In various embodiments, the feedback loop 204 with the DC 206, the first waveguide 208a, the second waveguide 208b, and the feedback loop 226 may be a continuous waveguide structure, e.g. formed from a single waveguide.

[0123] In various embodiments, light propagating in the first waveguide 208a may be reflected, at least partially, back and forth within the optical cavity 222 by the reflectors 202, 224. The reflected light may be coupled to the optical gain medium 228 where optical gain or lasing may occur, resulting in light amplification. A portion of light, originating from within the optical cavity 222 may be transmitted by the reflector 202 through the second waveguide 208b, thereby allowing light to exit from the optical light source 220. The optical light source 220 may be a uni-directional emissiter, allowing uni-directional emission of light from the optical light source 220, for example via the second waveguide 208b.

[0124] In various embodiments, by controlling the reflection of the reflector 202 with the help of the first heater 212a and the second heater 212b, tuning of the light propagating in the optical cavity 222 between the reflectors 202, 224, and the optical gain medium 228 may be carried out.

[0125] FIG. 2A further shows an arrangement for an optical light source 230, which may be as described above in the context of the optical light source 220, except that the reflector 224 of the optical light source 220 is replaced by the reflector 232 in the optical light source 230. The reflector 232 may include a feedback loop 234 which may be formed into two arms (please refer to FIG. 3 for detailed view of a loop mirror) and coupled to a DC 236, which subsequently may be coupled with the first waveguide 208a and a third waveguide (e.g. another output waveguide; silicon waveguide) 208c.

[0126] In various embodiments, the feedback loop 204 with the DC 206, the feedback loop 234 with the DC 236, the first waveguide 208a, the second waveguide 208b, and the third waveguide 208c may be a continuous waveguide structure, e.g. formed from a single waveguide.

[0127] In various embodiments, light propagating in the first waveguide 208a may be reflected, at least partially, back and forth within the optical cavity 222 by the reflectors 202, 232. The reflected light may be coupled to the optical gain medium 228 where optical gain or lasing may occur, resulting in light amplification. A portion of light originating from within the optical cavity 222 may be transmitted by the reflector 202 through the second waveguide 208b, thereby allowing light to exit from the optical light source 220. A portion of light originating from within the optical cavity 222 may also be transmitted by the reflector 232 through the third waveguide 208c, thereby allowing light to exit from the optical light source 220. The arrow 210c illustrates the propagation direction of light through the third waveguide 208c, which may be uni-directional. The optical light source 230 may be a bi-directional emissiter, allowing bi-directional emission of light from the optical light source 230, for example via the second waveguide 208b and/or the third waveguide 208c.

[0128] As similarly described for the reflector 202, in various embodiments, another thermo-optical device or electro-optical device, as an optical tuning element or as part of an optical tuning element, may be integrated with the DC 236, for controlling the reflection of the reflector 232 or the feedback loop 234. This may mean that the optical tuning element may function as a reflectivity tuning element. As a non-limiting example based on a thermo-optical device, the thermo-optical device may include one or more heaters, e.g. a third heater 212c and a fourth heater 212d.

[0129] FIG. 2B shows schematic views of different designs of optical light sources (e.g. hybrid lasers) incorporating at least one feedback loop with a Mach-Zehnder interferometer (MZI), according to various embodiments.

[0130] FIG. 2B shows an arrangement 250 for a feedback loop with a MZI, which may form a reflector or loop mirror 252, for the optical light source of various embodiments. The reflector 252 may include a feedback loop 254 which may be formed into two arms (please refer to FIG. 3 for detailed view of a loop mirror) and coupled to a MZI 256. The MZI 256 may include a first arm 257a and a second arm 257b respectively coupled to the arms of the feedback loop 254. The first arm 257a of the MZI 256 may also be coupled to a first waveguide (e.g. input waveguide; silicon waveguide) 258a, while the second arm 257b of the MZI 256 may also be coupled to a second waveguide (e.g. output waveguide; silicon waveguide) 258b. In various embodiments, the feedback loop 254, the first arm 257a and the second arm 257b of the MZI 256, the first waveguide 258a, and the second waveguide 258b may be a continuous waveguide structure, e.g. formed from a single waveguide.

[0131] Light may be provided into the first waveguide 258a towards the reflector 252, where a portion of the light may be reflected by the reflector 252 back through the first waveguide 258a, and a portion of the light may be transmitted by the reflector 252 into the second waveguide 258b. The double-headed arrow 260a illustrates the propagation directions of light through the first waveguide 258a, which may be bi-directional, while the arrow 260b illustrates the propagation direction of light through the second waveguide 258b, which may be uni-directional.

[0132] In various embodiments, a thermo-optical device or electro-optical device, as an optical tuning element or as part of an optical tuning element, may be integrated with the MZI 256, for controlling the reflection of the reflector 252 or the feedback loop 254. This may mean that the optical tuning element may function as a reflectivity tuning element. As a non-limiting example based on a thermo-optical device, the thermo-optical device may include one or more heaters, e.g. a first heater 262a provided with the first arm 257a and a second heater 262b provided with the second arm 257b.

[0133] FIG. 2B also shows an arrangement for an optical light source 270. The optical light source 270 may include an optical cavity 272 defined by the reflector 252, which may be as described above in the context of the arrangement 250, and another reflector 274 arranged spaced apart from the reflector 252. The reflector 274 may include a feedback loop 276. The first waveguide 258a may be coupled to the reflector 274, or may be formed into the feedback loop 276. The optical light source 270 may further include an optical gain medium 278, for example in the form of a III-V bonding layer, positioned in the optical cavity 272 and in an optical path between the reflectors 252, 274. The optical gain medium 278 may be arranged on or over the first waveguide 258a where light may be coupled between the first waveguide 258a and the optical gain medium 278.

[0134] In various embodiments, the feedback loop 254, the first arm 257a and the second arm 257b of the MZI 256, the first waveguide 258a, the second waveguide 258b, and the feedback loop 276 may be a continuous waveguide structure, e.g. formed from a single waveguide.

[0135] In various embodiments, light propagating in the first waveguide 258a may be reflected, at least partially, back and forth within the optical cavity 272 by the reflectors 252, 274. The reflected light may be coupled to the optical gain medium 278 where optical gain or lasing may occur, resulting in light amplification. A portion of light, originating from within the optical cavity 272 may be transmitted by the reflector 252 through the second waveguide 258b, thereby allowing light to exit from the optical light source 270. The optical light source 270 may be a uni-directional emissiter, allowing uni-directional emission of light from the optical light source 270, for example via the second waveguide 258b.

[0136] In various embodiments, by controlling the reflection of the reflector 252 with the help of the first heater 262a and the second heater 262b, tuning of the light propagating in the optical cavity 272 between the reflectors 252, 274, and the optical gain medium 278 may be carried out.

[0137] FIG. 2B further shows an arrangement for an optical light source 280, which may be as described above in the context of the optical light source 270, except that the reflector 274 of the optical light source 270 is replaced by the reflector 282 in the optical light source 280. The reflector 282 may include a feedback loop 284 which may be formed into two arms (please refer to FIG. 3 for detailed view of a loop mirror) and coupled to a MZI 286. The MZI 286 may include a first arm 287a and a second arm 287b respectively coupled to the arms of the feedback loop 284. The first arm 287a of the MZI 286 may also be coupled to the first waveguide 258a, while the second arm 287b of the MZI 286 may also be coupled to a third waveguide (e.g. another output waveguide; silicon waveguide) 258c.

[0138] In various embodiments, the feedback loop 254, the first arm 257a and the second arm 257b of the MZI 256, the feedback loop 284, the first arm 287a and the second arm 287b of the MZI 286, the first waveguide 258a, the second waveguide 258b, and the third waveguide 258c may be a continuous waveguide structure, e.g. formed from a single waveguide.

[0139] In various embodiments, light propagating in the first waveguide 258a may be reflected, at least partially, back and forth within the optical cavity 272 by the reflectors 252, 282. The reflected light may be coupled to the optical gain medium 278 where optical gain or lasing may occur, resulting in light amplification. A portion of light originating from within the optical cavity 272 may be transmitted by the reflector 252 through the second waveguide 258b, thereby allowing light to exit from the optical light source 280. A portion of light originating from within the optical cavity 272 may also be transmitted by the reflector 282 through the third waveguide 258c, thereby allowing light to exit from the optical light source 280. The arrow 260c illustrates the propagation direction of light through the third waveguide 258c, which may be uni-directional. The optical light source 280 may be a bi-directional emissiter, allowing bi-directional emission of light from the optical light source 280, for example via the second waveguide 258b and/or the third waveguide 258c.

[0140] As similarly described for the reflector 252, in various embodiments, another thermo-optical device or electro-optical device, as an optical tuning element or as part of an optical tuning element, may be integrated with the MZI 286, for controlling the reflection of the reflector 282 or the feedback loop 284. This may mean that the optical tuning element may function as a reflectivity tuning element. As a non-limiting example based on a thermo-optical device, the thermo-optical device may include one or more heaters, e.g. a third heater 262c provided with the first arm 287a of the MZI 286 and a fourth heater 262d provided with the second arm 287b of the MZI 286.

[0141] In various embodiments, the embodiments illustrated in FIGS. 2A and 2B may allow tunable reflectivity, which may enable lasing threshold optimization.

[0142] In various embodiments, it should be appreciated that the respective optical gain media 228, 278, may be arranged at least substantially at or along the same plane as that of the respective waveguides 208a, 258a. This may mean that light from the waveguides 208a, 258a, may cross into the respective optical gain medium 228, 278, for example the light may propagate axially or co-axially between the respective waveguides 208a, 258a, and the respective optical gain media 228, 278.

[0143] FIG. 3 shows a schematic view of a loop mirror 300, according to various embodiments. The loop mirror 300 may include a feedback loop 301 which may be formed into two arms, for example a first arm 302a and a second arm 302b. The first arm 302a may be coupled to an input waveguide (not shown) while the second arm 302b may be coupled to an output waveguide (not shown). Light may be provided to the loop mirror 300 via the first arm 302a, where the light may propagate via one or more of the following routes: (1) at least a portion of the light may be coupled from the first arm 302a into the second arm 302b and then propagate through the feedback loop 301 in an anti-clockwise direction, as represented by the dashed arrow 350, and through the first arm 302a, resulting in a reflected light as illustrated by the light path 310; (2) at least a portion of the light may propagate through the first arm 302a and then the feedback loop 301 in a clockwise direction, as represented by the dashed arrow 352 towards the second arm 302b, where a portion thereof may then be coupled back to the first arm 302a, resulting in a reflected light as illustrated by the light path 320; (3) at least a portion of the light may be coupled from the first arm 302a into the second arm 302b and then propagate through the feedback loop 301 in an anti-clockwise direction 350 towards the first arm 302a, where a portion thereof may then be coupled to the second arm 302b, resulting in a transmitted light as illustrated by the light path 330; (4) at least a portion of the light may propagate through the first arm 302a, the feedback loop 301 in a clockwise direction 352 towards and through the second arm 302b, resulting in a transmitted light as illustrated by the light path 340.

[0144] FIG. 4 shows a schematic partial perspective view of the optical light source 230 of the embodiment of FIG. 2A. As shown, the optical gain medium 228 may be positioned over the first waveguide 208a, for example directly on the first waveguide 208a. The double-headed arrow 402 illustrates the bi-directional propagation of light between the optical gain medium 228 and the reflector 202, while the double-headed arrow 404 illustrates the bi-directional propagation of light between the optical gain medium 228 and the reflector 232.

[0145] FIG. 5A shows a schematic partial perspective view of the optical light source 230 of the embodiment of FIG. 2A, FIGS. 5B and 5C show respective cross sectional views of the optical light source 230 taken along the lines A-A'and B-B' respectively shown in FIG. 5A, while FIG. 5D shows a cross-sectional side view of the optical light source 230. As shown in FIGS. 5A and 5B, the optical gain medium 228 may be positioned over the first waveguide 208a, for example directly on the first waveguide 208a. The optical gain medium 228 may include a multiple quantum well (MQW) region 530. A pair of supporting structures, for example a first supporting structure 500a and a second supporting structure 500b may be provided on either side of the first waveguide 208a for supporting the optical gain medium 228. The optical light source 230 may be formed or integrated on a substrate (e.g. silicon substrate) having an oxide layer 550.

[0146] The first heater 212a and the second heater 212b corresponding to the reflector 202 may be arranged on either side of the first waveguide 208a which may be coupled to the feedback loop 204 (not shown in the perspective view), for example coupled to an arm of the feedback loop 204. The structure 510 may be an extension of the other arm of the feedback loop 204 for coupling to the second waveguide 208b, or the structure 510 may be the second waveguide 208b.

[0147] The third heater 212c and the fourth heater 212d corresponding to the reflector 232 may be arranged on either side of the first waveguide 208a which may be coupled to the feedback loop 234 (not shown in the perspective view), for example coupled to an arm of the feedback loop 234. The structure 520 may be an extension of the other arm of the feedback loop 234 for coupling to the third waveguide 208c, or the structure 520 may be the third waveguide 208c.

[0148] As shown in FIGS. 5C and 5D, another oxide layer 551, which may be a deposition oxide (e.g. SiO_2), may also be provided. The oxide layer 551 may be deposited over the first waveguide 208a, the structure 510 and the structure 520 so as to embed the first waveguide 208a, the structure 510 and the structure 520. The oxide layer 551 may act as a passivation layer. The first heater 212a and the second heater 212b corresponding to the reflector 202, and the third heater 212c and the fourth heater 212d corresponding to the reflector 232 may be formed over the oxide layer 551.

[0149] Using the reflector 232 as a non-limiting example, an example of forming a reflector may be as shown in FIG. 5G. The first waveguide 208a and the structure 520 may first be formed on the oxide layer 550. Another oxide layer 551, e.g. SiO_2, may then be deposited over the first waveguide 208a, the structure 520 and the oxide layer 550. Subsequently, a metal layer 512 may be deposited over the deposited oxide layer 551. An etching process may then be carried out to etch the metal layer 512 so as to form the third heater 212c and the fourth heater 212d. Accordingly, a tunable reflector 232 may be formed.

[0150] FIG. 5E shows a schematic partial perspective view of an optical light source 240, according to various embodiments, while FIG. 5F shows a cross sectional view of the optical light source 240 taken along the line C-C' shown in FIG. 5E. The cross sectional view of the optical light source 240 taken along the line D-D' may be as shown in FIG. 5C. The optical light source 240 may be as described above in the context of the optical light source 230, except that the optical gain medium 228 in the optical light source 240 may be arranged at least substantially at or along the same plane as that of the first waveguide 208a. In other words, light from the first waveguide 208a may cross into the gain medium 228 on one side of the optical gain medium 228 and then exit from an opposite side of the optical gain medium.For example, the light may propagate axially or co-axially between the first waveguide 208a and the optical gain medium 228. In various embodiments, the first waveguide 208a and the optical gain medium 228 may be arranged at least substantially coplanar relative to each other. The optical gain medium 228 may be arranged on an oxide layer (e.g. SiO_2) 550 of a substrate (e.g. silicon substrate). Further, the first supporting structure 500a and a second supporting structure 500b of the optical light source 230 may not be needed in the optical light source 240.

[0151] FIG. 6A shows an optical microscope image 600 and an enlarged image 602 of an indium phosphide (InP) wafer 604 bonded to a silicon (Si) wafer 606, illustrating InP-to-Silicon wafer bonding. The scale bar in the image 600 represents 2 inches or approximately 5 cm while the scale bar in the image 602 represents 0.5 inch or approximately 1.3 cm. The InP wafer 604 may be directly bonded to the Si wafer 606. However, it should be appreciated that other bonding techniques such as bonding with one or more intermediate layers (e.g. benzocyclobutene (BCB), metal) may also be used.

[0152] FIG. 6B shows a C-mode scanning acoustic microscope (C-SAM) image 620 of an InP wafer 604 bonded to a Si wafer 606, showing >80% good bonding between the InP wafer 604 and the Si wafer 606.The scale bar in the image 620 represents 0.5 inch or approximately 1.3 cm.

[0153] FIG. 6C shows a transmission electron microscope (TEM) image 630 and an enlarged image 632 of a cross section of an InP wafer 604 bonded to a Si wafer having a silicon substrate 640 and a silicon oxide (SiO_2) layer 642, showing good bonding interface between the InP wafer 604 and the SiO_2 layer 642. The InP wafer 604 bonded to the Si wafer exhibit good bonding strength, with a shear strength of about 15 MPa.

[0154] Measurements relating to the tunable reflector of various embodiments will now be described by way of the following example.

[0155] FIG. 7A shows a set-up 700 for measurements of a tunable reflector 702. Shown for the tunable reflector 702 is a fabricated feedback loop 704 with a Mach-Zehnder interferometer (MZI) 706. The MZI 706 includes a first arm 708a having a first heater 710a arranged or integrated with the first arm 708a, and a second arm 708b having a second heater 710b arranged or integrated with the second arm 708b. Thermo-optical effect in the first arm 708a and the second arm 708b may be achieved with the help of the first heater 710a and the second heater 710b. Metal pads 750a, 750b with respective interconnects 752a, 752b are provided, coupled to the first heater 710a, for the supply of an electrical signal to the first heater 710a, while metal pads (not shown) with respective interconnects 754a, 754b are provided, coupled to the second heater 710b, for the supply of an electrical signal to the second heater 710b. The set-up 700 further includes a laser 730, as a light source, for supplying light at a wavelength of about 1550 nm, and a circulator 732 which receives light from the laser 730 via a first port 734a. The light propagating within the circulator 732 may be circulated or directed to its second port 734b to be coupled to the first arm 708a of the MZI 706. The MZI 706, in combination with the feedback loop 704, may transmit at least a portion of the coupled light out of the reflector 702, via the second arm 708b, while reflecting at least a portion of the coupled light, via the first arm 708a, back to the circulator 732 via the second port 734b. The reflected light propagating within the circulator 732 may then be circulated or directed to its third port 734c, from which the reflected light may exit.

[0156] FIG. 7B shows a plot 760 of measured transmission 762 and reflection 764 responses obtained based on the set-up 700 of FIG. 7A, upon electrical power supply to the first arm 708a and/or the second arm 708b of the MZI 706, via the use of thermo-optical effect. Therefore, the optical cavity reflector 702 may be controlled by supplying electrical power to the MZI first arm 708a and/or the second arm 708b. This means that for laser applications, the mirror reflection may be optimised by supplying a certain power supply to the MZI 706, which may balance the output power and the lasing threshold.

[0157] FIG. 8A shows a set-up 800 for measurements of light emission based on the tunable reflector 702 of FIG. 7A. The set-up further includes an external semiconductor optical amplifier (SOA) 806, as a gain medium, which may be coupled to the first arm 708a of the MZI 706, and a second reflector 802 including a fiber loop 804, coupled to the SOA 806, where the second reflector 803 acts as the other reflection mirror for the laser cavity, to show light emission from the laser cavity.

[0158] FIG. 8B shows a plot 820 of measured light emission obtained based on the set-up 800 of FIG. 8A, ilustrating the optical lasing emission obtained, upon optimized mirror reflection with electrical power supply to the first arm 708a and/or the second arm 708b of the MZI 706.

[0159] FIG. 8C shows a plot 840 illustrating an enlarged view of the peak wavelength 822 of the measured light emission of FIG. 8B, illustrating a lasing emission at about 1573.9 nm with a line-width of approximately 0.07 nm (or 70 pm).

[0160] FIG. 9 shows plots of measured light emission obtained based on the set-up of FIG. 8A, for different electrical power supplies (e.g. voltage applied on the loop heater, e.g. the first heater 710a and/or the second heater 710b) and a fixed applied current of about 75 mA on the SOA 806, illustrating laser spectra for different loop reflections.

[0161] Results are shown in plot 900 for a supply of about 1 V, resulting in a reflectivity of approximately 13%, plot 902 for a supply of about 1.5 V, resulting in a reflectivity of approximately 10.5%, plot 904 for a supply of about 2 V, resulting in a reflectivity of approximately 3.1%, and plot 906 for a supply of about 2.5 V, resulting in a reflectivity of approximately 2%.

[0162] Various embodiments may also provide optical light sources (e.g. hybrid lasers) with a resonance tunable optical cavity or laser cavity. The optical cavities with tunable cavity resonances or tunable resonator modes may be formed by different combinations of one or more basic elements, which may act as a reflector, e.g. a microresonator-coupled Y-splitter or a microresonator-coupled Mach-Zehnder interferometer (MZI), where the microresonator may include but not limited to a microring or a microdisk. In various embodiments, by thermo-optically or electro-optically tuning the microresonator (e.g. microring), the microresonator resonance or cavity resonance may be controlled, which may determine the laser cavity mode, where only such microresonator mode may lase thereafter. Therefore, by changing the cavity resonance, the lasing wavelength may be changed. By using various configurations, either uni-directional emission optical light sources or lasers, or bi-directional emission optical light sources or lasers, may be obtained.

[0163] FIG. 10A shows schematic views of different designs of optical light sources (e.g. hybrid lasers) incorporating at least one microring-coupled Y-splitter according to various embodiments.

[0164] FIG. 10A shows an arrangement 1000 for a microring-coupled Y-splitter, which may form a reflector 1002 or part of a reflector, for the optical light source of various embodiments. The reflector 1002 may include a Y-splitter 1004 having a first arm 1005a, a second arm 1005b, and a third arm 1005c which may intersect at an intersection point to form a substantially Y-shape. The reflector 1002 may further include a microring 1006 arranged in between and coupled (e.g. mechanically and/or optically coupled) to the first arm 1005a and the second arm 1005b. The third arm 1005c may be coupled to a waveguide (e.g. input waveguide; silicon waveguide) 1008. In various embodiments, the first arm 1005a, the second arm 1005b and the third arm 1005c of the Y-splitter 1004 and the waveguide 1008 may be formed as a continuous structure (e.g. continuous waveguide structure), for example formed from a single waveguide, e.g. where the first arm 1005a and the second arm 1005b may branch off from the third arm 1005c.

[0165] Light may be provided into the waveguide 1008 towards the reflector 1002, where respective portions of the light may be directed to the first arm 1005a and the second arm 1005b respectively. A portion of the light in the first arm 1005a may be transmitted out of the reflector 1002, as represented by the arrow 1010a, while a further portion of the light may be coupled via the microring 1006 to the second arm 1005b to be directed towards and through the third arm 1005c. Similarly, a portion of the light in the second arm 1005b may be transmitted out of the reflector 1002, as represented by the arrow 1010b, while a further portion of the light may be coupled via the microring 1006 to the first arm 1005a to be directed towards and through the third arm 1005c. The double-headed arrow 1010c illustrates the propagation directions of light through the third arm 1005c and the waveguide 1008, which may be bi-directional.

[0166] In various embodiments, a thermo-optical device or electro-optical device, as an optical tuning element or as part of an optical tuning element, may be integrated with the microring 1006, for controlling the resonator or cavity modes of the reflector 1002 or the microring 1006. This may mean that the optical tuning element may function as a cavity resonance tuning element. As a non-limiting example based on a thermo-optical device, the thermo-optical device may include one or more heaters (e.g. a heater 1012), for example arranged over and/or beneath and/or surrounding the microring 1006.

[0167] FIG. 10A also shows an arrangement for an optical light source 1020. The optical light source 1020 may include an optical cavity 1022 defined by the reflector 1002, which may be as described above in the context of the arrangement 1000, and another reflector 1024 arranged spaced apart from the reflector 1002. The reflector 1024 may include a feedback loop 1026. The waveguide 1008 may be coupled to the reflector 1024, or may be formed into the feedback loop 1026. The optical light source 1020 may further include an optical gain medium 1028, for example in the form of a III-V bonding layer (e.g. InP), positioned in the optical cavity 1022 and in an optical path between the reflectors 1002, 1024. The optical gain medium 1028 may be arranged on or over the waveguide 1008 where light may be coupled between the waveguide 1008 and the optical gain medium 1028.

[0168] In various embodiments, the first arm 1005a, the second arm 1005b, and the third arm 1005c of the Y-splitter 1004, the waveguide 1008 and the feedback loop 1026 may be formed as a continuous structure (e.g. continuous waveguide structure), for example formed from a single waveguide.

[0169] In various embodiments, light propagating in the waveguide 1008 may be reflected, at least partially, back and forth within the optical cavity 1022 by the reflectors 1002, 1024. The reflected light may be coupled to the optical gain medium 1028 where optical gain or lasing may occur, resulting in light amplification. A portion of light, originating from within the optical cavity 1022 may be transmitted by the reflector 1002 through the first arm 1010a and/or the second arm 1010b, thereby allowing light to exit from the optical light source 1020. The optical light source 1020 may be a uni-directional emissiter, allowing uni-directional emission of light from the optical light source 1020, for example via the first arm 1010a and/or the second arm 1010b.

[0170] In various embodiments, by controlling the cavity mode of the reflector 1002, and therefore the lasing mode, with the help of the heater 1012, tuning of the light propagating in the optical cavity 1022 between the reflectors 1002, 1024, and the optical gain medium 1028 may be carried out.

[0171] FIG. 10A further shows an arrangement for an optical light source 1030, which may be as described above in the context of the optical light source 1020, except that the reflector 1024 of the optical light source 1020 is replaced by the reflector 1032 in the optical light source 1030. The reflector 1032 may include a feedback loop 1034 which may be formed into two arms (please refer to FIG. 3 for detailed view of a loop mirror) and coupled to a DC 1035, which subsequently may be coupled to the waveguide 1008 and a second waveguide (e.g. an output waveguide; silicon waveguide) 1009.

[0172] In various embodiments, the first arm 1005a, the second arm 1005b, and the third arm 1005c of the Y-splitter 1004, the waveguide 1008 and the feedback loop 1034 with the DC 1035 may be formed as a continuous structure (e.g. continuous waveguide structure), for example formed from a single waveguide.

[0173] In various embodiments, light propagating in the waveguide 1008 may be reflected, at least partially, back and forth within the optical cavity 1022 by the reflectors 1002, 1032. The reflected light may be coupled to the optical gain medium 1028 where optical gain or lasing may occur, resulting in light amplification. A portion of light originating from within the optical cavity 1022 may be transmitted by the reflector 1002 through the first arm 1010a and/or the second arm 1010b, thereby allowing light to exit from the optical light source 1020. A portion of light originating from within the optical cavity 1022 may also be transmitted by the reflector 1032 through the second waveguide 1009, as represented by the arrow 1010c, thereby allowing light to exit from the optical light source 1020. The optical light source 1030 may be a bi-directional emissiter, allowing bi-directional emission of light from the optical light source 1030, for example via the first arm 1010a and/or the second arm 1010b and/or the second waveguide 1009.

[0174] In various embodiments, another thermo-optical device or electro-optical device, as an optical tuning element or as part of an optical tuning element, may be integrated with the DC 1035, for controlling the reflection of the reflector 1032 or the feedback loop 1034. This may mean that the optical tuning element may function as a reflectivity tuning element. As a non-limiting example based on a thermo-optical device, the thermo-optical device may include one or more heaters, e.g. a first heater 1036a and a second heater 1036b.

[0175] FIG. 10A further shows an arrangement for an optical light source 1040, which may be as described above in the context of the optical light source 1020, except that the reflector 1024 of the optical light source 1020 is replaced by the reflector 1042 in the optical light source 1040. The reflector 1042 may include a microring-coupled Y-splitter. The reflector 1042 may include a Y-splitter 1044 having a first arm 1045a, a second arm 1045b, and a third arm 1045c which may intersect at an intersection point to form a substantially Y-shape. The reflector 1042 may further include a microring 1046 arranged in between and coupled (e.g. mechanically and/or optically coupled) to the first arm 1045a and the second arm 1045b. The third arm 1045c may be coupled to the waveguide 1008.

[0176] In various embodiments, the first arm 1005a, the second arm 1005b and the third arm 1005c of the Y-splitter 1004, the waveguide 1008 and the the first arm 1045a, the second arm 1045b and the third arm 1045c of the Y-splitter 1044 may be formed as a continuous structure (e.g. continuous waveguide structure), for example formed from a single waveguide.

[0177] In various embodiments, light propagating in the waveguide 1008 may be reflected, at least partially, back and forth within the optical cavity 1022 by the reflectors 1002, 1042. The reflected light may be coupled to the optical gain medium 1048 where optical gain or lasing may occur, resulting in light amplification. A portion of light originating from within the optical cavity 1022 may be transmitted by the reflector 1002 through the first arm 1010a and/or the second arm 1010b, thereby allowing light to exit from the optical light source 1040. A portion of light originating from within the optical cavity 1022 may also be transmitted by the reflector 1042 through the first arm 1045a and/or the second arm 1045b, thereby allowing light to exit from the optical light source 1040. The optical light source 1040 may be a bi-directional emissiter, allowing bi-directional emission of light from the optical light source 1040, for example via the first arm 1010a and/or the second arm 1010b and/or the first arm 1045a and/or the second arm 1045b.

[0178] As similarly described for the reflector 1002, in various embodiments, another thermo-optical device or electro-optical device, as an optical tuning element or as part of an optical tuning element, may be integrated with the microring 1046, for controlling the resonator or cavity modes of the reflector 1042 or the microring 1046. This may mean that the optical tuning element may function as a cavity resonance tuning element. As a non-limiting example based on a thermo-optical device, the thermo-optical device may include one or more heaters (e.g. a heater 1048), for example arranged over and/or beneath and/or surrounding the microring 1046.

[0179] FIG. 10B shows schematic views of different designs of optical light sources (e.g. hybrid lasers) incorporating at least one microring-coupled Mach-Zehnder interferometer (MZI), according to various embodiments.

[0180] FIG. 10B shows an arrangement 1050 for a microring-coupled MZI, which may form a reflector 1052 or part of a reflector, for the optical light source of various embodiments. The reflector 1052 may include a MZI 1054 having a first arm 1055a, and a second arm 1055b. The reflector 1052 may further include a microring 1056 arranged in between and coupled (e.g. mechanically and/or optically coupled) to the first arm 1055a and the second arm 1055b. The first arm 1055a and the second arm 1055b may be coupled at one end to a first waveguide (e.g. input waveguide; silicon waveguide) 1058a, while the opposite end may be coupled to a second waveguide (e.g. output waveguide; silicon waveguide) 1058b. In various embodiments, the first arm 1055a, the second arm 1055b, the first waveguide 1058a and the second waveguide 1058b may be formed as a continuous structure (e.g. continuous waveguide structure), for example formed from a single waveguide.

[0181] Light may be provided into the first waveguide 1058a towards the reflector 1052, where a portion of the light may be reflected by the reflector 1052 back through the first waveguide 1058a, and a portion of the light may be transmitted by the reflector 1052 into the second waveguide 1058b. The double-headed arrow 1060a illustrates the propagation directions of light through the first waveguide 1058a, which may be bi-directional, while the arrow 1060b illustrates the propagation direction of light through the second waveguide 1058b, which may be uni-directional. For example, light may be provided into the first waveguide 1058a towards the reflector 1002, where respective portions of the light may be directed to the first arm 1055a and the second arm 1055b respectively. A portion of the light in the first arm 1055a may be transmitted out of the reflector 1052, as represented by the arrow 1060b, while a further portion of the light may be coupled via the microring 1056 to the second arm 1055b to be directed towards and through the first waveguide 1058a. Similarly, a portion of the light in the second arm 1055b may be transmitted out of the reflector 1052, as represented by the arrow 1060b, while a further portion of the light may be coupled via the microring 1056 to the first arm 1055a to be directed towards and through the first waveguide 1058a.

[0182] In various embodiments, a thermo-optical device or electro-optical device, as an optical tuning element or as part of an optical tuning element, may be integrated with the microring 1056, for controlling the resonator or cavity modes of the reflector 1052 or the microring 1056. This may mean that the optical tuning element may function as a cavity resonance tuning element. As a non-limiting example based on a thermo-optical device, the thermo-optical device may include one or more heaters (e.g. a heater 1062), for example arranged over and/or beneath and/or surrounding the microring 1056.

[0183] FIG. 10B also shows an arrangement for an optical light source 1070. The optical light source 1070 may include an optical cavity 1072 defined by the reflector 1052, which may be as described above in the context of the arrangement 1050, and another reflector 1074 arranged spaced apart from the reflector 1052. The reflector 1074 may include a feedback loop 1076. The first waveguide 1058a may be coupled to the reflector 1074, or may be formed into the feedback loop 1076. The optical light source 1070 may further include an optical gain medium 1078, for example in the form of a III-V bonding layer (e.g. InP), positioned in the optical cavity 1072 and in an optical path between the reflectors 1052, 1074. The optical gain medium 1078 may be arranged on or over the first waveguide 1058a where light may be coupled between the first waveguide 1058a and the optical gain medium 1078.

[0184] In various embodiments, the first arm 1055a and the second arm 1055b of the MZI 1054, the first waveguide 1058a, the second waveguide 1058b and the feedback loop 1076 may be formed as a continuous structure (e.g. continuous waveguide structure), for example formed from a single waveguide.

[0185] In various embodiments, light propagating in the first waveguide 1058a may be reflected, at least partially, back and forth within the optical cavity 1072 by the reflectors 1052, 1074. The reflected light may be coupled to the optical gain medium 1078 where optical gain or lasing may occur, resulting in light amplification. A portion of light, originating from within the optical cavity 1072 may be transmitted by the reflector 1052 through the second waveguide 1058b, thereby allowing light to exit from the optical light source 1070. The optical light source 1070 may be a uni-directional emissiter, allowing uni-directional emission of light from the optical light source 1070, for example via the second waveguide 1058b.

[0186] In various embodiments, by controlling the cavity mode of the reflector 1052, and therefore the lasing mode, with the help of the heater 1062, tuning of the light propagating in the optical cavity 1072 between the reflectors 1052, 1074, and the optical gain medium 1078 may be carried out.

[0187] FIG. 10B further shows an arrangement for an optical light source 1080, which may be as described above in the context of the optical light source 1070, except that the reflector 1074 of the optical light source 1070 is replaced by the reflector 1082 in the optical light source 1080. The reflector 1082 may include a feedback loop with a MZI. The reflector 1082 may include a feedback loop 1084 which may be formed into two arms (please refer to FIG. 3 for detailed view of a loop mirror) and coupled to a MZI 1085. The MZI 1085 may include a first arm 1086a and a second arm 1086b respectively coupled to the arms of the feedback loop 104. The first arm 1086a of the MZI 1085 may also be coupled to the first waveguide 1058a, while the second arm 1086b of the MZI 1085 may also be coupled to a third waveguide (e.g. another output waveguide; silicon waveguide) 1058c. In various embodiments, the first arm 1055a and the second arm 1055b of the MZI 1054, the first waveguide 1058a, the second waveguide 1058b, the third waveguide 1058c and the the first arm 1086a and the second arm 1086b of the MZI 1085 may be formed as a continuous structure (e.g. continuous waveguide structure), for example formed from a single waveguide.

[0188] In various embodiments, light propagating in the first waveguide 1058a may be reflected, at least partially, back and forth within the optical cavity 1072 by the reflectors 1052, 1082. The reflected light may be coupled to the optical gain medium 1078 where optical gain or lasing may occur, resulting in light amplification. A portion of light originating from within the optical cavity 1072 may be transmitted by the reflector 1052 through the second waveguide 1058b, thereby allowing light to exit from the optical light source 1080. A portion of light originating from within the optical cavity 1072 may also be transmitted by the reflector 1082 through the third waveguide 1058c, as represented by the arrow 1060c, thereby allowing light to exit from the optical light source 1080. The optical light source 1080 may be a bi-directional emissiter, allowing bi-directional emission of light from the optical light source 1080, for example via the second waveguide 1058b and/or the third waveguide 1058c.

[0189] In various embodiments, another thermo-optical device or electro-optical device, as an optical tuning element or as part of an optical tuning element, may be integrated with the MZI 1085, for controlling the reflection of the reflector 1082 or the feedback loop 1084. This may mean that the optical tuning element may function as a reflectivity tuning element. As a non-limiting example based on a thermo-optical device, the thermo-optical device may include one or more heaters, e.g. a first heater 1087a provided with the first arm 1086a and a second heater 1087b provided with the second arm 1086b.

[0190] FIG. 10B further shows an arrangement for an optical light source 1090, which may be as described above in the context of the optical light source 1070, except that the reflector 1074 of the optical light source 1070 is replaced by the reflector 1092 in the optical light source 1090. The reflector 1092 may include a microring-coupled MZI. The reflector 1092 may include a MZI 1094 having a first arm 1095a, and a second arm 1095b. The reflector 1092 may further include a microring 1096 arranged in between and coupled (e.g. mechanically and/or optically coupled) to the first arm 1095a and the second arm 1095b. The first arm 1095a and the second arm 1095b may be coupled at one end to the first waveguide 1058a, while the opposite end may be coupled to a third waveguide (e.g. another output waveguide; silicon waveguide) 1058c. In various embodiments, the first arm 1055a and the second arm 1055b of the MZI 1054, the first arm 1095a and the second arm 1095b of the MZI 1094, the first waveguide 1058a, the second waveguide 1058b and the third waveguide 1058c may be formed as a continuous structure (e.g. continuous waveguide structure), for example formed from a single waveguide.

[0191] In various embodiments, light propagating in the first waveguide 1058a may be reflected, at least partially, back and forth within the optical cavity 1072 by the reflectors 1052, 1092. The reflected light may be coupled to the optical gain medium 1078 where optical gain or lasing may occur, resulting in light amplification. A portion of light originating from within the optical cavity 1072 may be transmitted by the reflector 1052 through the second waveguide 1058b, as represented by the arrow 1060b, thereby allowing light to exit from the optical light source 1090. A portion of light originating from within the optical cavity 1072 may also be transmitted by the reflector 1092 through the third waveguide 1058c, as represented by the arrow 1060c, thereby allowing light to exit from the optical light source 1090. The optical light source 1090 may be a bi-directional emissiter, allowing bi-directional emission of light from the optical light source 1090, for example via the second waveguide 1058b and/or the third waveguide 1058c.

[0192] As similarly described for the reflector 1052, in various embodiments, another thermo-optical device or electro-optical device, as an optical tuning element or as part of an optical tuning element, may be integrated with the microring 1096, for controlling the resonator or cavity modes of the reflector 1092 or the microring 1096. This may mean that the thermo-optical device may function as a cavity resonance tuning element. As a non-limiting example based on a thermo-optical device, the thermo-optical device may include one or more heaters (e.g. a heater 1098), for example arranged over and/or beneath and/or surrounding the microring 1096.

[0193] In various embodiments, the embodiments illustrated in FIGS. 10A and 10B may allow tunable cavity resonances, which may enable or provide controllable emission wavelength.

[0194] In various embodiments, it should be appreciated that the respective optical gain media 1028, 1078, may be arranged at least substantially at or along the same plane as that of the respective waveguide 1008 or first waveguide 1058a. This may mean that light from the waveguides 1008, 1058a, may cross into the respective optical gain medium 1028, 1078, for example the light may propagate axially or co-axially between the respective waveguides 1008, 1058a, and the respective optical gain media 1028, 1078.

[0195] Various embodiments may also provide an optical transmitter. FIG. 11 shows a schematic block diagram of an optical transmitter (or an optical transceiver) 1100, according to various embodiments. The optical transmitter 1100 may be a hybrid wavelength division multiplexing (WDM) transmitter. The optical transmitter 1100 may include an optical cavity 1102 defined by two sets of reflectors for mirror reflection, for example a first reflector block 1110 and a second reflector block 1120 arranged spaced apart from each other. The optical transmitter 1100 may further include a filter block or multiplexer block 1130 arranged or embedded in the optical cavity 1102. The multiplexer block 1130 may also be arranged in an optical path between the first reflector block 1110 and the second reflector block 1120. The optical transmitter 1100 may further include an optical amplifier block 1150 arranged or embedded in the optical cavity 1102, and in an optical path between the second reflector block 1120 and the multiplexer block 1130.

[0196] The first reflector block 1110 may include a first reflector 1112. The first reflector 1112 may be a tunable reflector for tuning reflectivity of the first reflector 1112.

[0197] The second reflector block 1120 may include at least one second reflector arranged spaced apart from the first reflector 1112. As a non-limiting example as shown in FIG. 11, the second reflector block 1120 may include four second reflectors; a first second reflector 1122a, a second second reflector 1122b, a third second reflector 1122c, and a fourth second reflector 1122d. Any one of or each of the first second reflector 1122a, the second second reflector 1122b, the third second reflector 1122c, and the fourth second reflector 1122d may be a tunable reflector for tuning reflectivity of the respective second reflector.

[0198] The multiplexer block 1130 may include a multiplexer element (MUX) 1132 arranged or embedded in the optical cavity 1102. The MUX 1132 may be a WDM MUX. The MUX 1132 may include a first port (e.g. output port) 1134. The first port 1134 may be optically coupled to the first reflector 1112. The MUX 1132 may further include at least two second ports (e.g. input ports). As a non-limiting example as shown in FIG. 11, the MUX 1132 may include four second ports; a first second port 1136a, a second second port 1136b, a third second port 1136c, and a fourth second port 1136d. A respective second port may be associated with a respective channel wavelength of the MUX 1132, where the respective channel wavelength may be associated with a respective optical channel or MUX channel of the MUX 1132. Different second ports may be associated with different channel wavelengths. For example, the first second port 1136a may be associated with a first channel wavelength, λ_1, of the first optical channel of the MUX 1132, the second second port 1136b may be associated with a second channel wavelength, λ_2, of the second optical channel of the MUX 1132, the third second port 1136c may be associated with a third channel wavelength, λ_3, of the third optical channel of the MUX 1132, and the fourth second port 1136d may be associated with a fourth channel wavelength, λ_4, of the fourth optical channel of the MUX 1132.

[0199] The optical amplifier block 1150 may include at least two optical gain media positioned in the optical cavity 1102. As a non-limiting example as shown in FIG. 11, the optical amplifier block 1150 may include four optical gain media; a first optical gain medium 1152a, a second optical gain medium 1152b, a third optical gain medium 1152c, and a fourth optical gain medium 1152d. Any one of or each of the first optical gain medium 1152a, the second optical gain medium 1152b, the third optical gain medium 1152c, and the fourth optical gain medium 1152d may include a III-V material, for example in the form of a III-V bonding layer, which may be bonded to a silicon (Si) waveguide or a respective silicon (Si) waveguide.

[0200] In various embodiments, a respective optical gain medium may be arranged in a respective optical path between a respective second port of the MUX 1132 and a respective second reflector. As a non-limiting example, the first optical gain medium 1152a may be arranged in an optical path between the first second port 1136a of the MUX 1132 and the first second reflector 1122a.

[0201] In various embodiments, a respective optical gain medium may emit light to be received by a respective second port, where the light may have a range of wavelengths including the channel wavelength associated with the respective second port. For example, the first optical gain medium 1152a may emit light of a range of wavelengths of, for example, $\lambda_{m1},\ldots, \lambda_1,\ldots, \lambda_{n1}$ to be received by the first second port 1136a of the MUX 1132.

[0202] The MUX 1132 may receive respective lights via the respective second ports 1136a, 1136b, 1136c, 1136d, and may provide a light at the respective channel wavelengths to the first port 1134 for transmission therefrom. This may mean that the MUX 1132 may filter light received on each of the second ports 1136a, 1136b, 1136c, 1136d, which may remove at least substantially light of wavelengths other than the respective channel wavelengths, λ_1, λ_2, λ_3, λ_4. Respective lights or filtered lights at the respective channel wavelengths, λ_1, λ_2, λ_3, λ_4 may be combined into one optical signal or light, e.g. multiplexed, to provide a resultant light or multiplexed light having wavelengths at least substantially at λ_1, λ_2, λ_3, λ_4, to the first port 1134 for transmission of the multiplexed light.

[0203] A portion of the resultant light transmitted from the first port 1134 may be transmitted via the first reflector 1112, while another portion of the resultant light transmitted from the first port 1134 may be reflected by the first reflector 1112. This may mean that the first reflector 1112 may be a partial reflector. The portion of the resultant light reflected by the first reflector 1112 may be directed towards the first port 1134, where respective lights of respective channel wavelengths may be directed towards and through the respective second ports, e.g. demultiplexed by the MUX 1132, where the respective lights may then interact with the respective optical gain media so that lasing may occur. Using the first second port 1136a as a non-limiting example, after demultiplexing by MUX 1132, light at the wavelength of λ_1 may exit via the first second port 1136a and propagate through the first optical gain medium 1152a, and be reflected by the first second reflector 1122a back through the first optical gain for a second time, towards the MUX 1132 to be received by the first second port 1136a and transmitted from the first port 1134. During each passage through the first optical gain medium 1152a, light at the wavelength of λ_1 may be amplified as a result of optical gain. Therefore, as the WDM MUX 1132 may be embedded inside the optical laser cavity 1102 for the selection of the lasing modes or operation wavelengths, the WDM laser wavelengths may be self-aligned to the WDM MUX channels, where only the wavelengths that align with the WDM channels may be amplified and lasing may. Accordingly, the set of first second reflector 1122a, second second reflector 1122b, third second reflector 1122c, and fourth second reflector 1122d arranged at one end may serve as the respective mirror for the respective WDM optical channel or laser channel, while the first reflector block 1110 at the other end may serve as a common facet.

[0204] In various embodiments, a respective waveguide (e.g. Si waveguide) may be provided for optical coupling between the respective second reflector and the respective second port. In various embodiment, the respective optical gain medium (e.g. III-V gain medium) may be arranged at least substantially at or along the same plane as that of the respective waveguide, or arranged over or on top of the respective waveguide by various wafer bonding techniques to form a hybrid system.

[0205] Therefore, various embodiments may provide a combination of WDM MUX and an optical light source (e.g. WDM light source), thus simplifying the design of the optical transmitter. Various embodiments may also enable wavelength self-alignment between the WDM light source and the WDM MUX. For example, this may be achieved by using the MUX as a cavity mode selector. This may potentially address or solve the wavelength misalignment problem between the WDM light source and the WDM MUX associated with conventional transmitters.

[0206] In various embodiments, any one of or each of the first reflector 1112, first second reflector 1122a, second second reflector 1122b, third second reflector 1122c, and fourth second reflector 1122d may be a tunable reflector, which for example may provide tunable mirror reflections for controlling the mirror reflection, thus controlling the properties of the laser cavity 1102, including the Q-factor, the output reflection, among other properties/paramters. Such cavity parameters may subsequently affect the laser properties, such as the lasing threshold, the output power, among others. There are different embodiments for the realization of such tunable reflector, as illustrated in FIG. 12.

[0207] FIG. 12 shows schematic views of different designs for a tunable reflector, according to various embodiments. The tunable reflector may be a tunable loop mirror 1200, a tunable Mach-Zehnder interferometer (MZI) loop mirror 1240, or a tunable ring mirror 1280.

[0208] The tunable loop mirror 1200 may include a feedback loop with a directional coupler, having a feedback loop 1204 which may be formed into two arms (please refer to FIG. 3 for detailed view of a loop mirror) and coupled to a DC 1206, which subsequently may be coupled to a first waveguide (e.g. input waveguide; silicon waveguide) 1208a and a second waveguide (e.g. output waveguide; silicon waveguide) 1208b. In various embodiments, the feedback loop 1204 with the DC 1206, the first waveguide 1208a and the second waveguide 1208b may be a continuous waveguide structure, e.g. formed from a single waveguide. In various embodiments, a thermo-optical device or electro-optical device, as an optical tuning element or as part of an optical tuning element, may be integrated with the DC 1206, for controlling the reflection of the reflector 1202 or the feedback loop 1204. This may mean that the optical tuning element may function as a reflectivity tuning element. As a non-limiting example based on a thermo-optical device, the thermo-optical device may include one or more heaters, e.g. a first heater 1212a and a second heater 1212b. The tunable loop mirror 1200 and its associated operations may be as described in the context of the reflector 202 of FIG. 2A.

[0209] The tunable Mach-Zehnder interferometer (MZI) loop mirror 1240 may include a feedback loop with a MZI, having a feedback loop 1244 which may be formed into two arms (please refer to FIG. 3 for detailed view of a loop mirror) and coupled to a MZI 1246. The MZI 1246 may include a first arm 1247a and a second arm 1247b respectively coupled to the arms of the feedback loop 1244. The first arm 1247a of the MZI 1246 may also be coupled to a first waveguide (e.g. input waveguide; silicon waveguide) 1248a, while the second arm 1247b of the MZI 1246 may also be coupled to a second waveguide (e.g. output waveguide; silicon waveguide) 1248b. In various embodiments, the feedback loop 1244, the first arm 1247a and the second arm 1247b of the MZI 1246, the first waveguide 1248a, and the second waveguide 1248b may be a continuous waveguide structure, e.g. formed from a single waveguide. In various embodiments, a thermo-optical device or electro-optical device, as an optical tuning element or as part of an optical tuning element, may be integrated with the MZI 1246, for controlling the reflection of the reflector 1240 or the feedback loop 1244. This may mean that the optical tuning element may function as a reflectivity tuning element. As a non-limiting example based on a thermo-optical device, the thermo-optical device may include one or more heaters, e.g. a first heater 1252a provided with the first arm 1247a and a second heater 1252b provided with the second arm 1247b. The tunable MZI loop mirror 1240 and its associated operations may be as described in the context of the reflector 252 of FIG. 2B.

[0210] The tunable ring mirror 1280 may include a microring-coupled Y-splitter, having a Y-splitter 1284 having a first arm 1285a, a second arm 1285b, and a third arm 1285c which may intersect at an intersection point to form a substantially Y-shape. The reflector 1280 may further include a microring 1286 arranged in between and coupled (e.g. mechanically and/or optically coupled) to the first arm 1285a and the second arm 1285b. The third arm 1285c may be coupled to a waveguide (e.g. input waveguide; silicon waveguide) 1288. In various embodiments, the first arm 1285a, the second arm 1285b and the third arm 1285c of the Y-splitter 1284 and the waveguide 1288 may be formed as a continuous structure (e.g. continuous waveguide structure), for example formed from a single waveguide. In various embodiments, a thermo-optical device or electro-optical device, as an optical tuning element or as part of an optical tuning element, may be integrated with the microring 1286, for controlling the resonator or cavity modes of the reflector 1280 or the microring 1286. This may mean that the optical tuning element may function as a cavity resonance tuning element. As a non-limiting example based on a thermo-optical device, the thermo-optical device may include one or more heaters (e.g. a heater 1292), for example arranged over and/or beneath and/or surrounding the microring 1286. The tunable ring mirror 1280 and its associated operations may be as described in the context of the reflector 1002 of FIG. 10A. It should be appreciated that a microring-coupled MZI as described in the context of the reflector 1052 of FIG. 10B may be employed instead as a tunable ring mirror.

[0211] The optical transmitter of various embodiments may be used for WDM applications, for example as a hybrid WDM transmitter employed to select the lasing wavelengths. In various embodiments, the MUX 1132 shown in FIG. 11 may be a WDM MUX. Different structures may be employed to realise the WDM MUX function as shown in FIGS. 13A and 13C.

[0212] In various embodiments, the multiplexer element may include a microresonator-based multiplexer arrangement, for example a microring resonator based MUX as shown in FIG. 13A, where, each of the channels may include either one or two (a pair) microrings with tunability. The multiplexer element may be a single microring MUX 1300 or a dual-microring MUX 1320 with tunable free space range (FSR). In the context of various embodiments, the term "free space range" may mean the frequency spacing of its axial resonator modes or the frequency spacing between two successive reflected or transmitted optical intensity maxima or minima.

[0213] The single microring MUX 1300 may include a plurality of microrings. As a non-limiting example as shown in FIG. 13A, the single microring MUX 1300 may include four microrings coupled to a plurality of input waveguides respectively; a first microring 1302a coupled to a first input waveguide 1304a, a second microring 1302b coupled to a second input waveguide 1304b, a third microring 1302c coupled to a third input waveguide 1304c, and a fourth microring 1302d coupled to a fourth input waveguide 1304d. The microrings 1302a, 1302b, 1302c, 1302d may also be coupled to a common output waveguide 1306. In various embodiments, the plurality of input waveguides 1304a, 1304b, 1304c, 1304d, may be coupled to respective optical gain media. It should be appreciated that light may propagate bi-directionally between the plurality of input waveguides 1304a, 1304b, 1304c, 1304d and the output waveguide 1306.

[0214] The dual-microring MUX 1320 may include a plurality of pairs of microrings. As a non-limiting example as shown in FIG. 13A, the dual-microring MUX 1320 may include four pairs of microrings; a first pair of microrings 1322a, a second pair of microrings 1322b, a third pair of microrings 1322c, and a fourth pair of microrings 1322d. The first pair of microrings 1322a may include a first microring 1324a coupled to a first input waveguide 1330a, and a second microring 1326a coupled to the first microring 1324a via a first intermediate waveguide 1332a. The second pair of microrings 1322b may include a first microring 1324b coupled to a second input waveguide 1330b, and a second microring 1326b coupled to the first microring 1324b via a second intermediate waveguide 1332b. The third pair of microrings 1322c may include a first microring 1324c coupled to a third input waveguide 1330c, and a second microring 1326c coupled to the first microring 1324c via a third intermediate waveguide 1332c. The fourth pair of microrings 1322d may include a first microring 1324d coupled to a fourth input waveguide 1330d, and a second microring 1326d coupled to the first microring 1324d via a fourth intermediate waveguide 1332d. The pairs of microrings 1322a, 1322b, 1322c, 1322d may also be coupled to a common output waveguide 1334. In various embodiments, the plurality of input waveguides 1330a, 1330b, 1330c, 1330d, may be coupled to respective optical gain media. It should be appreciated that light may propagate bi-directionally between the plurality of input waveguides 1330a, 1330b, 1330c, 1330d and the output waveguide 1334.

[0215] The dual-microring MUX 1320 may allow tunable FSR. In various embodiments, the transmission spectrum of a microring may include a plurality of period peaks, where the pitch of adjacent peaks may be defined as the FSR (free space range). For a laser, a small number of peaks may be expected and a double ring structure may realise this. FIG. 13B shows an operation of the dual-microring MUX 1320. As a non-limiting example using the first pair of microrings 1322a, the FSR of the first microring 1324a may be FSR_1 as shown in the spectrum 1340 while the FSR of the second microring 1326a may be FSR_2 as shown in the spectrum 1342. In various embodiments, the respective FSRs of the first microring 1324a and the second microring 1326a may be designed to be different. Tuning the first microring 1324a and the second microring 1326a may make some of the peaks align together, thereby providing a final FSR for the first pair of microrings 1322a, as shown in FIG. 13B. The total peaks number may be very small, and therefore may be beneficial for laser. It should be appreciated that each of the first pair of microrings 1322a, second pair of microrings 1322b, third pair of microrings 1322c, and fourth pair of microrings 1322d may be tuned to obtain a final FSR as substantially described above or a different final FSR. Further, it should be appreciated that any one of or each of the first pair of microrings 1322a, second pair of microrings 1322b, third pair of microrings 1322c, and fourth pair of microrings 1322d may have the at least substantially similar final FSR or different final FSRs.

[0216] In various embodiments, the multiplexer element may include an arrayed waveguide grating (AWG) 1350 as shown in FIG. 13C. The AWG 1350 may include a plurality of input waveguides, collectively represented as 1352, coupled to an input port 1354, and an output waveguide 1356 coupled to an output port 1358. A plurality of intermediate fibers or waveguides, collectively represented as 1360, of different lengths, may be coupled between the input port 1354 and the output port 1358. In various embodiments, the plurality of input waveguides 1352 may be coupled to respective optical gain media. It should be appreciated that light may propagate bi-directionally between the plurality of input waveguides 1352 and the output waveguide 1356.

[0217] In various embodiments, the multiplexer element may include a concave grating 1372, as shown in FIG. 13C, which may be placed in an arrangement 1370 where the concave grating 1372 may be optically coupled to a plurality of input waveguides, collectively represented as 1374, and an output waveguide 1376. In various embodiments, the plurality of input waveguides 1374 may be coupled to respective optical gain media. It should be appreciated that light may propagate bi-directionally between the plurality of input waveguides 1374 and the output waveguide 1376.

[0218] FIGS. 14A and 14B show schematic views of optical transmitters, according to various embodiments.

[0219] The optical transmitter 1400 of FIG. 14A may include a first reflector block 1410, a second reflector block 1420, a multiplexer block 1430 and an optical amplifier block 1450, which may be similar to the embodiment as described in the context of optical transmitter 1100 of FIG. 11. The first reflector block 1410 may include a reflector 1412 having a feedback loop with a MZI, which may be as described in the context of the reflector 252 of FIG. 2B. The second reflector block 1420 may include a plurality of feedback loops; for example a first feedback loop 1422a, a second feedback loop 1422b, a third feedback loop 1422c, and a fourth feedback loop 1422d. The multiplexer block 1430 may include a dual-microring MUX 1432 which may be as described in the context of the dual-microring MUX 1320 of FIG. 13A. The optical amplifier block 1450 may include a plurality of optical gain media, for example a first optical gain medium 1452a, a second optical gain medium 1452b, a third optical gain medium 1452c, and a fourth optical gain medium 1452d, which may be as described in the context of the optical amplifier block 1150 of FIG. 11.

[0220] The optical transmitter 1460 of FIG. 14B may be as described above in the context of the optical transmitter 1400, except that the dual-microring MUX 1432 in the multiplexer block 1430 is replaced by a single microring MUX 1464 in the optical transmitter 1460. The single microring MUX 1464 may be as described in the context of the single microring MUX 1300 of FIG. 13A.

[0221] The optical transmitter 1480 of FIG. 14C may be as described above in the context of the optical transmitter 1460, except that the plurality of feedback loops 1422a, 1422b, 1422c, 1422d in the second reflector block 1420 are replaced by a plurality of reflectors 1482a, 1482b, 1482c, 1482d, respectively, each having a feedback loop with a MZI, in the optical transmitter 1480. Each of the reflectors 1482a, 1482b, 1482c, 1482d may be as described in the context of the reflector 252 of FIG. 2B.

[0222] It should be appreciated that other combinations of structures for the first reflector block 1410, the second reflector block 1420, the multiplexer block 1430 and the optical amplifier block 1450 respectively may also be employed.

[0223] FIG. 15A shows a set-up 1500 for measurements of light emission based on the tunable MZI-ring reflector 1280 as described in the context of FIG. 12, for a wavelength-tunable hybrid laser. The set-up 1500 further includes an external/off-chip semiconductor optical amplifier (SOA) 1502, as a gain medium. The SOA 1502 may be coupled, via the waveguide 1288 to the third arm 1285c of the Y-splitter 1284 of the reflector 1280. For the set-up 1500, the laser cavity is defined by an off-chip fiber loop 1504 and the on-chip tunable MZI-ring reflector 1280. By thermo-optically tuning the MZI-ring resonator 1286, for example by applying an electrical signal to the heater 1292 via the metal pads 1510, the cavity wavelength may be changed, and thus the laser operation wavelength may change.

[0224] FIG. 15B shows plots of measured light emission obtained based on the set-up of FIG. 15A, illustrating the measured lasing wavelength upon the thermo-optical tunability to the microring resonator. Results are shown in plot 1500 where no voltage is applied to the heater 1292, plot 1502 for a supply of about 3 V applied to the heater 1292, plot 1504 for a supply of about 4 V, plot 1506 for a supply of about 5 V, and plot 1508 for a supply of about 6 V. As may be observed, the lasing wavelength changes depending on the amount of voltage applied to the heater 1292.

[0225] FIG. 16A shows a set-up for measurements of an optical transmitter (e.g. hybrid WDM transmitter) 1600. The optical transmitter 1600 includes an external/off-chip semiconductor optical amplifier (SOA) 1602, as a gain medium. The laser cavity is defined by an off-chip fiber loop 1604 and a plurality of on-chip reflectors, for example as represented by 1620, 1622 for two reflectors. Each of the reflectors, e.g. 1620, 1622, may be a tunable MZI loop mirror having a feedback loop with a MZI, which may be as described in the context of the reflector 252 of FIG. 2B. The optical transmitter 1600 may further include a multiplexer element, in the form of an 8-channel arrayed-waveguide grating (AWG) 1640. The AWG 1640 includes eight input waveguides, collectively represented by 1642, coupled to respective reflectors, e.g. 1620, 1622, and an output waveguide 1644 coupled, via a waveguide 1650, to the SOA 1602. A plurality of on-chip metal pads 1610 are provided for electrical communication with heaters for thermo-optical tuning of the reflectors, e.g. 1620, 1622.

[0226] FIG 16B shows plots of WDM spectra obtained based on the set-up of FIG. 16A, for an example where a 4-channel output is selectively chosen. FIG. 16B shows pairs of plots, for example plot 1660a for an "off" state and plot 1660b for an "on" state, plot 1662a for an "off" state and plot 1662b for an "on" state, plot 1664a for an "off" state and plot 1664b for an "on" state, and plot 1666a for an "off" state and plot 1666b for an "on" state, corresponding to respective channels. The WDM spectra as illustrated in FIG. 16B show relatively low intensity as a result of on-chip loss.

[0227] The results showns in the plots 1660b, 1662b, 1664b, 1666b show the lasing operation, illustrating the respective lasing wavelengths 1661, 1663, 1665, 1667. While indications for the WDM channels are not clearly shown in the plots 1660b, 1662b, 1664b, 1666b due to overlaps with the respective lasing wavelengths 1661, 1663, 1665, 1667, self-alignment between the WDM laser and the WDM MUX channels may be observed, where each of the lasing wavelengths 1661, 1663, 1665, 1667 may be aligned to the respective WDM channel.

[0228] It should be appreciated that while various embodiments of the optical light source and the optical transmitter have been described in the context of a gain medium being arranged on or above a waveguide (e.g. silicon (Si) waveguide), the gain medium may be arranged adjacent to the waveguide, at least substantially at or along the same plane as that of the waveguide. In other words, light from the waveguide may cross into the gain medium, for example the light may propagate axially or co-axially between the waveguide and the gain medium.

[0229] It should be appreciated that while various embodiments of the optical light source and the optical transmitter have been described in the context of silicon (Si) waveguides, various embodiments may be applicable also for other materials, including but not limited to silicon nitride (SiN), polymer, or SiO_2 which may be employed for planar lightwave circuit (PLC).

[0230] It should be appreciated that modifications to the optical light source of various embodiments may be carried out to improve performances. For example, optimisation of the device implantation scheme in order to reduce optical loss, and/or optimisation of the directional coupler, may be carried out. Modifications to the optical light source of various embodiments may also be carried out to provide hybrid integration of advanced light source, such as Q-switched laser, and mode-locked laser.

[0231] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. An optical light source comprising:

at least two reflectors arranged spaced apart from each other, the at least two reflectors defining an optical cavity therebetween, wherein at least one reflector of the at least two reflectors comprises an optical tuning element; and

an optical gain medium positioned in the optical cavity and in an optical path between the at least two reflectors;

wherein the optical tuning element is configured to allow tuning of light propagating in the optical cavity between the at least two reflectors and the optical gain medium in response to an applied voltage to the optical tuning element.

2. The optical light source according to claim 1, wherein the optical tuning element is controlled by a thermo-optical device or an electro-optic device.

3. The optical light source according to claim 1, wherein the optical tuning element comprises a reflectivity tuning element or a cavity resonance tuning element.

4. The optical light source according to claim 3, wherein the reflectivity tuning element comprises:

a feedback loop; and

a directional coupler or a Mach-Zehnder interferometer.

5. The optical light source according to claim 4, wherein the feedback loop comprises silicon, silicon nitride, or silicon oxide.

6. The optical light source according to claim 3, wherein the cavity resonance tuning element comprises a microresonator-coupled Y-splitter or a microresonator-coupled Mach-Zehnder interferometer.

7. The optical light source according to claim 1, wherein at least one reflector of the at least two reflectors is configured to allow light to exit from the optical light source.

8. The optical light source according to claim 1, further comprising:

a waveguide optically coupled between the at least two reflectors.

9. The optical light source according to claim 8, wherein the optical gain medium is positioned over the waveguide.

10. The optical light source according to claim 1, wherein the optical gain medium is configured to receive energy from an external source so as to provide an initial light to the at least two reflectors and to subsequently amplify a reflected light propagating there-between the at least two reflectors.

11. The optical light source according to claim 10, wherein the external source comprises a voltage supplier as current injection light source or external photons as optical pumping light source.

12. The optical light source according to claim 1, wherein the optical gain medium comprises a III-V bonding layer or a material configured to provide the gain.

13. The optical light source according to claim 1, wherein the optical gain medium comprises a multiple quantum well region.

14. An optical transmitter comprising:

a first reflector;

at least one second reflector arranged spaced apart from the first reflector, the first reflector and the at least one second reflector defining an optical cavity therebetween;

a multiplexer element arranged in the optical cavity, the multiplexer element comprising:

a first port; and

at least two second ports, wherein a respective second port of the at least two second ports is associated with a respective channel wavelength;

wherein the multiplexer element is configured to receive light on each of the at least two second ports and to provide light at the respective channel wavelength to the first port based on the respective received light, and wherein the multiplexer element is further configured to transmit the light at the respective channel wavelengths from the first port; and

at least two optical gain media positioned in the optical cavity, wherein a respective optical gain medium of the at least two optical gain media is in a respective optical path between the respective second port and the at least one second reflector, the respective optical gain medium configured to emit light to be received by the respective second port, the light comprising the respective channel wavelength,

wherein the at least one second reflector is configured to reflect light from the at least two optical gain media, and wherein the first reflector is configured to reflect at least a portion of the light at the respective channel wavelengths transmitted from the first port to the at least two optical gain media, so as to cause lasing in the optical cavity at the channel wavelengths.

15. The optical transmitter according to claim 14, comprising a plurality of second reflectors arranged spaced apart from the first reflector, wherein the respective optical gain medium is in a respective optical path between the respective second port and a respective second reflector of the plurality of second reflectors.

16. The optical transmitter according to claim 14, wherein at least one of the first reflector or the at least one second reflector comprises an optical tuning element, wherein the optical tuning element is configured to allow tuning of light propagating in the optical cavity in response to an applied voltage to the optical tuning element.

17. The optical transmitter according to claim 14, wherein the optical tuning element is controlled by a thermo-optical device or an electro-optic device.

18. The optical transmitter according to claim 16, wherein the optical tuning element comprises at least one of

a feedback loop; and a directional coupler or a Mach-Zehnder interferometer;

a microresonator-coupled Y-splitter; or

a microresonator-coupled Mach-Zehnder interferometer.

19. The optical transmitter according to claim 14, wherein the multiplexer element comprises at least one of

a microresonator-based multiplexer arrangement;

an arrayed waveguide grating (AWG); or

a concave grating.

20. The optical transmitter according to claim 19, wherein the microresonator-based multiplexer arrangement comprises at least one of

a plurality of microrings, wherein a respective microring of the plurality of microrings is optically coupled to the respective optical gain medium; or

a plurality of pairs of microrings, wherein a respective pair of microrings of the plurality of pairs of microrings is optically coupled to the respective optical gain medium.

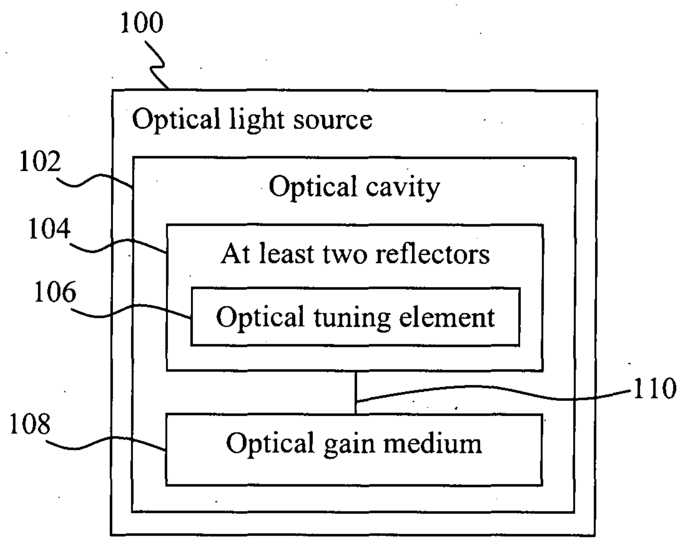

100
Optical light source
102
Optical cavity
104
At least two reflectors
106
Optical tuning element
110
108
Optical gain medium

FIG. 1A

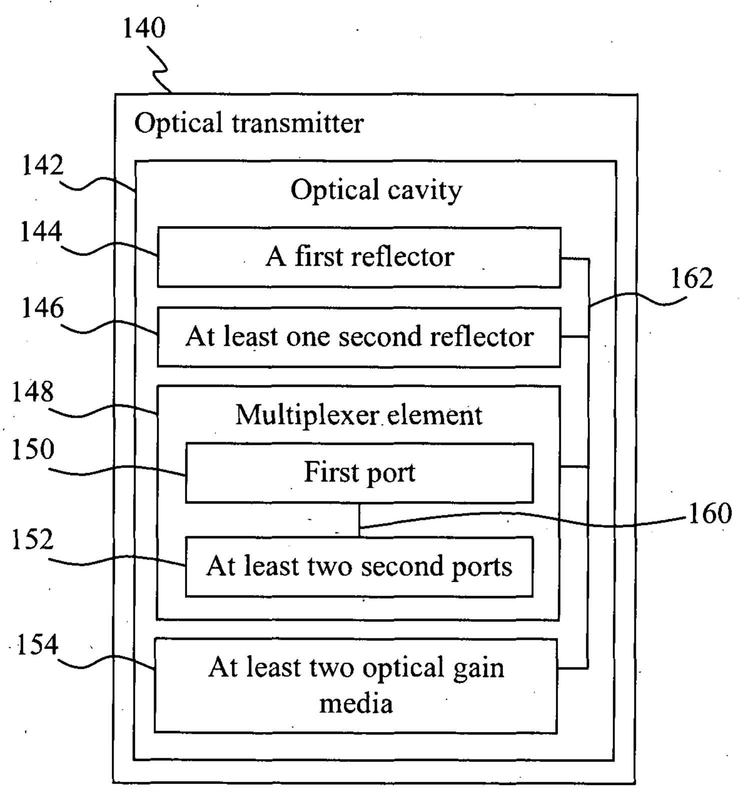

140
Optical transmitter
142
Optical cavity
144
A first reflector
162
146
At least one second reflector
148
Multiplexer element
150
First port
160
152
At least two second ports
154
At least two optical gain media

FIG. 1B

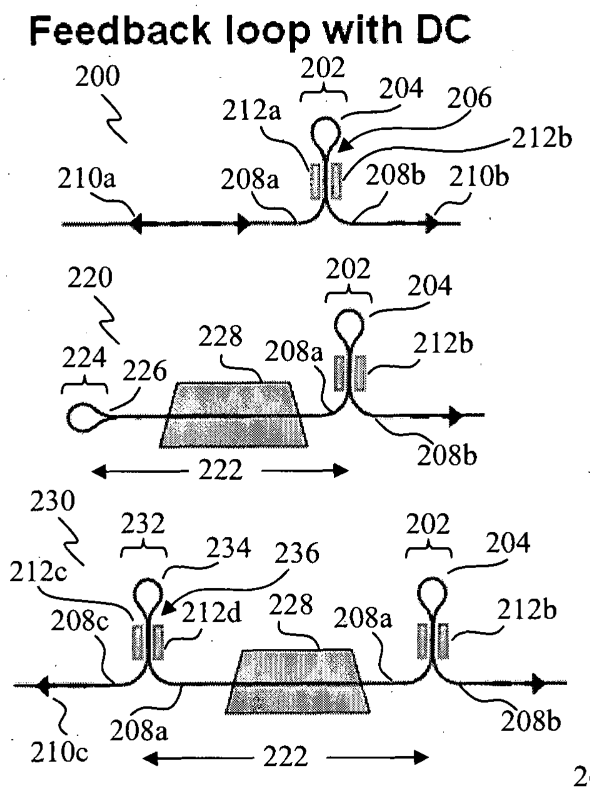


FIG. 2A

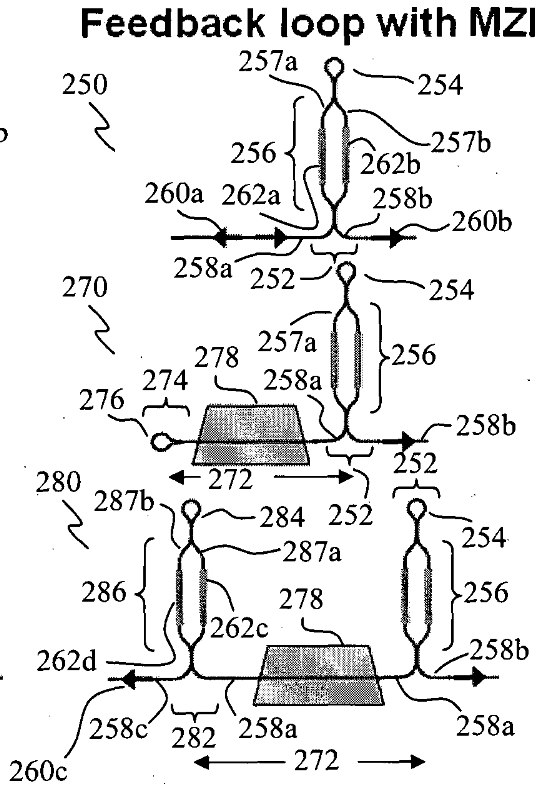


FIG. 2B

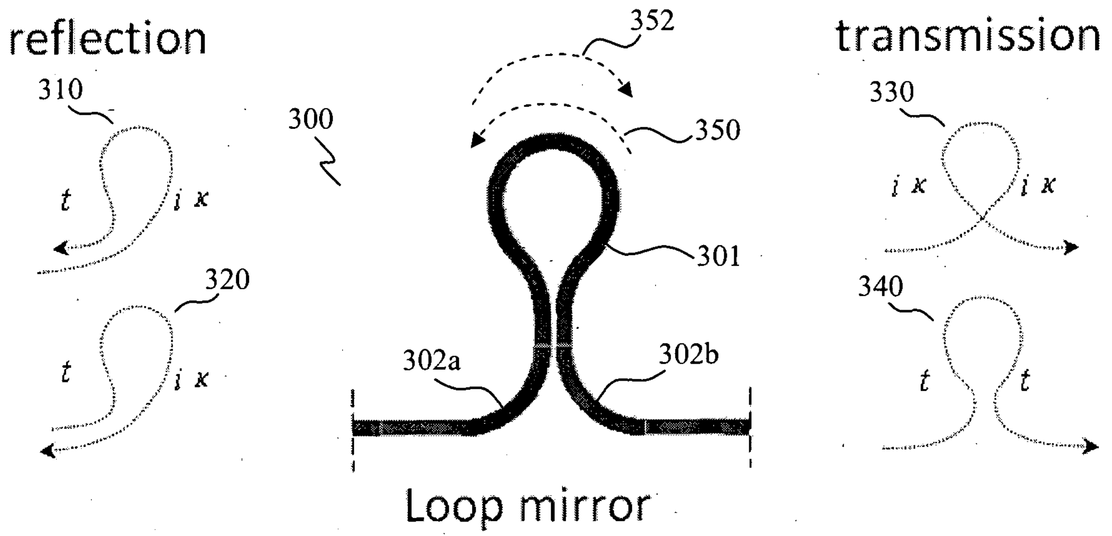


FIG. 3

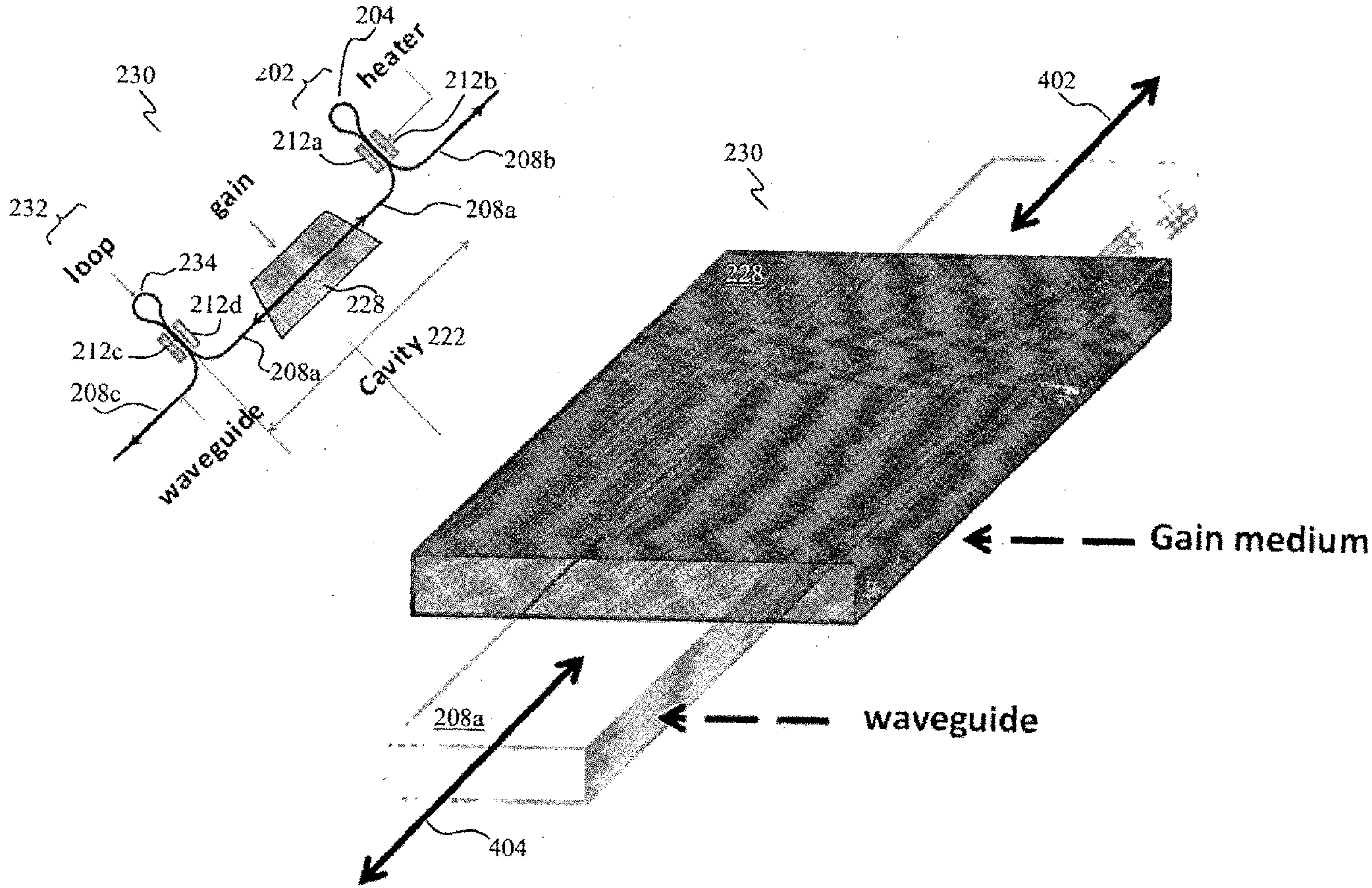

230
202
204
heater
212b
212a
208b
208a
gain
232
loop
234
212d
228
212c
Cavity 222
208a
208c
waveguide
402
230
228
Gain medium
208a
waveguide
404

FIG. 4

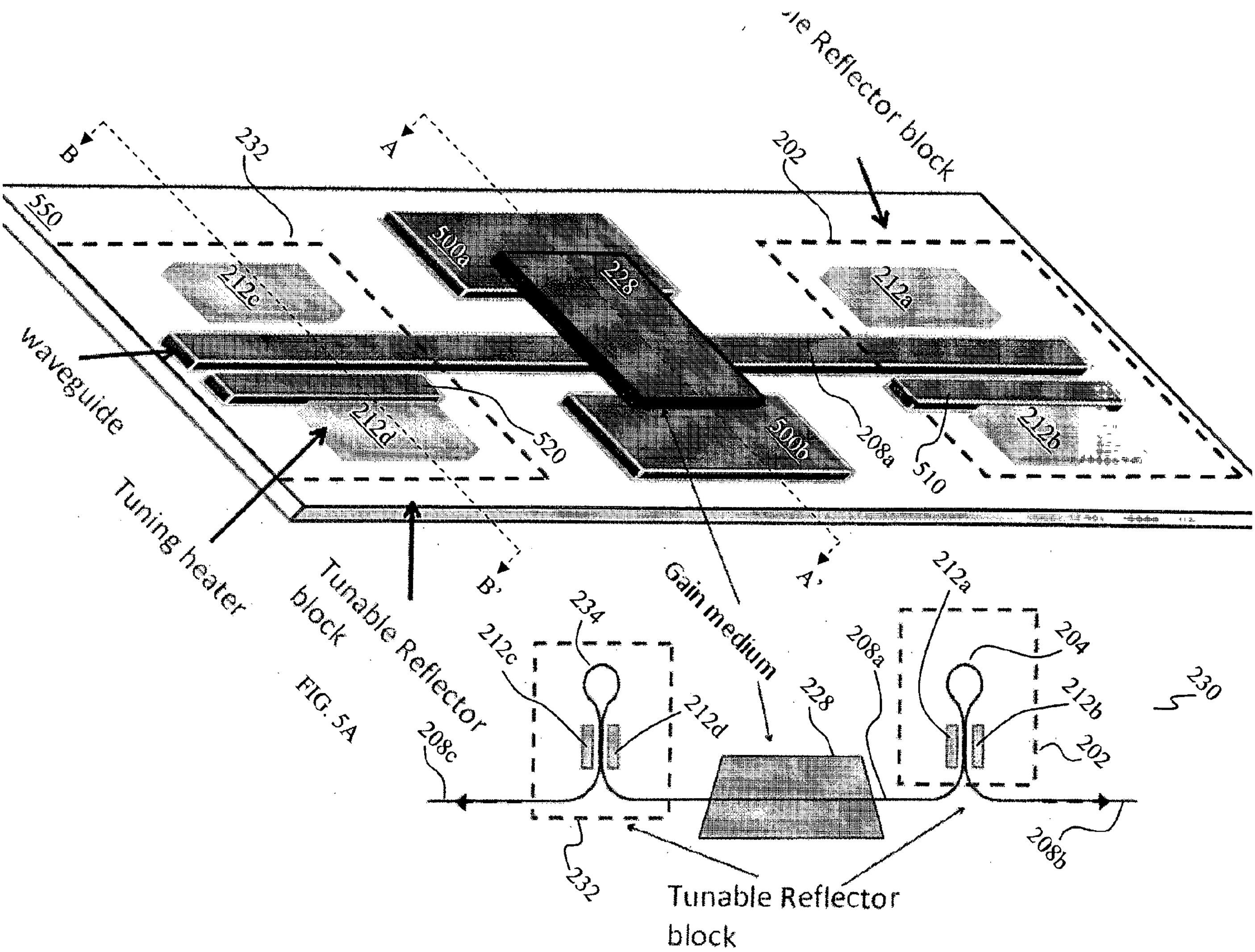

le Reflector block
B
232
A
202
550
500a
228
212c
212a
waveguide
212d
520
500b
208a
510
212b
Tuning heater
Tunable Reflector block
B'
Gain medium
A'
212a
234
212c
208a
204
230
212d
228
212b
202
208c
232
Tunable Reflector block
208b

FIG. 5A

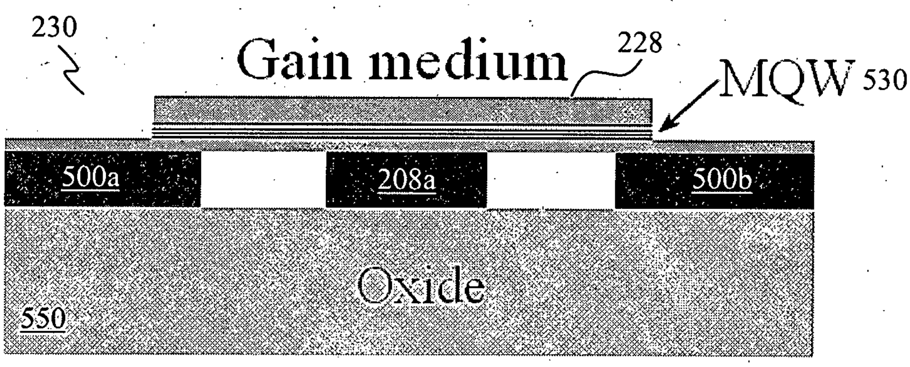


FIG. 5B

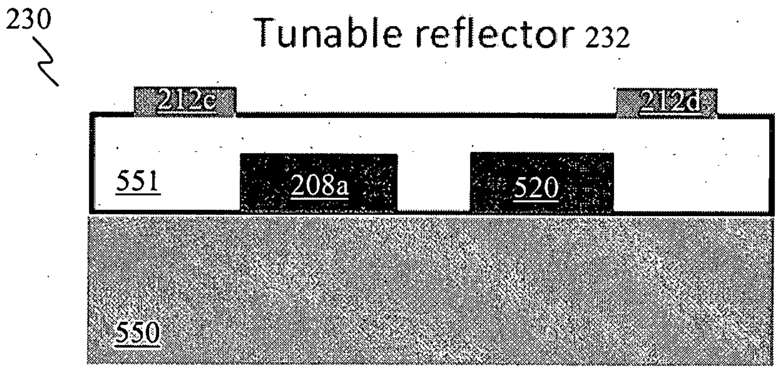


FIG. 5C

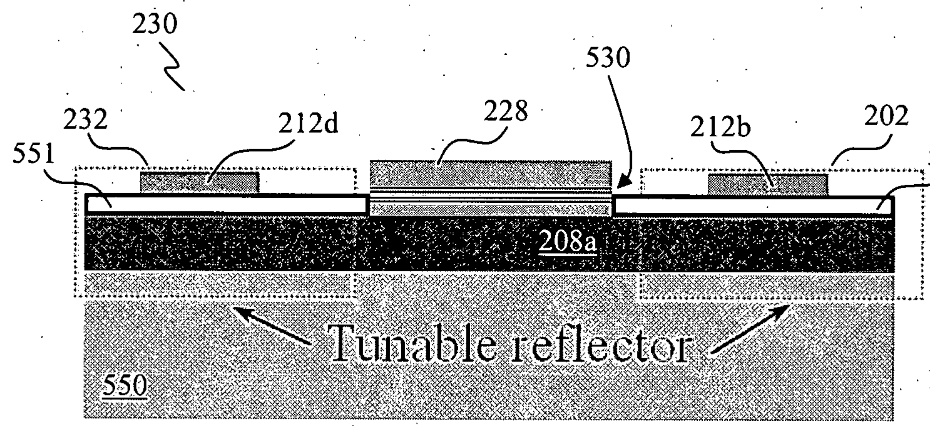
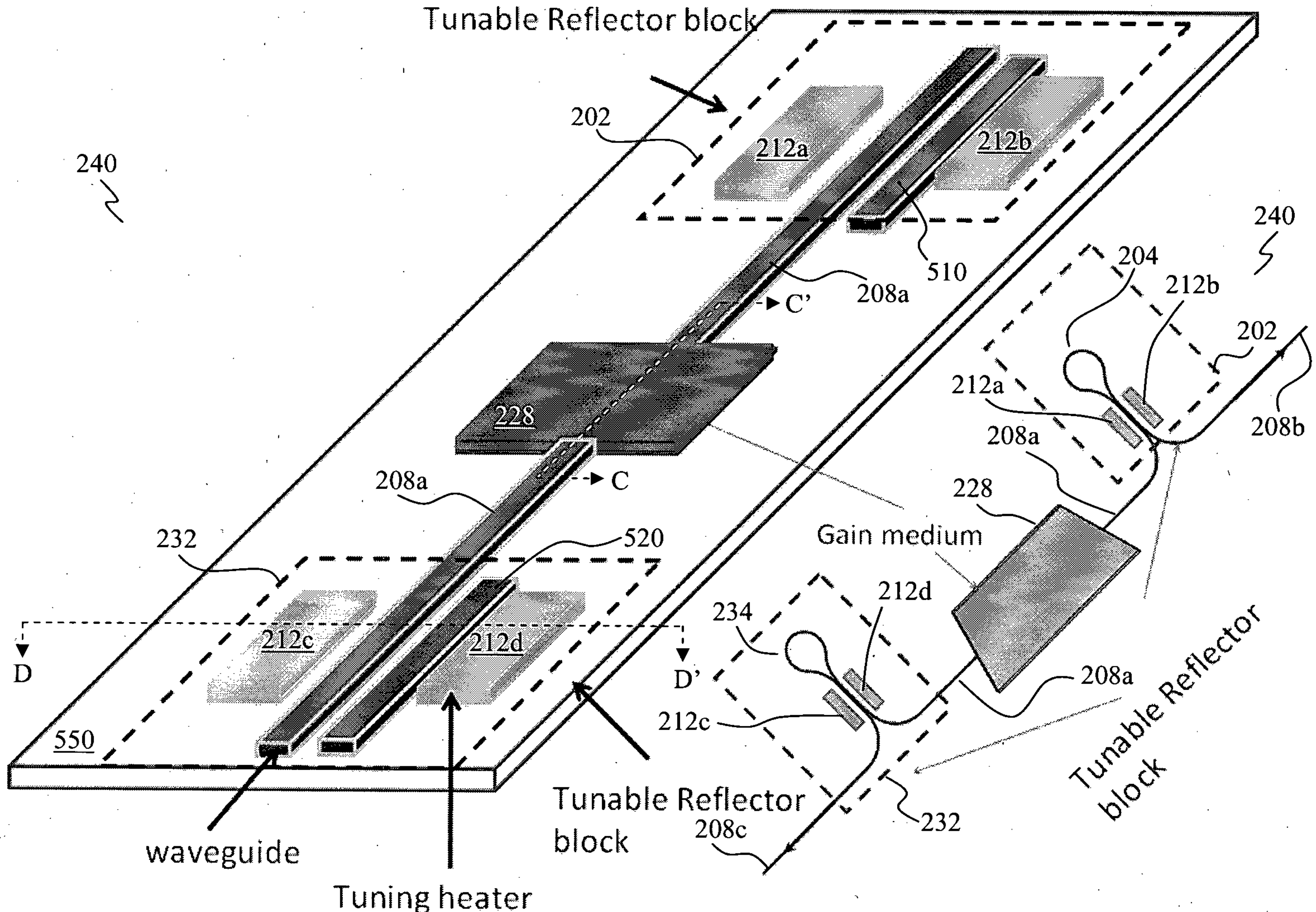


FIG. 5D



Tunable Reflector block
240
202
212a
212b
510
208a
C'
228
C
208a
520
232
212c
212d
D
D'
550
waveguide
Tuning heater
Tunable Reflector
block
240
204
212b
202
212a
208b
208a
228
Gain medium
212d
234
208a
212c
Tunable Reflector
block
232
208c

FIG. 5E

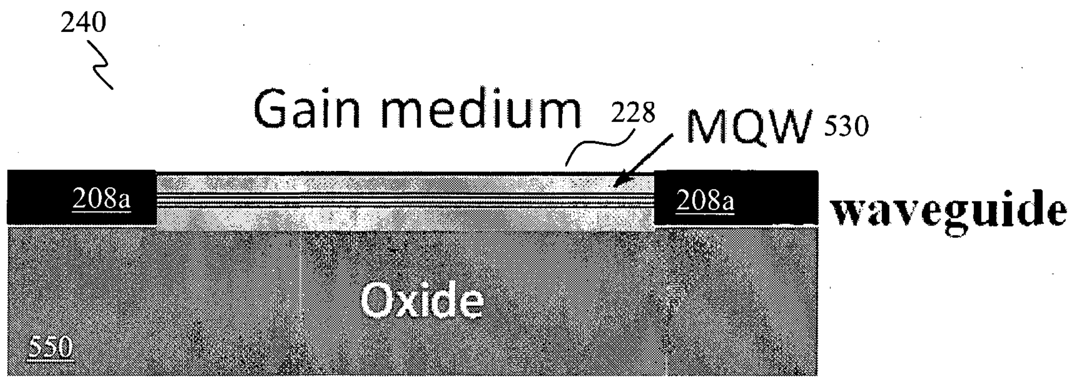

240
Gain medium
228
MQW
530
208a
208a
waveguide
Oxide
550

FIG. 5F

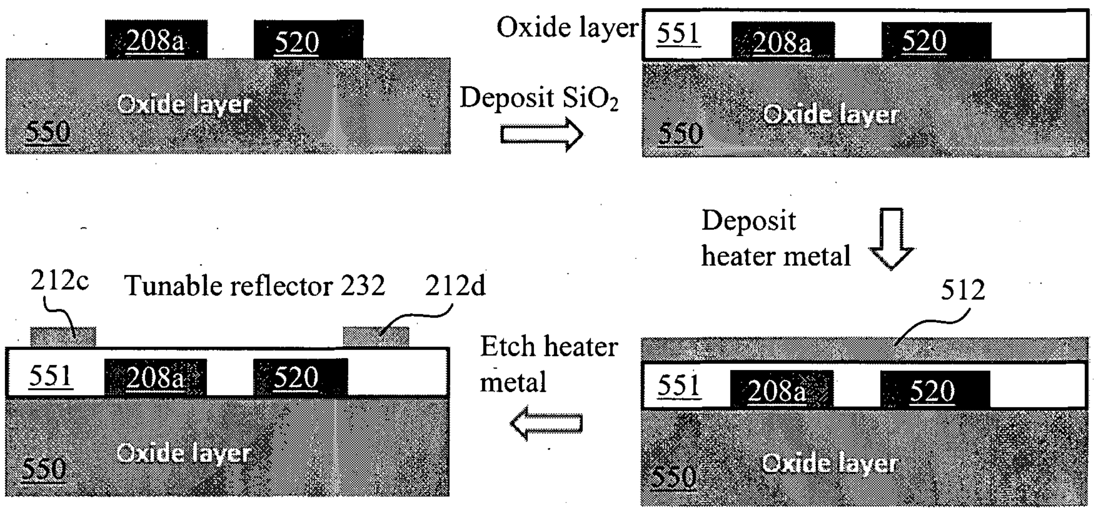

208a
520
Oxide layer
550
Oxide layer
551
208a
520
Deposit SiO2
550
Oxide layer
Deposit
heater metal
212c
Tunable reflector 232
212d
512
551
208a
520
Etch heater
metal
551
208a
520
550
Oxide layer
550
Oxide layer

FIG. 5G

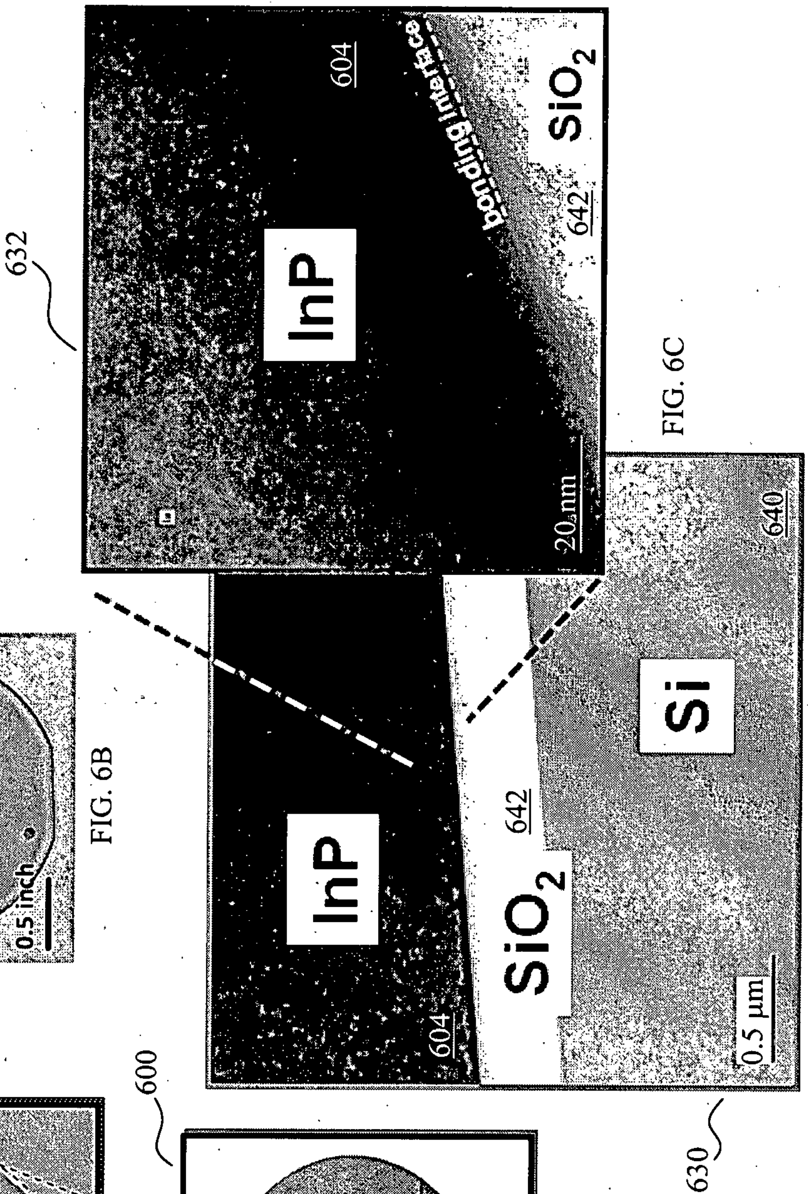


FIG. 6C

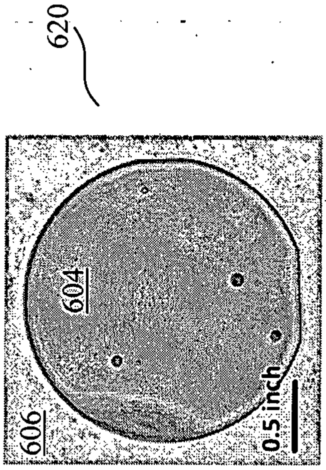


FIG. 6B

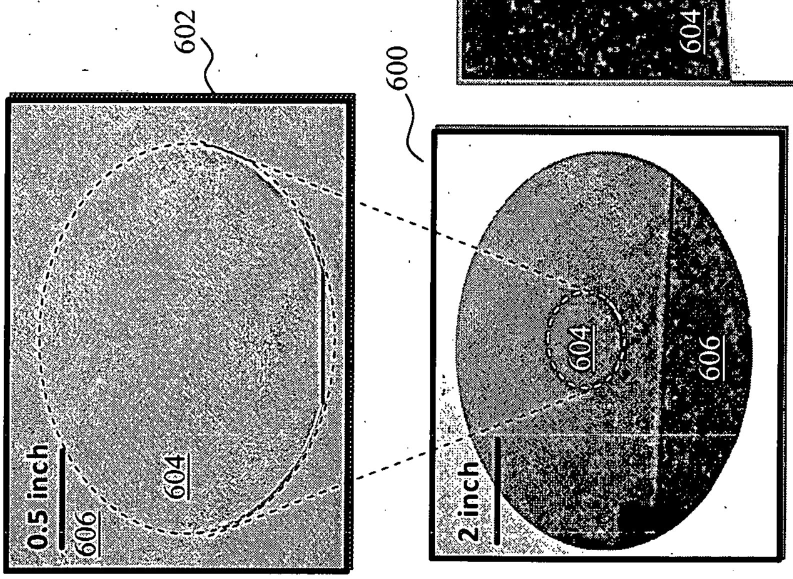


FIG. 6A

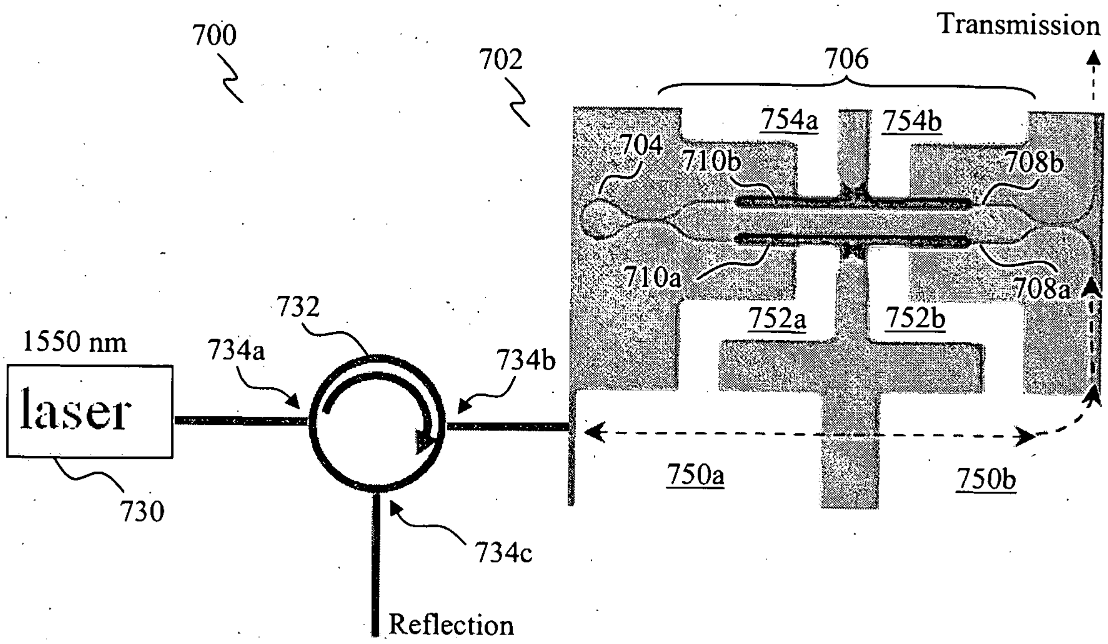

700
702
706
Transmission
754a
754b
704
710b
708b
710a
708a
752a
752b
732
1550 nm
734a
734b
laser
730
750a
750b
734c
Reflection

FIG. 7A

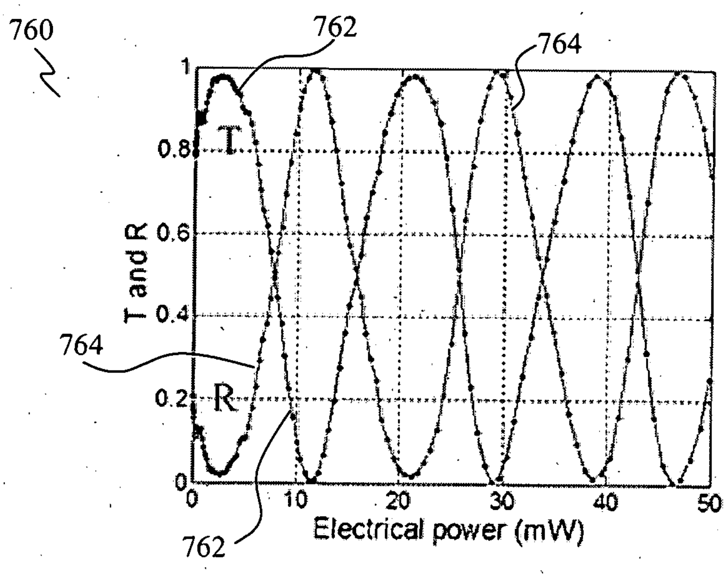

760
762
764
T
R
764
762
T and R
Electrical power (mW)
0
0.2
0.4
0.6
0.8
1
0
10
20
30
40
50

FIG. 7B

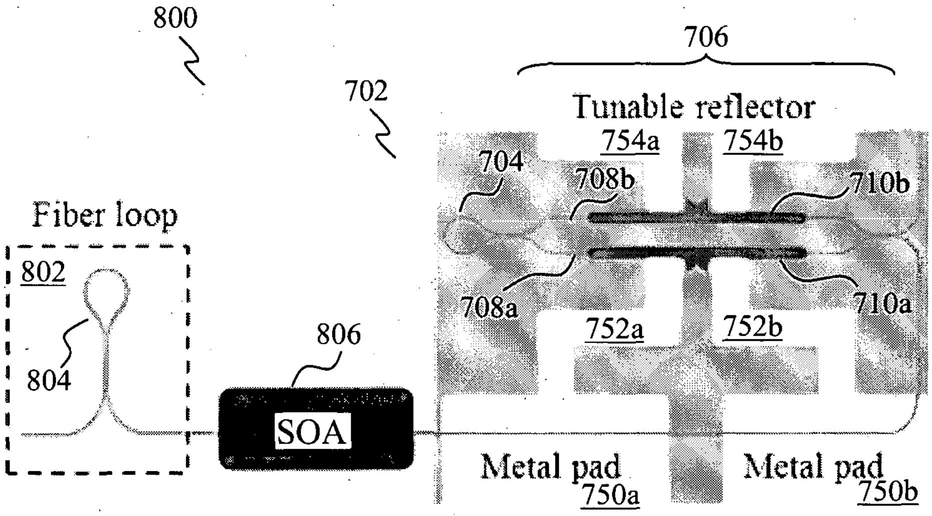


FIG. 8A

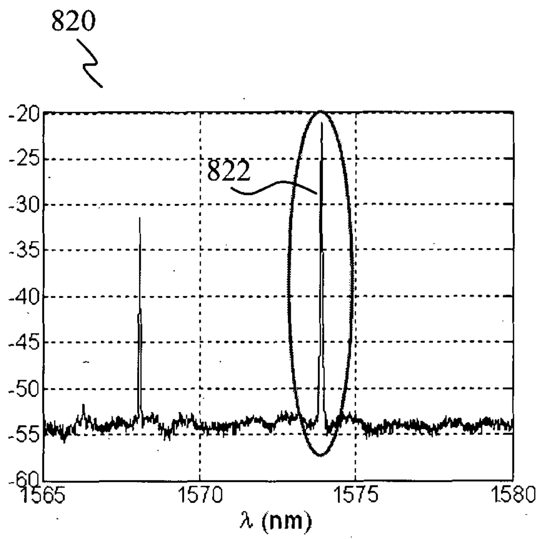


FIG. 8B

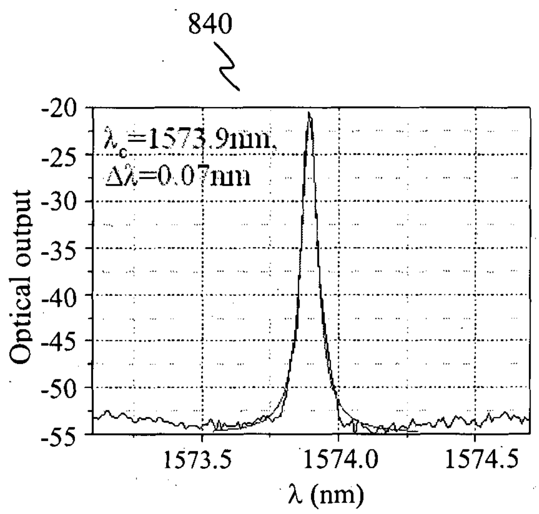


FIG. 8C

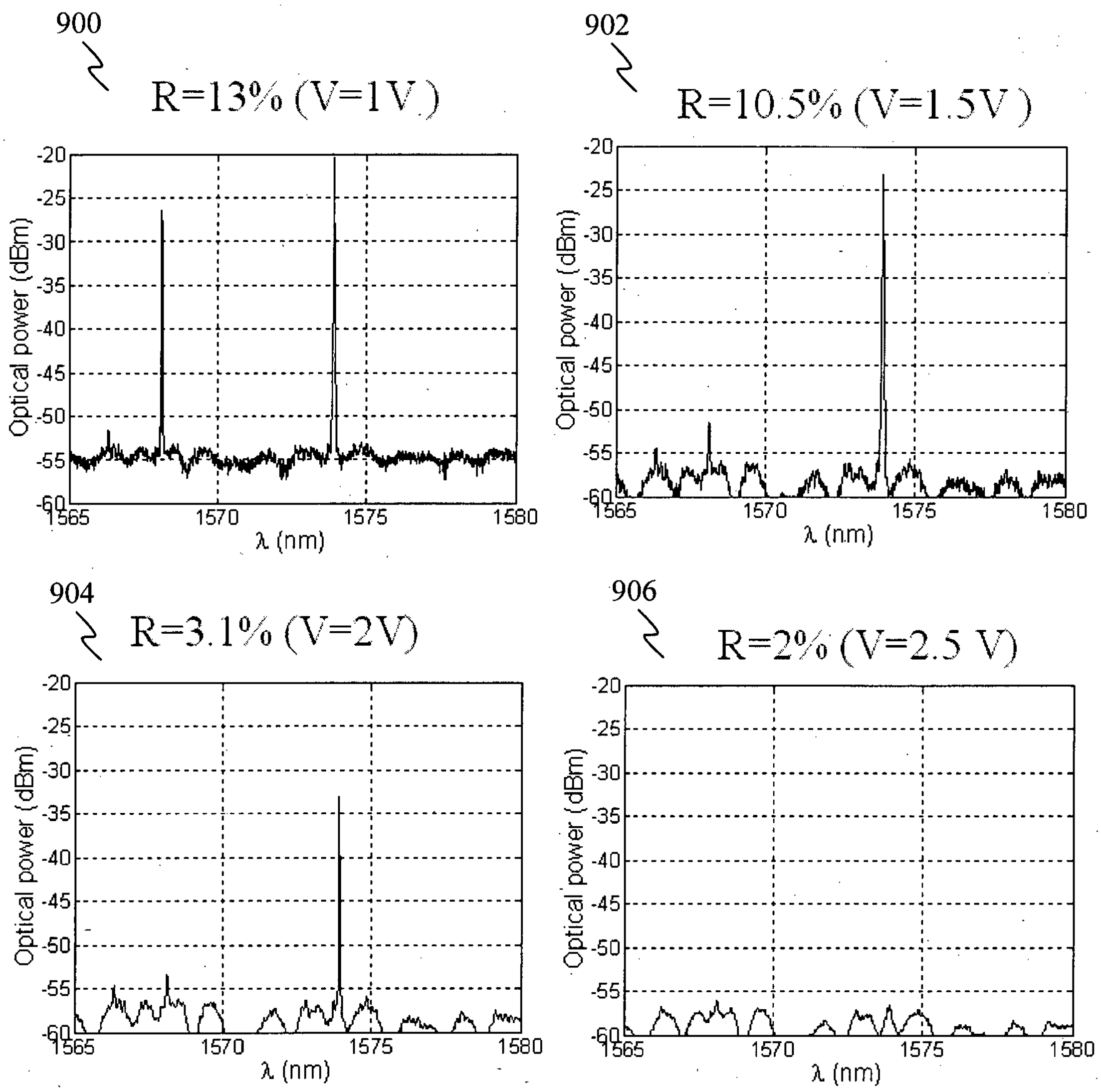

900
R=13% (V=1V)
902
R=10.5% (V=1.5V)
904
R=3.1% (V=2V)
906
R=2% (V=2.5 V)
Optical power (dBm)
λ (nm)
-20
-25
-30
-35
-40
-45
-50
-55
-60
1565
1570
1575
1580

FIG. 9

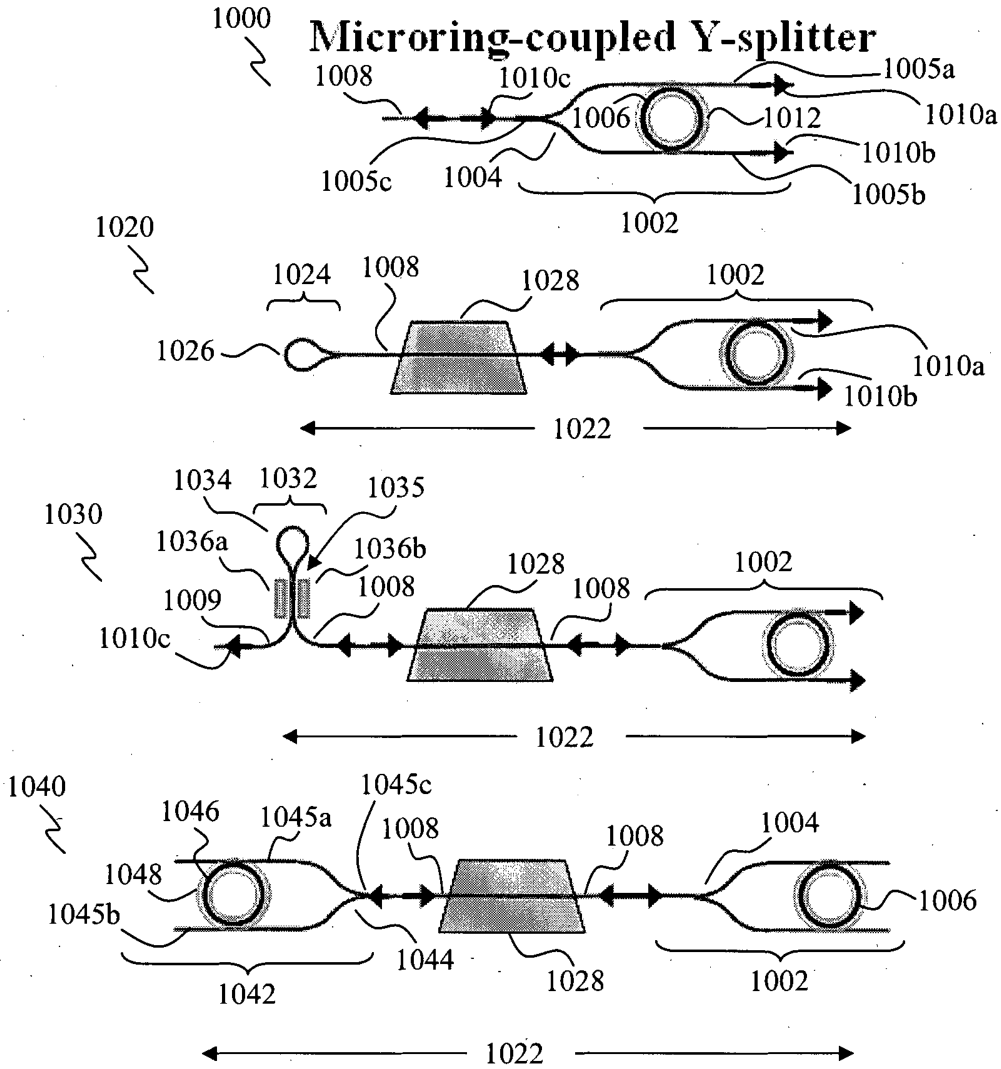
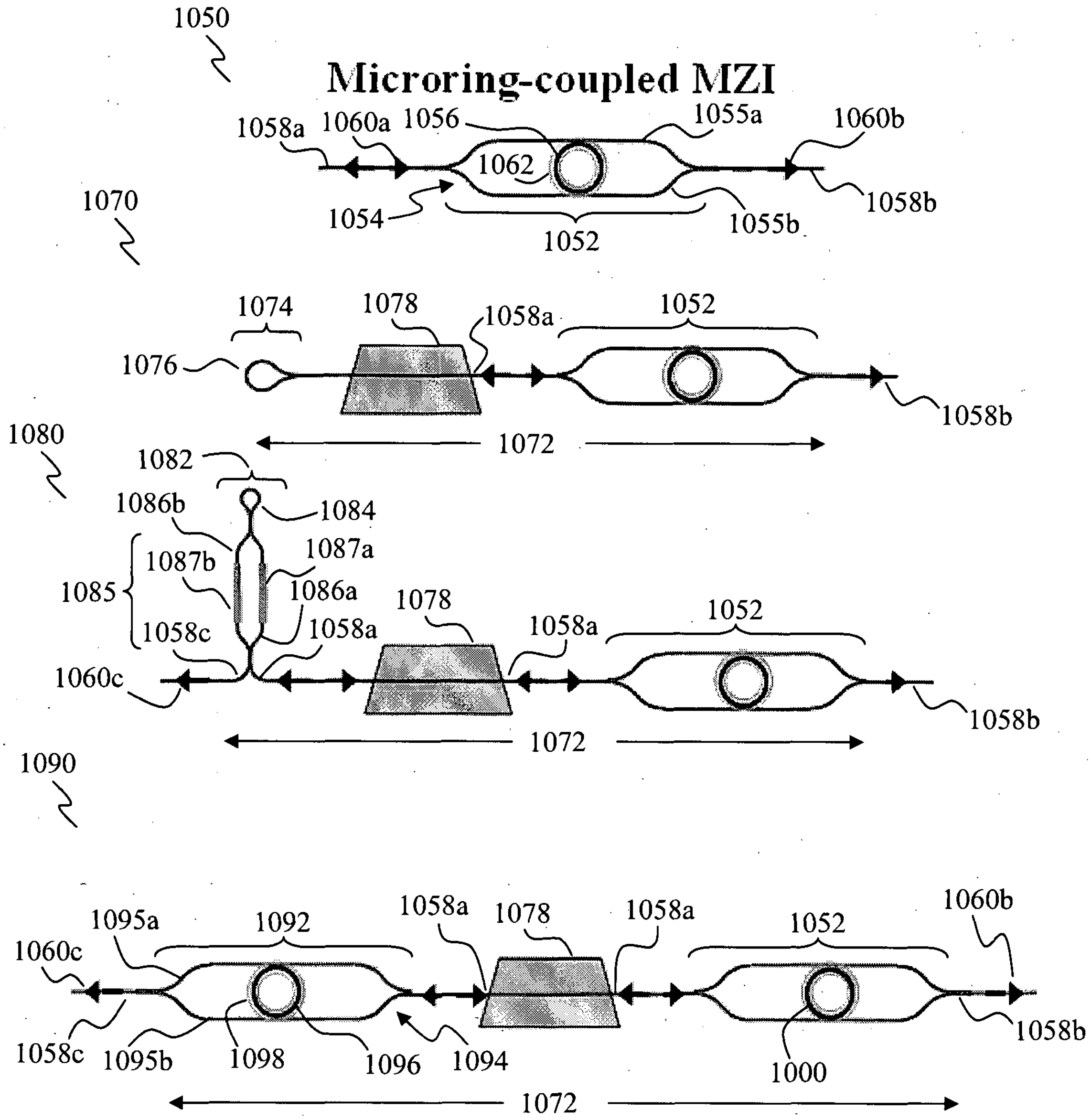

1000
Microring-coupled Y-splitter
1008
1010c
1005a
1006
1012
1010a
1010b
1005c
1004
1005b
1002
1020
1024
1008
1028
1002
1026
1010a
1010b
1022
1034
1032
1035
1030
1036a
1036b
1028
1002
1009
1008
1008
1010c
1022
1040
1045c
1046
1045a
1008
1008
1004
1048
1006
1045b
1044
1028
1002
1042
1022

FIG. 10A



1050
Microring-coupled MZI
1058a
1060a
1056
1055a
1060b
1062
1054
1052
1055b
1058b
1070
1074
1078
1058a
1052
1076
1058b
1072
1080
1082
1084
1086b
1087a
1087b
1085
1086a
1078
1058c
1058a
1058a
1052
1060c
1058b
1072
1090
1095a
1092
1058a
1078
1058a
1060b
1052
1060c
1058c
1095b
1098
1096
1094
1000
1058b
1072

FIG. 10B

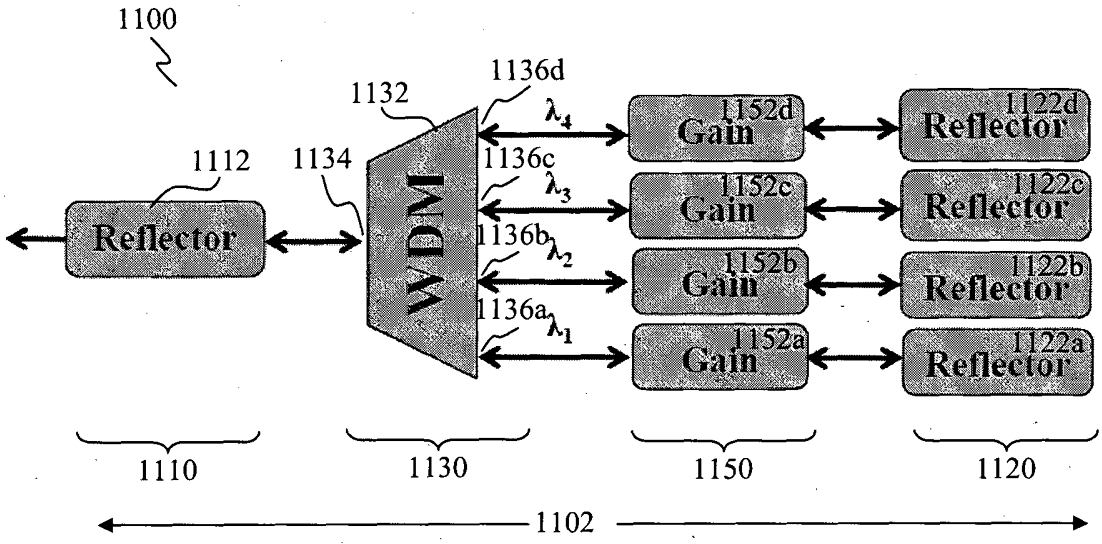

1100
1132
1136d
1112
1134
Reflector
WDM
λ4
1136c
λ3
1136b
λ2
1136a
λ1
Gain
1152d
1152c
1152b
1152a
Reflector
1122d
1122c
1122b
1122a
1110
1130
1150
1120
1102

FIG. 11

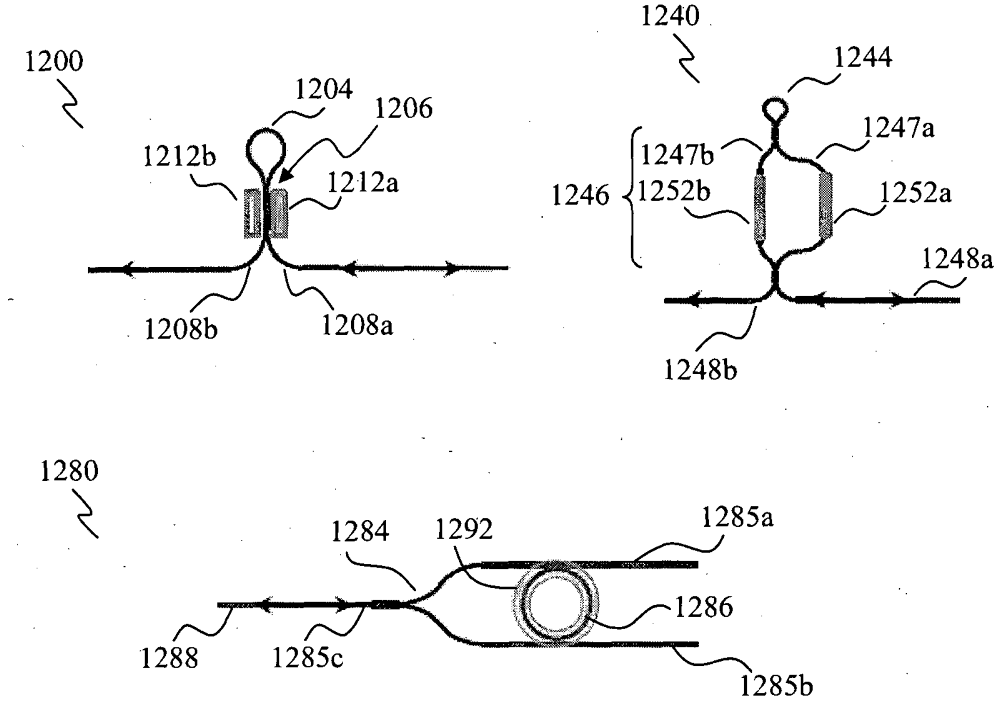

1200
1204
1206
1212b
1212a
1208b
1208a
1240
1244
1247a
1247b
1246
1252b
1252a
1248a
1248b
1280
1284
1292
1285a
1286
1288
1285c
1285b

FIG. 12

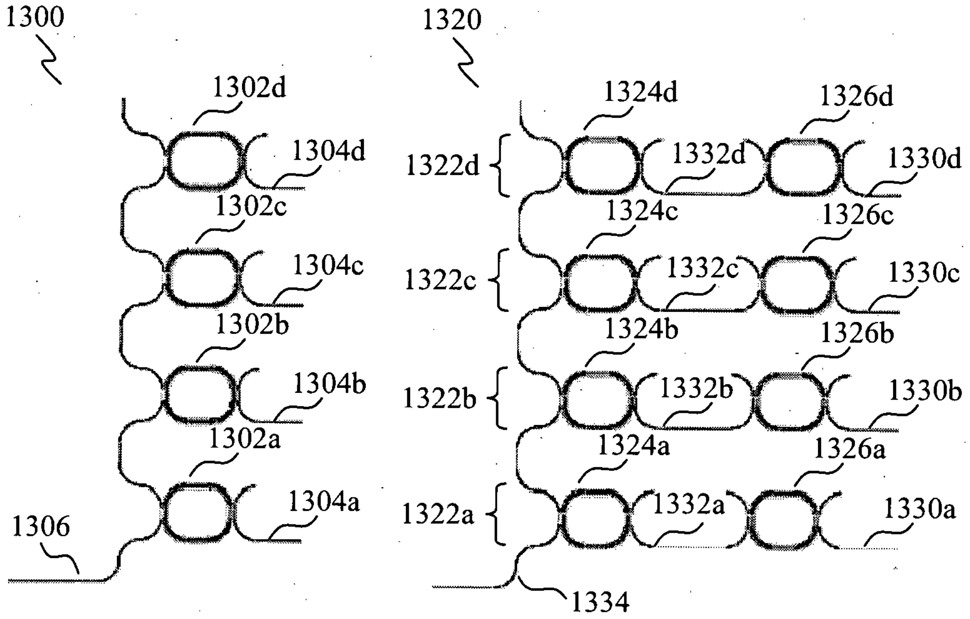


FIG. 13A

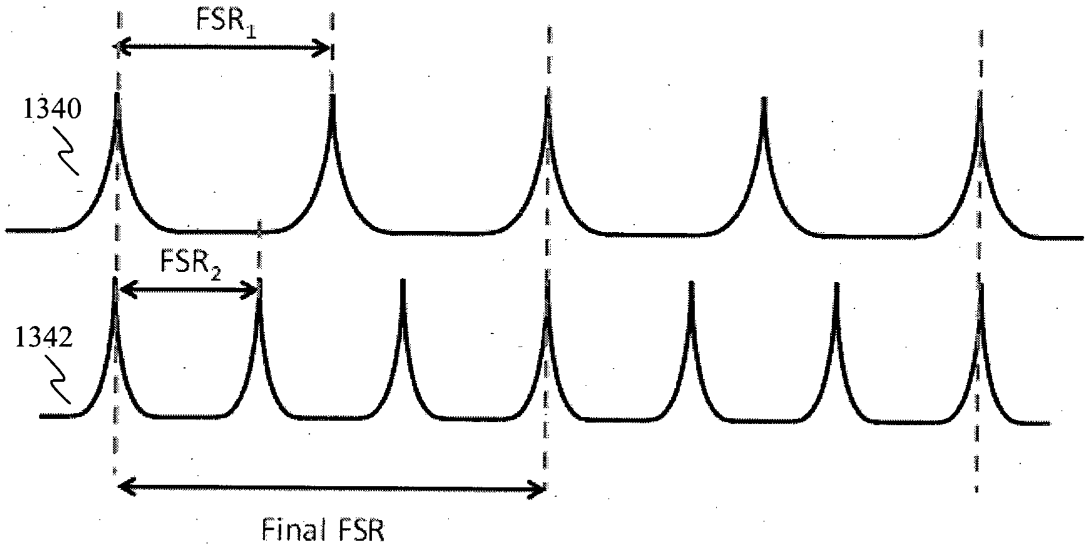


FIG. 13B

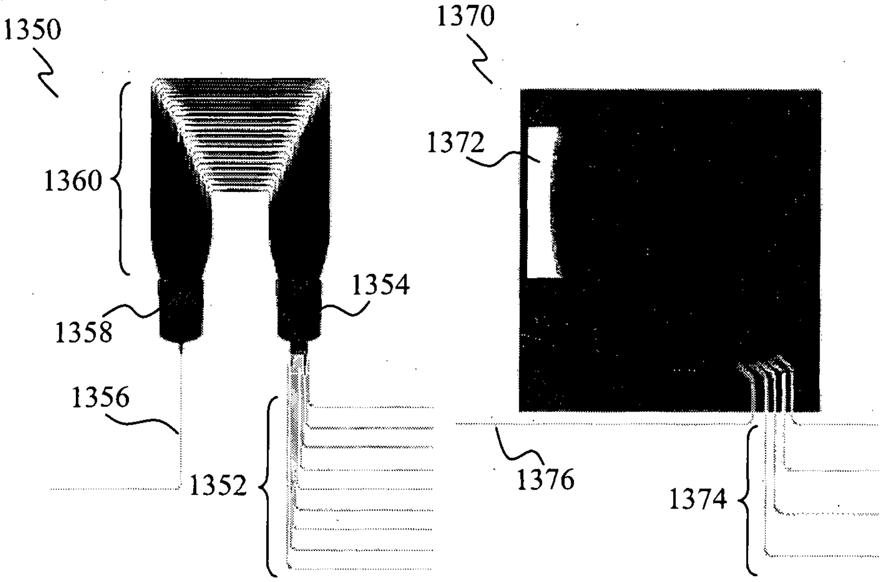


FIG. 13C

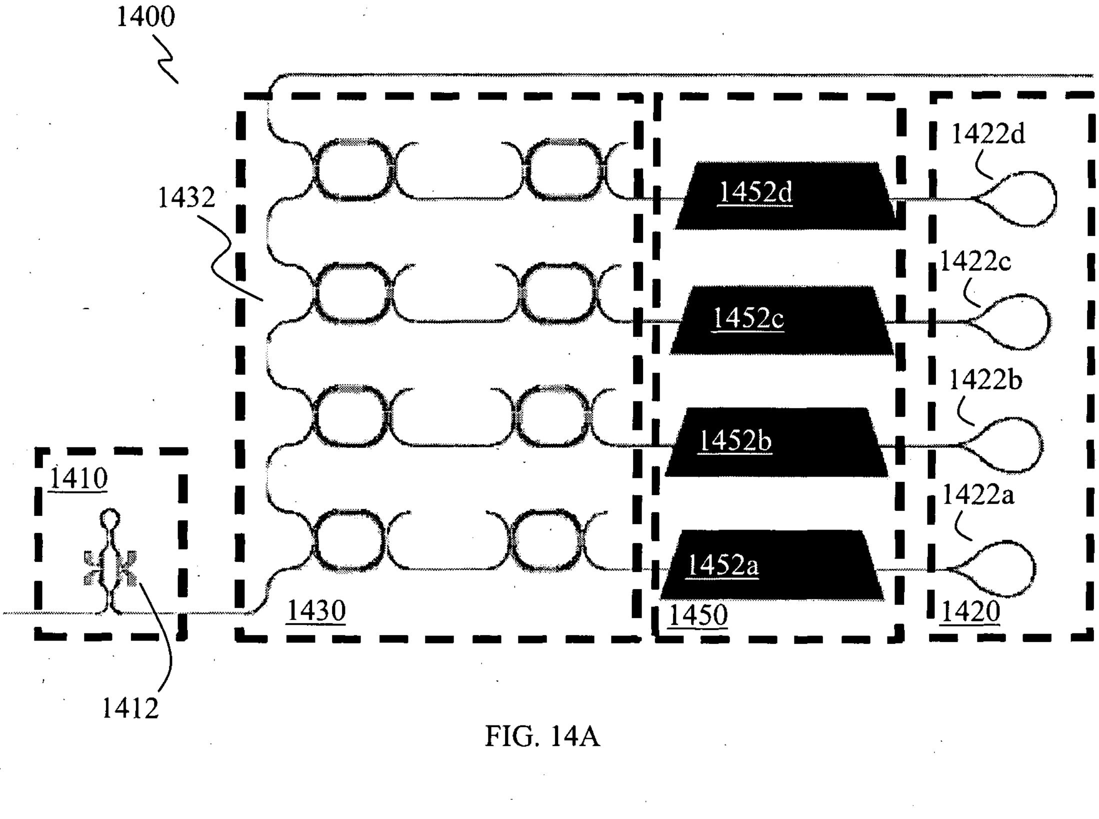


FIG. 14A

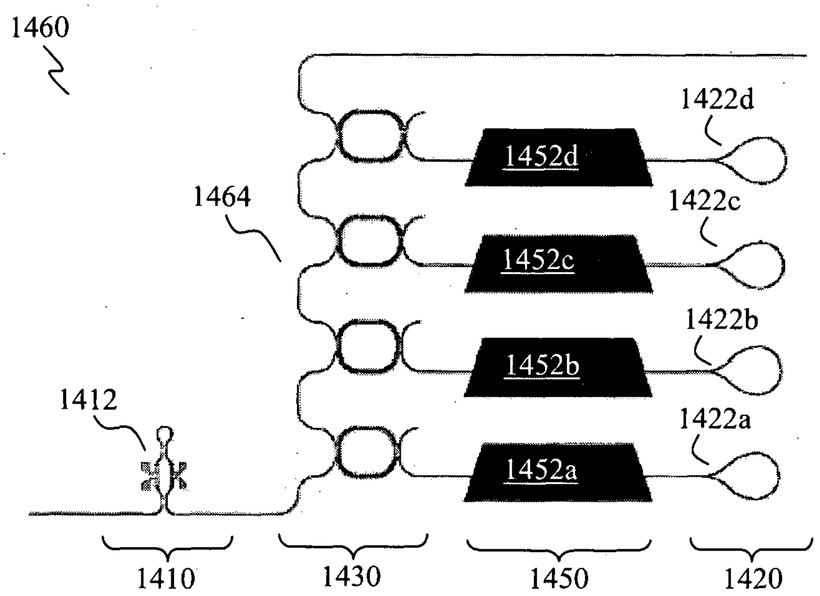


FIG. 14B

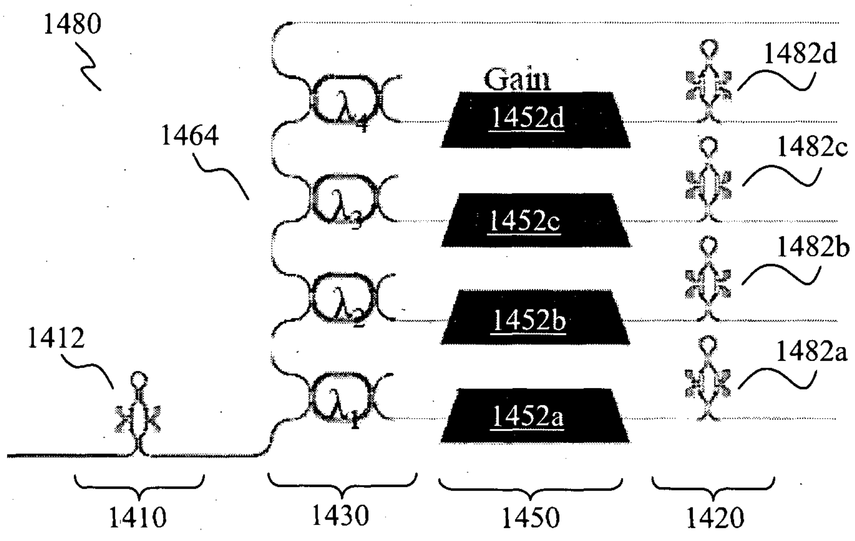


FIG. 14C

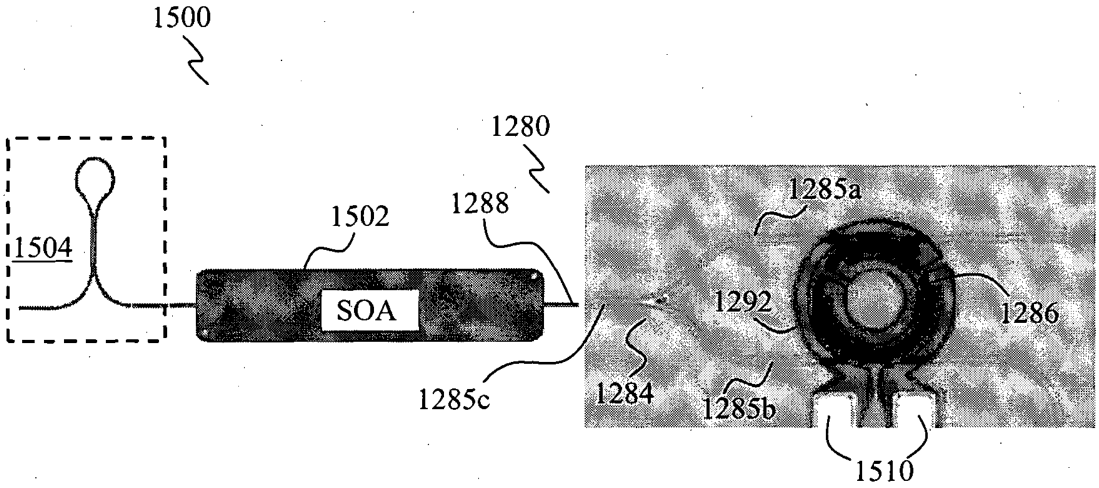


FIG. 15A

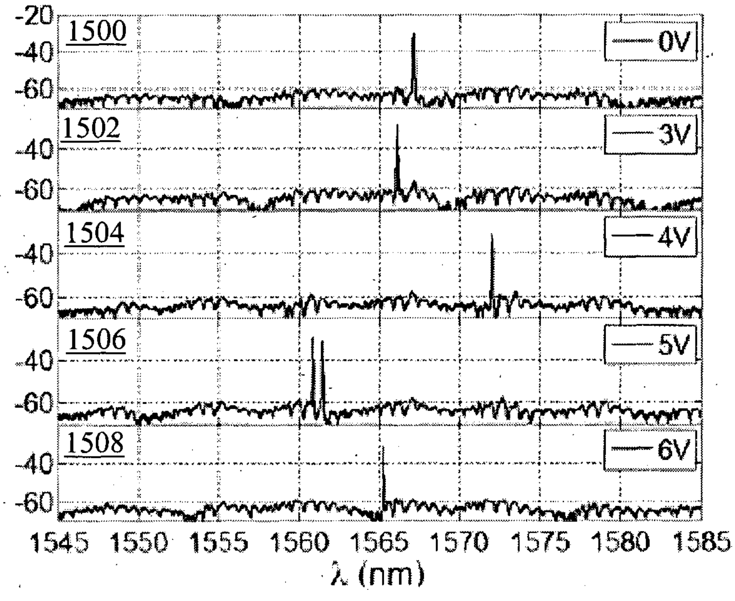


FIG. 15B

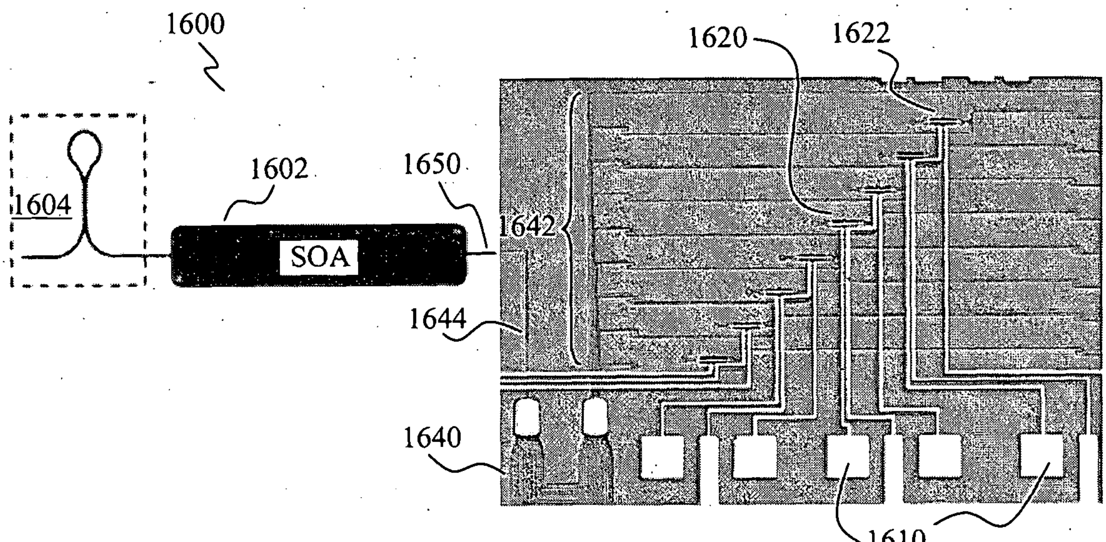


FIG. 16A

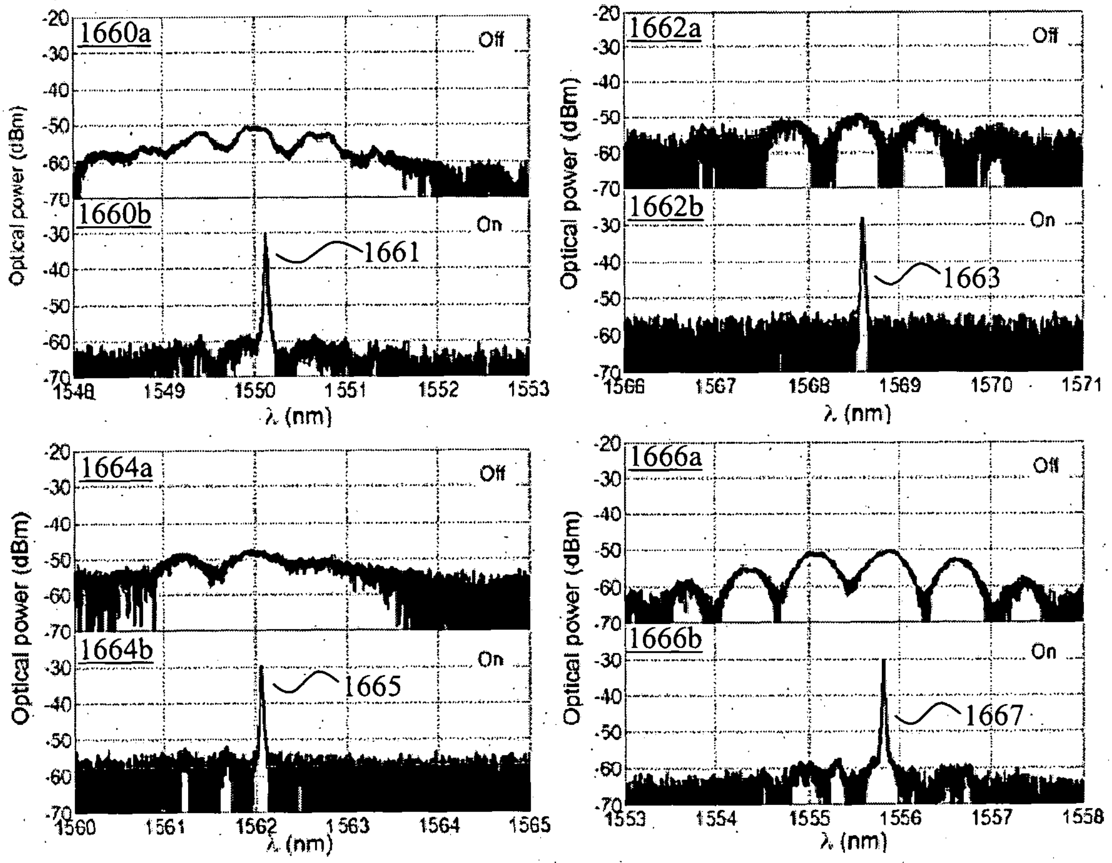


FIG. 16B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SG2013/000321

A. CLASSIFICATION OF SUBJECT MATTER

H01S 3/08 (2006.01) G02F 1/00 (2006.01)

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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

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

WPI & EPODOC - Keywords (optic, reflect, waveguide, cavity, gain medium, feedback, quantum, resonator, direct coupler) and like terms;

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	

[X] Further documents are listed in the continuation of Box C [X] See patent family annex

* Special categories of cited documents:

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

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 November 2013	27 November 2013

Name and mailing address of the ISA/AU	**Authorised officer**
AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA Email address: pct@ipaustralia.gov.au Facsimile No.: +61 2 6283 7999	Jae Cho AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No. 0262223668

INTERNATIONAL SEARCH REPORT

International application No. **PCT/SG2013/000321**

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2012/0105932 A1 (LEDENTSOV) 03 May 2012 Abstract, Figs 3, 7, 10-14, paragraphs [0005]-[0009], [0017], [0032]-[0033], [0040], [0049]-[0060], [0062]-[0071]	1-13
A	US 2005/0163184 A1 (HILLIARD) 28 July 2005	
A	US 6366596 B1 (YIN et al.) 02 April 2002	
A	US 6141359 A (CUNNINGHAM et al.) 31 October 2000	
A	US 5392308 A (WELCH et al.) 21 February 1995	

INTERNATIONAL SEARCH REPORT Information on patent family members	International application No. **PCT/SG2013/000321**

This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	**Publication Date**	**Publication Number**	**Publication Date**
US 2012/0105932 A1	03 May 2012	US 8576472 B2	05 Nov 2013
US 2005/0163184 A1	28 Jul 2005	US 2005163184 A1	28 Jul 2005
		US 7408969 B2	05 Aug 2008
		US 2008267244 A1	30 Oct 2008
		US 7907655 B2	15 Mar 2011
		US 2011164631 A1	07 Jul 2011
		WO 2006045111 A2	27 Apr 2006
US 6366596 B1	02 Apr 2002	US 2002080841 A1	27 Jun 2002
		US 6584134 B2	24 Jun 2003
US 6141359 A	31 Oct 2000	None	
US 5392308 A	21 Feb 1995	US 5499261 A	12 Mar 1996
		US 5537432 A	16 Jul 1996
		US 5592503 A	07 Jan 1997
		US 5602864 A	11 Feb 1997
		US 5651018 A	22 Jul 1997
		US 5696779 A	09 Dec 1997
		US 5703897 A	30 Dec 1997
		US 5864574 A	26 Jan 1999
		US 5894492 A	13 Apr 1999
		US 5914978 A	22 Jun 1999

End of Annex

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.