



US009136672B2

(12) **United States Patent**  
**Luo et al.**

(10) **Patent No.:** **US 9,136,672 B2**  
(45) **Date of Patent:** **Sep. 15, 2015**

(54) **OPTICAL LIGHT SOURCE**

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(\* ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/090,543**

(22) Filed: **Nov. 26, 2013**

(65) **Prior Publication Data**  
US 2014/0153600 A1 Jun. 5, 2014

(30) **Foreign Application Priority Data**  
Nov. 29, 2012 (SG) ..... 201208824

(51) **Int. Cl.**  
**H01S 5/00** (2006.01)  
**H01S 5/10** (2006.01)  
**H01S 5/02** (2006.01)  
**B82Y 20/00** (2011.01)  
**H01S 5/343** (2006.01)  
**H01S 5/065** (2006.01)  
**H01S 5/125** (2006.01)

(52) **U.S. Cl.**  
CPC ..... **H01S 5/1032** (2013.01); **B82Y 20/00** (2013.01); **H01S 5/021** (2013.01); **H01S 5/0657** (2013.01); **H01S 5/1014** (2013.01); **H01S 5/125** (2013.01); **H01S 5/343** (2013.01)

(58) **Field of Classification Search**  
CPC ..... H01S 5/026; H01S 5/141; H01S 5/34; H01S 5/021; H01S 5/1032; H01S 5/0064; H01S 5/1096; H01S 5/125; H01S 5/18361  
USPC ..... 372/40, 43.01, 44.01, 45.012, 45.013, 372/18  
See application file for complete search history.

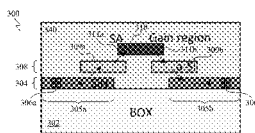
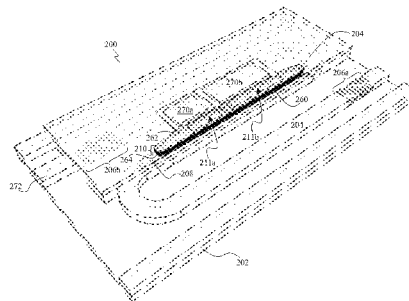
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(57) **ABSTRACT**  
An optical light source is provided. The optical light source includes a waveguide including two reflectors arranged spaced apart from each other to define an optical cavity therebetween, an optical gain medium, and a coupling structure arranged to couple light between the optical cavity and the optical gain medium.

**18 Claims, 5 Drawing Sheets**



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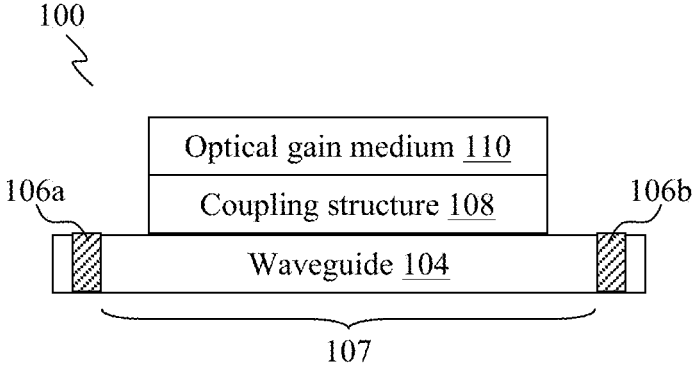


FIG. 1A

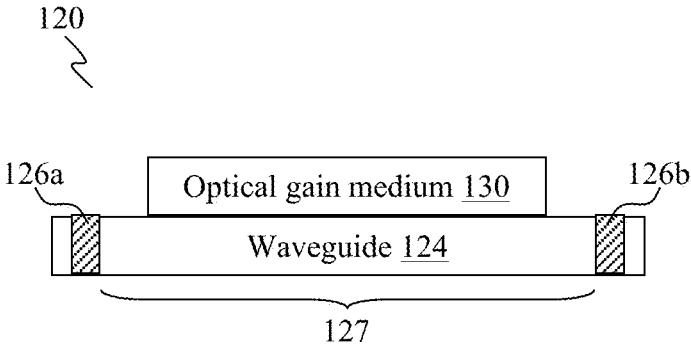
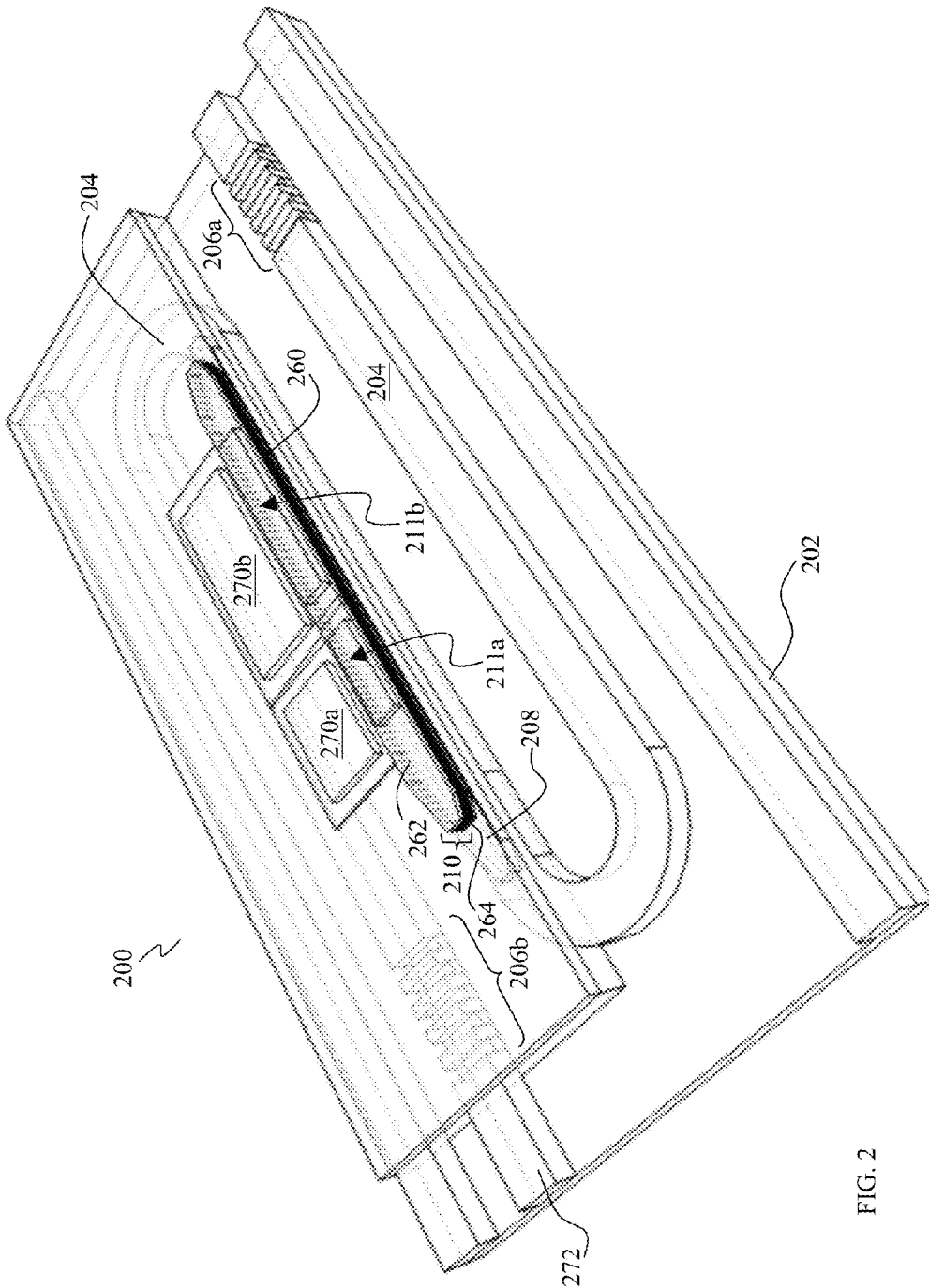


FIG. 1B



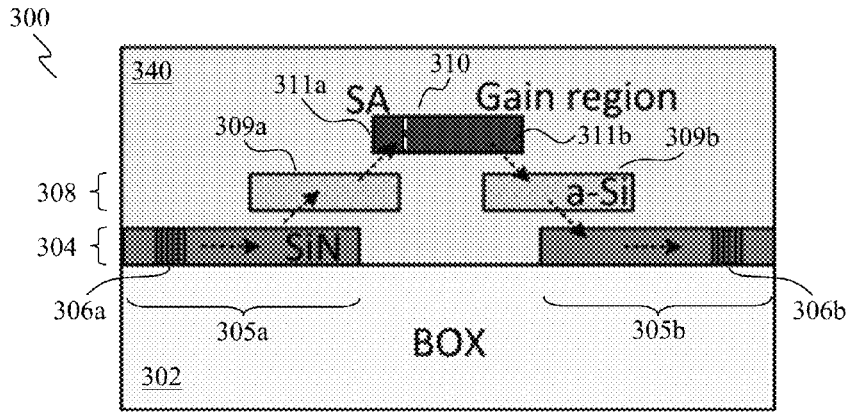


FIG. 3A

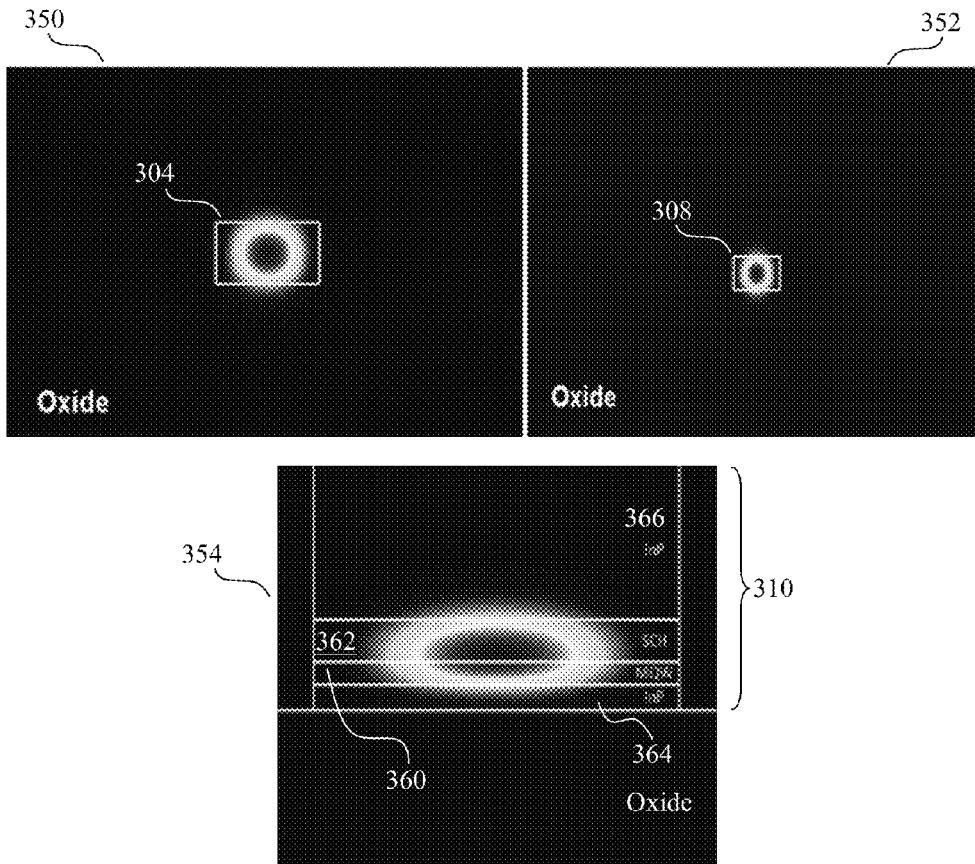


FIG. 3B

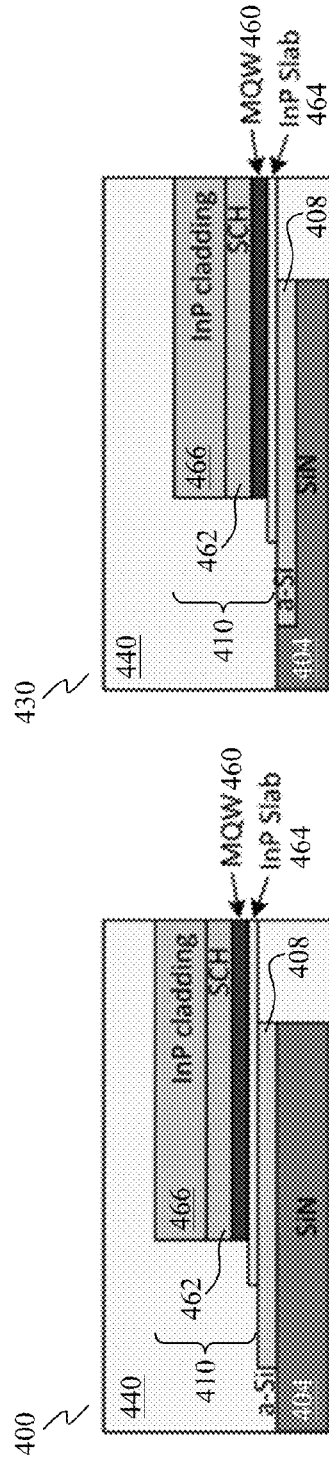
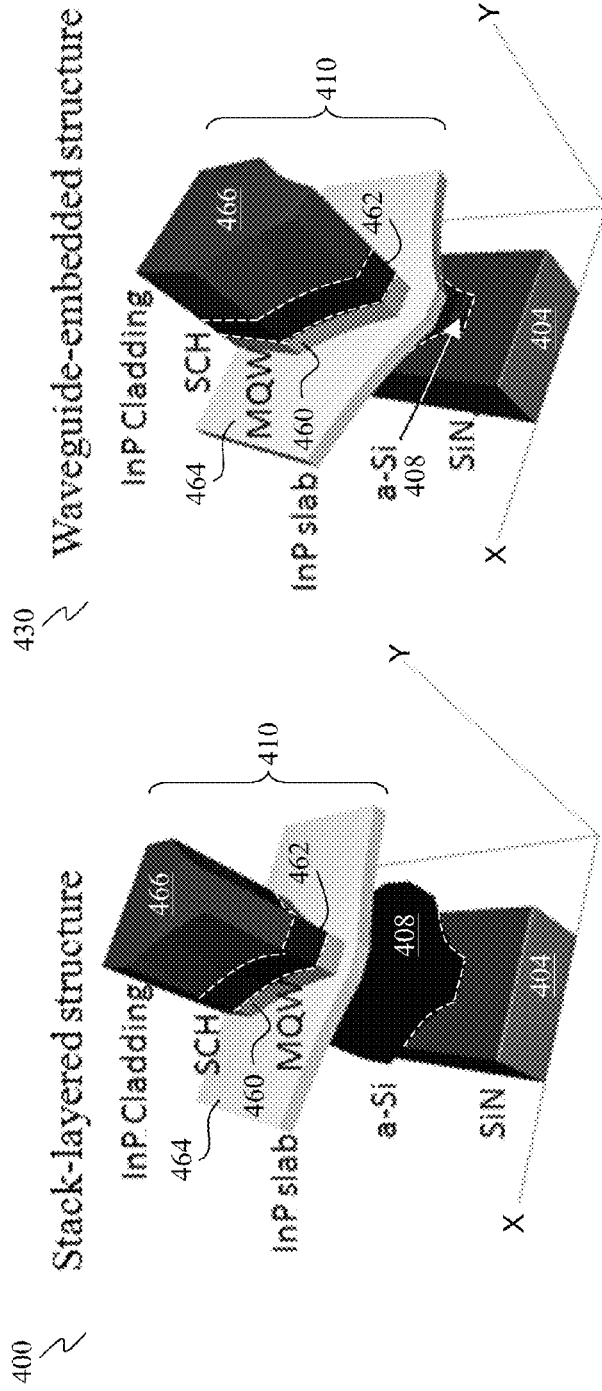
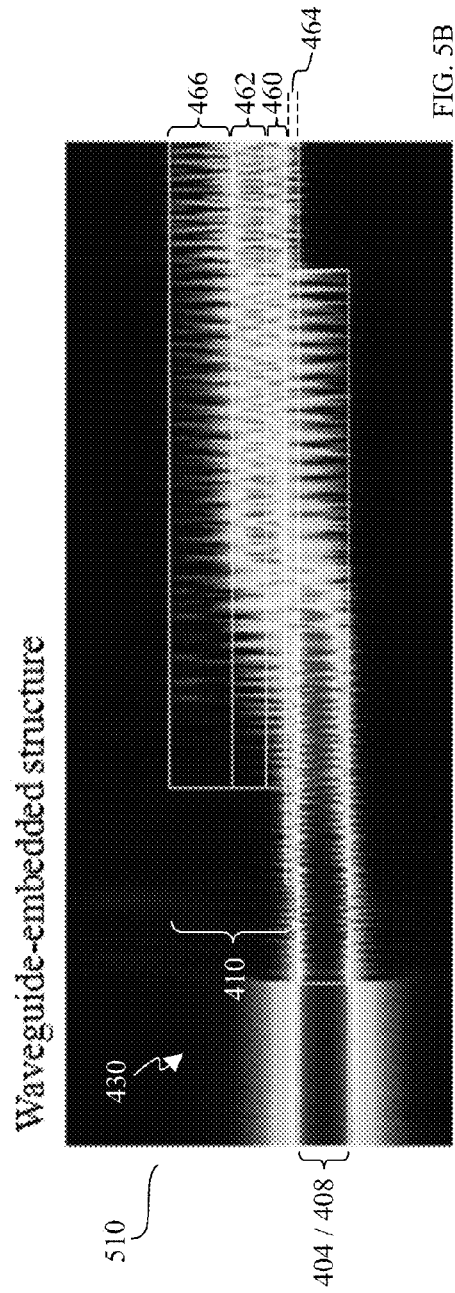
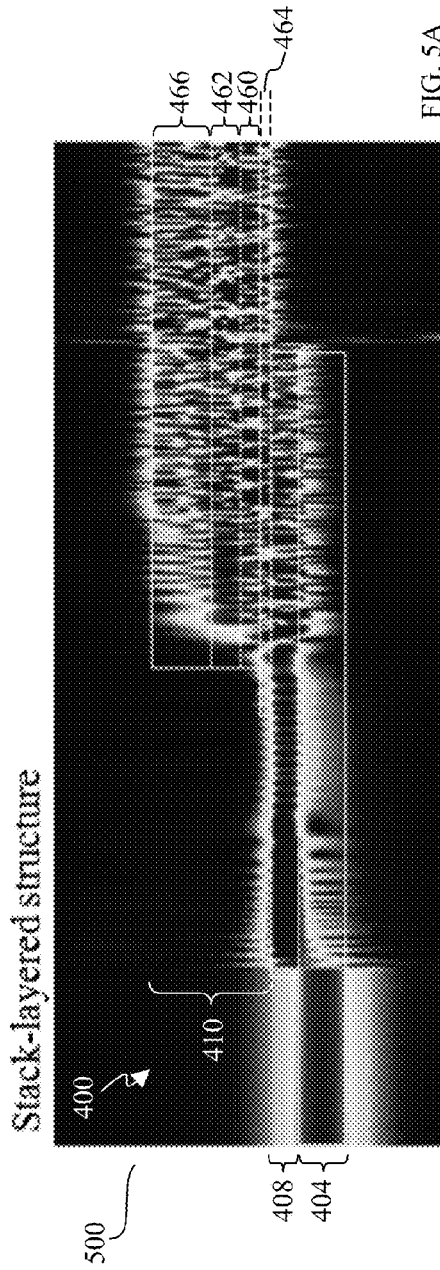


FIG. 4A

FIG. 4B



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**OPTICAL LIGHT SOURCE****CROSS-REFERENCE TO RELATED APPLICATION**

This application claims the benefit of priority of Singapore patent application No. 201208824-1, filed Nov. 29, 2012, the contents of which are incorporated herein by reference for all purposes.

**TECHNICAL FIELD**

Various embodiments relate to an optical light source.

**BACKGROUND**

In next-generation high-bandwidth low-power computing, the conventional on-chip copper interconnects, which route the electronic signals, will become bandwidth-limiting and also cause excessive electrical power consumption. Silicon photonics based optical interconnects are considered as one potential solution, where high bandwidth optical signals are routed through integrated low-loss optical waveguides. In contrast to the electrical interconnects (the copper wires), optical interconnects have many advantages, such as low crosstalk, immunity to electromagnetic interference, and low power consumption. Most importantly, optical interconnects are expected to provide a much larger bandwidth than the electrical interconnects. Wavelength-division multiplexing (WDM) technology provides a way to further increase the data capacity.

An optical light source is a key component for applications such as long-haul and data-center optical communication and on-chip optical interconnection. In the past ten years, silicon photonics has experienced unprecedented growth in research and development activities, as a possible technology towards next-generation multi-channel optical communications and optical interconnects for computer communication (comp-com). However, silicon, as an indirect bandgap material, cannot emit light efficiently. While SOI (silicon-in-insulator) is a promising material platform for low-cost low-power-consumption devices for on-chip interconnection and optical communications, yet it lacks an efficient light source. This means that it is required to adopt an off-chip optical light source for signal transmission.

Although silicon is an indirect bandgap material which is not considered as an efficient light source, various solutions including erbium (Er)-doped silicon laser, hybrid-integrated evanescent lasers, and Ge-on-Si laser have been proposed, among which the hybrid-integrated evanescent lasers, such as a hybrid optical light source using III-V bonding to silicon wafer, are considered as the most promising way for on-chip light sources. Thanks to the enabling complementary Complementary Metal-Oxide-Semiconductor (CMOS) fabrication technologies, a myriad of essential silicon photonic passive and active components have been fabricated, including micrometer-scale optical filters, 10-40 Gbit/s-speed low-power-consumption modulators, and GHz-bandwidth germanium (Ge)-on-silicon (Si) and hybrid III-V-on-Si photodetectors.

Almost all of today's hybrid silicon (Si) lasers use a dual-material system, which means direct bonding of III-V onto a Si waveguide. The laser cavity is defined by the Si waveguide and the cleaved/polished interfaces, which means a relatively high cavity loss. The optical light is mostly confined in the Si waveguide, which means low amplification efficiency. The issues for such a dual-waveguide system for a laser cavity

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include: 1) The Si waveguide usually has ~2 dB/cm propagation loss, which is relatively high, especially for some advanced light sources, such as mode-locked lasers where optical loss is critical; 2) The light is mostly confined inside the Si waveguide with only ~4.3% light confined in the III-V gain medium, thus the amplification efficiency is low; 3) Cleaved/polished interface(s) for the formation of a laser cavity provides less optical control and low productivity.

Therefore, the problem for conventional hybrid Si lasers is the relatively high Si waveguide loss for the laser cavity, leading to a high threshold and high power consumption. Such high loss could be a major issue for advanced hybrid lasers, such as the mode-locked lasers.

**SUMMARY**

According to an embodiment, an optical light source is provided. The optical light source may include a waveguide including two reflectors arranged spaced apart from each other to define an optical cavity therebetween, an optical gain medium, and a coupling structure arranged to couple light between the optical cavity and the optical gain medium.

According to an embodiment, an optical light source is provided. The optical light source may include a waveguide including two Bragg reflectors arranged spaced apart from each other to define an optical cavity therebetween, wherein the waveguide includes at least one of a silicon nitride-based material or silicon oxynitride-based material, and an optical gain medium optically coupled to the optical cavity.

**BRIEF DESCRIPTION OF THE DRAWINGS**

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:

FIG. 1A shows a schematic cross-sectional view of an optical light source, according to various embodiments.

FIG. 1B shows a schematic cross-sectional view of an optical light source, according to various embodiments.

FIG. 2 shows a perspective view of an optical light source, according to various embodiments.

FIG. 3A shows a cross-sectional view of an optical light source, according to various embodiments.

FIG. 3B shows the light confinements in different waveguide structures of the embodiment of FIG. 3A.

FIG. 4A shows a partial perspective view and a partial cross-sectional view of an optical light source having a stack-layered structure, according to various embodiments.

FIG. 4B shows a partial perspective view and a partial cross-sectional view of an optical light source having a waveguide-embedded structure, according to various embodiments.

FIG. 5A shows a plot of the calculated intensity transitions between the different waveguide layers of the embodiment of FIG. 4A.

FIG. 5B shows a plot of the calculated intensity transitions between the different waveguide layers of the embodiment of FIG. 4B.

**DETAILED DESCRIPTION**

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, 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.

Embodiments described in the context of one of the devices are analogously valid for the other device.

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.

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.

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

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.

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

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.

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.

Various embodiments may provide an optical light source (e.g. a hybrid Si laser) using a multi-layered waveguide structure. Various embodiments may provide a triple-layered waveguide structure for the optical light source, having an arrangement of a waveguide configured as an optical or laser cavity, an optical gain medium, and a coupling structure or intermediate layer therebetween for coupling light between the waveguide and the optical gain medium. As non-limiting examples, the optical light source may employ silicon nitride (SiN) or silicon oxynitride (SiON) for the long laser cavity, a bonded III-V layer or structure as the gain medium, and amorphous silicon (a-Si) for enhancing the light coupling between the SiN or SiON waveguide and the III-V layer. Various embodiments may employ chirped distributed Bragg reflectors (DBRs) as the mirror reflectors to define the optical cavity. The mirror reflectors may be formed as part of the SiN or SiON waveguide. Various embodiments may adopt inverse tapers for the coupling between the SiN or SiON waveguide and the a-Si coupling structure, and/or between the a-Si coupling structure and the III-V layer.

Various embodiments may provide an optical light source (e.g. a hybrid Si laser) using a low-loss waveguide, such as silicon nitride (SiN) or silicon oxynitride (SiON) as the laser cavity waveguide, and/or using distributed Bragg mirrors (DBRs) for the laser cavity mirrors.

A SiN or SiON waveguide may provide a low-loss waveguide for the laser cavity. A SiN waveguide may have a propagation loss of about 0.6 dB/cm, while a SiON waveguide may have a propagation loss of about 0.1 dB/cm, as compared to a silicon waveguide having a propagation loss of about 2 dB/cm. Therefore, using SiN and SiON waveguides may significantly reduce the cavity loss. A reduced cavity loss may enable a lower threshold voltage and a lower power consumption.

In various embodiments, employing SiN or SiON DBRs to form the optical laser cavity may allow a controllable fabrication process that may enable potential mass production, and may avoid the low yield end-face polishing and antireflection coating for forming reflecting mirrors.

Various embodiments may provide a high-performance hybrid laser with a low threshold and a low power consumption. Various embodiments may provide a cost effective hybrid laser for silicon integrated circuits.

FIG. 1A shows a schematic cross-sectional view of an optical light source **100**, according to various embodiments. The optical light source **100** includes a waveguide **104** including two reflectors **106a**, **106b** arranged spaced apart from each other to define an optical cavity **107** therebetween, an optical gain medium **110**, and a coupling structure **108** arranged to couple light between the optical cavity **107** and the optical gain medium **110**.

In other words, the optical light source **100** may include a waveguide **104**, and a first reflector **106a** and a second reflector **106b** formed or defined in the waveguide **104**. The first reflector **106a** and the second reflector **106b** may define an optical cavity **107** in the spacing between them in the waveguide **104** and serve to reflect light propagating in the optical cavity **107**. The optical light source **100** may further include an optical gain medium **110** which may provide optical gain for light propagating in the optical light source **100** and which interacts with the optical gain medium **110**. The optical light source **100** may further include a coupling structure **108** optically coupled to the optical cavity **107** and the optical gain medium **110**.

In various embodiments, light may be coupled between the waveguide **104** and the optical gain medium **110**. For example, light may be coupled in a direction from the waveguide **104** to the coupling structure **108** and then to the optical gain medium **110**. Light may also be coupled in the reverse direction.

In various embodiments, light propagating in the optical cavity **107** may be reflected by the two reflectors **106a**, **106b** and coupled to the optical gain medium **110**. Light may be coupled to the optical gain medium **110** one or more times, where the light may be amplified. Therefore, the two reflectors **106a**, **106b** and the optical gain medium **110** may cooperate to cause lasing within the optical cavity **107**. In this way, the optical cavity **107** may act as a laser cavity or lasing cavity that may enable amplification of light within the optical light source **100**, where the amplified light may be emitted from the optical light source **100** as an optical signal.

In various embodiments, the coupling structure **108** may be arranged in between the waveguide **104** and the optical gain medium **110**. The coupling structure **108** may be arranged between the optical cavity **107** and the optical gain medium **110**. This may mean that the optical gain medium **110** may be spaced apart from the waveguide **104** and the optical cavity **107**. Further, this may mean that the waveguide **104** having the optical cavity **107**, the coupling structure **108** and the optical gain medium **110** may be arranged in a stack structure, where the coupling structure **108** may be arranged over the optical cavity **107** and the optical gain medium **110** may be

arranged over the coupling structure **108**. Therefore, the optical light source **100** may include a triple-layered structure including the waveguide **104**, the coupling structure **108** and the optical gain medium **110**.

In various embodiments, the waveguide **104**, the coupling structure **108** and the optical gain medium **110** may be formed as respective or individual layers.

In various embodiments, the waveguide **104**, the coupling structure **108** and the optical gain medium **110** may be formed at different planes.

In various embodiments, the coupling structure **108** may be arranged in contact with the optical cavity **107** (and therefore also the waveguide **104**) and/or the optical gain medium **110**.

In various embodiments, the coupling structure **108** may be arranged overlapping with at least one of the optical cavity **107** or the optical gain medium **110**. The entire coupling structure **108** may overlap with the optical cavity **107**. The entire optical gain medium **110** may overlap with the coupling structure **108**.

In various embodiments, the coupling structure **108** may be another waveguide.

In various embodiments, the optical gain medium **110** may be arranged over the waveguide **104**, for example over the optical cavity **107** defined in the waveguide **104**. The optical gain medium **110** may be arranged overlapping with the optical cavity **107**. The entire optical gain medium **110** may overlap with the optical cavity **107**. The optical gain medium **110** may be optically coupled to the optical cavity **107**.

In various embodiments, at least one reflector of the two reflectors **106a**, **106b** may allow light to exit from the optical light source **100**. For example, the second reflector **106b** may be a partial reflector to allow some light to be reflected and some light to be transmitted through the second reflector **106b** to be emitted from the optical light source **100**. In various embodiments, the first reflector **106a** may be a full reflector or a partial reflector.

In various embodiments, the coupling structure **108** may be arranged spaced apart from at least one of the optical cavity **107** or the optical gain medium **110**. This may mean that the coupling structure **108** may not be in contact with the optical cavity **107** and/or the optical gain medium **110**. Further, this may mean that the coupling structure **108** may be spaced apart from the waveguide **104**.

In the context of various embodiments, the waveguide **104** may include a material capable of inducing a propagation loss of less than 2 dB/cm. Therefore, the material of the waveguide **104** may be capable of inducing a propagation loss that is less than that for silicon, which has a propagation loss of 2 dB/cm or more. As non-limiting examples, the material of the waveguide **104** may be capable of inducing a propagation loss of less than about 1.5 dB/cm, less than about 1.0 dB/cm, or less than about 0.5 dB/cm, for example a propagation loss of about 1 dB/cm, about 0.6 dB/cm or about 0.1 dB/cm. With a propagation loss of less than 2 dB/cm, the waveguide **104** may be referred to as a low-loss waveguide.

In the context of various embodiments, the waveguide **104** may include at least one of a silicon nitride-based material (e.g. SiN) or silicon oxynitride-based material (e.g. SiON). A silicon nitride-based waveguide **104** may induce a propagation loss of approximately 0.6 dB/cm, while a silicon oxynitride-based waveguide **104** may induce a propagation loss of approximately 0.1 dB/cm. Therefore, a silicon nitride-based waveguide **104** or a silicon oxynitride-based waveguide **104** may be a low-loss waveguide.

In various embodiments, the coupling structure **108** may be embedded in the waveguide **104**. For example, the coupling structure **108** may be embedded in the waveguide **104** such

that at least one surface of the coupling structure **108** and at least one surface of the waveguide **104** may be at least substantially coplanar.

In the context of various embodiments, the coupling structure **108** may have a refractive index in between respective refractive indices of the waveguide **104** and the optical gain medium **110**. In various embodiments, the refractive index of the coupling structure **108** may be biased towards the refractive index of the optical gain medium **110**, for example close to the refractive index of the optical gain medium **110**, e.g. at least substantially matched to the refractive index of the optical gain medium **110**.

In the context of various embodiments, the refractive index of the waveguide **104** may be in a range of between about 1.45 (such as a SiON waveguide) and about 2.0 (such as a SiN waveguide), for example between about 1.45 and about 1.8, between about 1.45 and about 1.6, or between about 1.6 and about 2.0.

In the context of various embodiments, the refractive index of the optical gain medium **110** may be in a range of between about 3.0 and about 3.8, for example between about 3.0 and about 3.5, between about 3.0 and about 3.2, between about 3.2 and about 3.8 or between about 3.2 and about 3.5.

In the context of various embodiments, the refractive index of the coupling structure **108** may be in a range of between about 3.5 (e.g. a poly-crystalline Si coupling structure) and about 4.0 (e.g. an amorphous Si coupling structure), for example between about 3.5 and about 3.8, between about 3.5 and about 3.6, or between about 3.8 and about 4.0.

In the context of various embodiments, the coupling structure **108** may have a thickness between about 50 nm and about 500 nm, for example between about 50 nm and about 300 nm, between about 50 nm and about 100 nm, between about 100 nm and about 500 nm, between about 100 nm and about 200 nm, or between about 200 nm and about 400 nm.

In the context of various embodiments, the coupling structure **108** may include amorphous silicon (a-Si) or poly-crystalline Si (poly-Si).

In the context of various embodiments, the optical gain medium **110** may include a multiple quantum well (MQW) region, with an arrangement including but not limited to  $8 \times \text{In}_{0.653}\text{Al}_{0.055}\text{Ga}_{0.292}\text{As}$  well/ $9 \times \text{In}_{0.45}\text{Al}_{0.089}\text{Ga}_{0.461}\text{As}$  barriers.

In various embodiments, the optical gain medium **110** may further include at least one separate confinement heterostructure (SCH) layer arranged over the MQW region. At least one lower separate confinement heterostructure layer may additionally or alternatively be arranged below the multiple quantum well region. In various embodiments, a separate confinement heterostructure (SCH) layer may have a refractive index that may be lower than that of the MQW region, for effectively confining light in the MQW region.

In various embodiments, the optical gain medium **110** may further include a cladding layer. The cladding layer may be arranged over the MQW region. The cladding layer may also be arranged over the SCH layer. In the context of various embodiments, the cladding layer may have a thickness between about 0.1 micron ( $\mu\text{m}$ ) and about 1.5 micron ( $\mu\text{m}$ ), for example between about 0.1  $\mu\text{m}$  and about 1.0  $\mu\text{m}$ , between about 0.1  $\mu\text{m}$  and about 0.5  $\mu\text{m}$ , between about 0.5  $\mu\text{m}$  and about 1.5  $\mu\text{m}$ , between about 1.0  $\mu\text{m}$  and about 1.5  $\mu\text{m}$ , or between about 0.3  $\mu\text{m}$  and about 0.8  $\mu\text{m}$ .

In various embodiments, the optical gain medium **110** may further include an underlayer or slab below the MQW region. The underlayer or slab may be in the form of a waveguide.

In the context of various embodiments, a section of the optical gain medium **110** may be configured as a saturable

absorber section. The remaining section of the optical gain medium **110** may be configured as a gain region or section (e.g. a saturable gain section). In various embodiments, the saturable absorber section may be electrically isolated from the gain section of the optical gain medium **110**. The term “saturable absorber section” may mean a section where the absorption of light may decrease with increasing light intensity. By having a saturable absorber section, the optical light source **100** may be configured as a mode-locked laser.

In the context of various embodiments, the optical gain medium **110** may include a III-V material, for example in the form of a III-V bonding layer. Therefore, the optical light source **100** may be a hybrid optical light source (e.g. a hybrid laser) integrating a III-V optical gain medium **110** with the waveguide **104**, for example a silicon nitride-based or silicon oxynitride-based waveguide **104**.

In the context of various embodiments, the III-V material may be selected from the group consisting of 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), and indium phosphide (InP).

In the context of various embodiments, at least one of the two reflectors **106a**, **106b** may be or may include a Bragg reflector, e.g. a Bragg reflection grating or a distributed Bragg reflector (DBR). The Bragg reflector may have a structure with a varying (periodic or non-periodic) refractive index, for example alternating refractive indices, which may generate a wavelength specific reflector that may reflect one or more wavelengths of light. In various embodiments, the Bragg reflector may be a chirped Bragg reflector, e.g. a chirped distributed Bragg reflector, where variation in the refractive index of the chirped Bragg reflector may be non-periodic (or non-uniform).

In the context of various embodiments, the optical light source **100** may further include a substrate, where the waveguide **104** may be arranged over or on the substrate. The substrate may be a semiconductor substrate, e.g. a silicon (Si) substrate or a silicon-on-insulator (SOI) substrate.

In various embodiments, at least one of the coupling structure **108** or the optical gain medium **110** may include a tapering region, for example having an inverse taper configuration. Respective tapering regions of the coupling structure **108** and the optical gain medium **110** may at least substantially overlap with each other.

In the context of various embodiments, the waveguide **104** may include a first waveguide section and a second waveguide section spaced apart from the first waveguide section, and the coupling structure **108** may include a first coupling section arranged to couple light between the first waveguide section and the optical gain medium **110**, and a second coupling section arranged to couple light between the second waveguide section and the optical gain medium **110**. In various embodiments, the second coupling section may be spaced apart from the first coupling section.

In various embodiments, at least a portion of the first waveguide section may be arranged at least substantially overlapping with a portion of the first coupling section, and at least a portion of the second waveguide section may be arranged at least substantially overlapping with a portion of the second coupling section.

In various embodiments, the first waveguide section and the first coupling section may be arranged offset (e.g. horizontally offset) relative to each other and the second waveguide section and the second coupling section may be arranged offset (e.g. horizontally offset) relative to each other.

In various embodiments, a first portion of the optical gain medium **110** may be arranged at least substantially overlapping with a portion of the first coupling section, and a second portion of the optical gain medium **110** may be arranged at least substantially overlapping with a portion of the second coupling section. The optical gain medium **110** may be arranged offset (e.g. horizontally offset) relative to each of the first coupling section and the second coupling section of the coupling structure **108**. In various embodiments, the optical gain medium **110** may not overlap with the first waveguide section and the second waveguide section.

In various embodiments, the first coupling section, the second coupling section and the optical gain medium **110** may form part of the optical cavity **107**.

In various embodiments, light may be coupled, in sequence, in a direction from the first waveguide section to the first coupling section, the optical gain medium **110**, the second coupling section and the second waveguide section. Light may also be coupled in the reverse direction. Therefore, a first optical path may be defined between the first waveguide section and the optical gain medium **110**, through the first coupling section, while a second optical path may be defined between the second waveguide section and the optical gain medium **110**, through the second coupling section. In this way, light may be at least substantially fully coupled to the optical gain medium **110**.

In various embodiments, the first waveguide section and the second waveguide section may be arranged at least substantially coplanar with each other, and/or the first coupling section and the second coupling section may be arranged at least substantially coplanar with each other.

In various embodiments, the first waveguide section and the first coupling section may be arranged spaced apart (e.g. vertically separated) from each other, and the second waveguide section and the second coupling section may be arranged spaced apart (e.g. vertically separated) from each other.

In various embodiments, the optical gain medium **110** may be arranged spaced apart (e.g. vertically separated) from the first coupling section and the second coupling section.

FIG. 1B shows a schematic cross-sectional view of an optical light source **120**, according to various embodiments. The optical light source **120** includes a waveguide **124** including two Bragg reflectors **126a**, **126b** arranged spaced apart from each other to define an optical cavity **127** therebetween, wherein the waveguide **124** includes at least one of a silicon nitride-based material or silicon oxynitride-based material, and an optical gain medium **130** optically coupled to the optical cavity.

In other words, the optical light source **120** may include a silicon nitride-based (e.g. SiN) waveguide **124** or a silicon oxynitride-based (e.g. SiON) waveguide **124**. The optical light source **120** may include a first Bragg reflector **126a** and a second Bragg reflector **126b** formed or defined in the waveguide **124**. The first Bragg reflector **126a** and the second Bragg reflector **126b** may define an optical cavity **127** in the spacing between them in the waveguide **124** and serve to reflect light propagating in the optical cavity **127**. The optical cavity **127** may be a lasing cavity or a laser cavity.

In various embodiments, at least one of the two Bragg reflectors **126a**, **126b** may be or may include a distributed Bragg reflector (DBR) or a Bragg reflection grating.

In various embodiments, the optical gain medium **130** may be arranged over the waveguide **124**, for example over the optical cavity **127**. The optical gain medium **130** may include a III-V material. Non-limiting examples of the III-V material may be as described above.

In various embodiments, the optical light source **120** may further include a coupling structure arranged to couple light between the optical cavity **127** and the optical gain medium **130**. The coupling structure may be another waveguide. The coupling structure may be arranged in between the waveguide **124** and the optical gain medium **130**. The coupling structure may include amorphous silicon (a-Si).

It should be appreciated that the optical light source **120** may include one or more features as described in the context of the optical light source **100**.

Various embodiments may provide an optical light source having one or more of the following: (1) a low-loss waveguide to form the laser cavity for high-performance optical light emission, (2) enhanced light confinement in a multiple quantum well (MQW) gain region for increased lasing efficiency, or (3) a distributed Bragg reflector (DBR) mirror design with controllable optical properties and mass production potential.

The optical light source of various embodiments may adopt a low-loss SiN or SiON platform for the optical or laser cavity, for example in the form of a waveguide. A III-V gain medium may be fusion bonded onto the passive optical light source device for optical gain. The optical light source may adopt amorphous silicon (a-Si) between the SiN or SiON waveguide and the III-V gain medium for enhanced light coupling.

FIG. 2 shows a perspective view of an optical light source **200**, according to various embodiments. The optical light source **200** may include a silicon-on-insulator (SOI) substrate having a buried oxide (BOX) layer **202**. The optical light source **200** may employ a triple-layered waveguide structure formed on the substrate, for example over the BOX layer **202**. The triple-layered waveguide structure may include a waveguide (e.g. a low-loss optical waveguide) **204** with a first reflector (e.g. a distributed Bragg reflector (DBR) or a Bragg reflection grating) **206a** and a second reflector (e.g. a distributed Bragg reflector (DBR) or a Bragg reflection grating) **206b** to define an optical or laser cavity, an optical gain medium **210**, which may be in the form of a III-V bonded layer, and a sandwiched waveguide **208**, as a coupling structure, between them for efficient light coupling between the waveguide **204** and the optical gain medium **210**. The waveguide **204** may provide a low-loss guide in the cavity.

The optical gain medium **210** may include a stack arrangement including a multiple quantum well (MQW) region **260**. The stack arrangement may further include an underlayer **264** below the MQW **260** and a separate confinement heterostructure (SCH) layer **262** over the MQW **260**. The optical gain medium **210** may be defined into a saturable absorber section **211a** and a saturable gain section **211b**. The saturable absorber section **211a** and the saturable gain section **211b** may be electrically isolated from each other. Each of the saturable absorber section **211a** and the saturable gain section **211b** may include a cladding layer and a contact layer arranged over the SCH layer **262**. The contact layer of the saturable absorber section **211a** may be electrically coupled to the reverse-biased electrode **270a** for application of a reverse bias electrical signal (e.g. a voltage) to the saturable absorber section **211a**. The contact layer of the saturable gain section **211b** may be electrically coupled to a current injection electrode **270b** for application of an electrical signal (e.g. a voltage) to the saturable gain section **211b**.

The coupling structure **208** may be formed on top of the waveguide **204**, and the optical gain medium **210** may be formed on top of the coupling structure **208**. As a non-limiting example, the optical gain medium **210** may be bonded to the coupling structure **208**. The waveguide **204** may have a meander or serpentine shape, as shown in FIG. 2, a linear (straight) shape, or any other suitable shape for light propagation and coupling.

In various embodiments, in silicon (Si) platform, the waveguide **204**, as a low-loss waveguide, may be a silicon nitride-based waveguide or a silicon oxynitride-based waveguide. As non-limiting examples, the waveguide **204** may be a silicon nitride (SiN) waveguide which may have a propagation loss of about 0.6 dB/cm or a silicon oxynitride (SiON) waveguide which may have a propagation loss of about 0.1 dB/cm, compared to a propagation loss of 2 dB/cm for a silicon (Si) waveguide.

In various embodiments, the optical gain medium **210** may include a III-V bonding material, for example including an indium phosphide (InP) multiple quantum well (MQW) structure **260** which may provide optical gain. Such on-silicon III-V gain material may be achieved via wafer bonding technique, for example fusion bonding.

The sandwiched waveguide structure **208** may be provided for efficiency coupling purposes. In various embodiments, as the refractive index of SiN and SiON is approximately 2 while InP has a refractive index of approximately 4, there may be challenges in efficiently coupling light between the SiN or SiON waveguide **204** and the optical gain medium **210** due to the large index mismatch. Thus, a relatively high index material may be provided in order to match the III-V material refractive index. In various embodiments, amorphous silicon (a-Si) may be employed for the sandwiched waveguide structure **208**. This may mean that the waveguide structure **208** may be an amorphous silicon layer. By integrating a III-V optical gain medium and a silicon nitride-based waveguide or a silicon oxynitride-based waveguide, the optical light source **200** may be a hybrid Si optical light source (e.g. a hybrid Si laser).

In operation, light may propagate within the waveguide **204**, in the optical cavity defined between the first reflector **206a** and the second reflector **206b**. Light propagating in the optical cavity may be reflected, at least once, by each of the first reflector **206a** and the second reflector **206b**. Light may be fully reflected by the first reflector **206a**, and partially reflected by the second reflector **206b** so that light may exit from the optical cavity via the second reflector **206b** and exit the optical light source **200** through an output port **272**. Light propagating in the optical cavity may be coupled to the optical gain medium **210** to provide optical gain so as to amplify the light that interacts with the optical gain medium **210**. By passing through the optical cavity and the optical gain medium **210** a plurality of times, lasing may occur and the light may be amplified. In this way, the optical light source **200** may act as a laser (e.g. a hybrid Si laser). By having the saturable absorber section **211a**, the optical light source **200** may be configured as a mode-locked laser.

FIG. 3A shows a cross-sectional view of an optical light source **300**, according to various embodiments. The optical light source **300** may include a silicon-on-insulator (SOI) substrate having a buried oxide layer (BOX) layer **302**. The optical light source **300** includes a silicon nitride-based (e.g. SiN) or a silicon oxynitride-based (e.g. SiON) waveguide **304** arranged over the BOX layer **302**, the waveguide **304** having a first waveguide section **305a** and a second waveguide section **305b** arranged spaced apart from the first waveguide section **305a**. Therefore, the waveguide **304** may include

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individual first waveguide section **305a** and second waveguide section **305b** separated from each other. The first waveguide section **305a** and the second waveguide section **305b** may be arranged at least substantially coplanar to each other. A first reflector (e.g. a distributed Bragg reflector (DBR)) **306a** may be formed or defined in the first waveguide section **305a**, and a second reflector (e.g. a distributed Bragg reflector (DRB)) **306b** may be formed or defined in the second waveguide section **305b**.

The optical light source **300** may further include an amorphous silicon (a-Si) coupling structure, in the form of an a-Si waveguide **308** arranged over the waveguide **304**. The a-Si waveguide **308** may have a first coupling section **309a** and a second coupling section **309b** arranged spaced apart from the first coupling section **309a**. Therefore, the a-Si waveguide **308** may include individual first coupling section **309a** and second coupling section **309b** separated from each other. The first coupling section **309a** and the second coupling section **309b** may be arranged at least substantially coplanar to each other.

The optical light source **300** may further include an optical gain medium (e.g. a III-V gain medium) **310**, for example in the form of a waveguide. The optical gain medium **310** may be defined into a saturable absorber (SA) section **311a** and a gain region or section **311b**. The SA section **311a** and the gain section **311b** may be electrically isolated from each other. The optical gain medium **310** may include a multiple quantum well (MQW) region (not shown).

As shown in FIG. 3A, the waveguide **304**, the a-Si waveguide **308** and the optical gain medium **310** may be formed at different planes.

The waveguide **304** including the first waveguide section **305a** and the second waveguide section **305b**, the a-Si waveguide **308** including the first coupling section **309a** and the second coupling section **309b**, and the optical gain medium **310** may be embedded in a cladding layer or an insulation layer (e.g. an oxide layer) **340**.

As shown in FIG. 3A, the first coupling section **309a** may be vertically spaced apart from the first waveguide section **305a**. The first coupling section **309a** may be horizontally offset relative to the first waveguide section **305a**. A coupling region, with a predetermined coupling length (e.g. from a few microns to 100s of microns depending on the designed coupling efficiency, for example between about 1  $\mu\text{m}$  and about 500  $\mu\text{m}$ , e.g. between about 1  $\mu\text{m}$  and about 200  $\mu\text{m}$ ), may be defined where a portion of the first coupling section **309a** at least substantially overlaps with a portion of the first waveguide section **305a**, for coupling of light, as represented by the dashed arrow, between the first coupling section **309a** and the first waveguide section **305a**.

The second coupling section **309b** may be vertically spaced apart from the second waveguide section **305b**. The second coupling section **309b** may be horizontally offset relative to the second waveguide section **305b**. A coupling region, with a predetermined coupling length (e.g. from a few microns to 100s of microns depending on the designed coupling efficiency, for example between about 1  $\mu\text{m}$  and about 500  $\mu\text{m}$ , e.g. between about 1  $\mu\text{m}$  and about 200  $\mu\text{m}$ ) may be defined where a portion of the second coupling section **309b** at least substantially overlaps with a portion of the second waveguide section **305b**, for coupling of light, as represented by the dashed arrow, between the second coupling section **309b** and the second waveguide section **305b**.

The optical gain medium **310** may be vertically spaced apart from the first coupling section **309a** and the second coupling section **309b**. The optical gain medium **310** may be horizontally offset relative to the first coupling section **309a**

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and the second coupling section **309b**. The optical gain medium **310** may also be vertically spaced apart from the first waveguide section **305a** and the second waveguide section **305b**. The optical gain medium **310** may also be horizontally offset relative to the first waveguide section **305a** and the second waveguide section **305b**.

A coupling region, with a predetermined coupling length (e.g. from a few microns to 100s of microns depending on the designed coupling efficiency, for example between about 1  $\mu\text{m}$  and about 500  $\mu\text{m}$ , e.g. between about 1  $\mu\text{m}$  and about 200  $\mu\text{m}$ ), may be defined where a portion of the optical gain medium **310** at least substantially overlaps with a portion of the first coupling section **309a**. The first coupling section **309a** may overlap with the SA section **311a** of the optical gain medium **310**. Another coupling region, with a predetermined coupling length (e.g. from a few microns to 100s of microns depending on the designed coupling efficiency, for example between about 1  $\mu\text{m}$  and about 500  $\mu\text{m}$ , e.g. between about 1  $\mu\text{m}$  and about 200  $\mu\text{m}$ ), may be defined where a portion of the optical gain medium **310** at least substantially overlaps with a portion of the second coupling section **309b**. The second coupling section **309b** may overlap with the gain region **311b** of the optical gain medium **310**. In various embodiments, the optical gain medium **310** may not overlap with the first waveguide section **305a** and the second waveguide section **305b**.

An optical cavity may be defined between the first reflector **306a** and the second reflector **306b**. The optical cavity may include the first waveguide section **305a**, the second waveguide section **305b**, the first coupling section **309a**, the second coupling section **309b** and the optical gain medium **310**.

Light may be coupled between the first waveguide section **305a** and the second waveguide section **305b**. A first optical path may be defined between the first waveguide section **305a** and the optical gain medium **310**, and a second optical path may be defined between the second waveguide section **305b** and the optical gain medium **310**. Light may be coupled from the first waveguide section **305a** to the second waveguide section **305b**, via, in sequence, the first coupling section **309a**, the optical gain medium **310** and the second coupling section **309b**, and/or vice versa from the second waveguide section **305b** to the first waveguide section **305a**, via, in sequence, the second coupling section **309b**, the optical gain medium **310** and the first coupling section **309a**. As a non-limiting example, light propagating in the first waveguide section **305a** may be coupled (e.g. at least substantially entirely coupled) to the first coupling section **309a**, which in turn may be coupled (e.g. at least substantially entirely coupled) to the SA section **311a** of the optical gain medium **310**. The light may then propagate through the SA section **311a** and the gain region **311b** of the optical gain medium **310**, coupled (e.g. at least substantially entirely coupled) to the second coupling section **309b**, which in turn may be coupled (e.g. at least substantially entirely coupled) to the second waveguide section **305b**. As a non-limiting example, light propagating in the optical cavity may be partially reflected by the second reflector **306b** and partially transmitted out of the optical light source **300**, via the second reflector **306b**.

In various embodiments, therefore, the three different waveguides, in terms of the waveguide **304**, the a-Si waveguide **308** and the optical gain medium **310**, may be separated with only respective overlaps in the respective coupling regions. In this manner, light may propagate back and forth between the first reflector (e.g. a DBR) **306a** and the second reflector (e.g. a DBR) **306b** in the waveguide **304**, and goes through separately the passive waveguide **304** and the

optical gain medium (e.g. a III-V gain medium) **310**. In the gain medium region **310**, the light may be at least substantially fully or completely confined, where the confined light may interact with the gain medium **310** for light amplification. In contrast, in conventional devices, most of the light is confined in the waveguide. In various embodiments, employing a separate waveguide design, e.g. as illustrated in FIG. 3A with the first waveguide section **305a** and the second waveguide section **305b**, may enable enhanced light confinement in the gain region **310**, resulting in enhanced lasing efficiency.

FIG. 3B shows the light confinements in different waveguide structures of the embodiment of FIG. 3A. FIG. 3B shows a plot **350** of light confinement in the waveguide **304**, a plot **352** of light confinement in the a-Si waveguide **308**, and a plot **354** of light confinement in the III-V optical gain medium **310**. As shown in plot **354** of FIG. 3B, light may be confined in the multiple quantum well (MQW) region **360** and the separate confinement heterostructure (SCH) layer **362**, which may be sandwiched between an indium phosphide (InP) underlayer or slab **364** and an InP cladding layer **366**. The overall light confinement in the III-V MQW region **360** may be as high as about 27.63% (confinement factor), without optimization, as compared to approximately 4.3% in conventional designs or devices.

Taking into consideration the coupling scheme between different waveguide layers, various embodiments may provide different vertical structures having different vertical coupling schemes, for example, a stack-layered structure and a waveguide-embedded structure.

FIG. 4A shows a partial perspective view and a partial cross-sectional view of an optical light source **400** having a stack-layered structure, according to various embodiments. The optical light source **400** may include a SiN (or SiON) waveguide **404**, an amorphous silicon (a-Si) coupling structure or waveguide **408** arranged over and overlapping with the SiN waveguide **404**, and a III-V optical gain medium **410** arranged over and overlapping with the a-Si waveguide **408** and the SiN waveguide **404**. Therefore, in the stack-layered structure, the three waveguide layers (SiN waveguide **404**, a-Si coupling waveguide **408** and III-V optical gain medium **410**) may be stacked vertically. The SiN waveguide **404**, the a-Si coupling waveguide **408** and the III-V optical gain medium **410** may be formed over a substrate (not shown), e.g. an SOI substrate, and may be embedded in a cladding layer or an insulation layer (e.g. an oxide layer) **440**. It should be appreciated that the different partial views of the optical light source **400** shown in FIG. 4A may correspond to one half of the optical light source **400**. For example, this may mean that the waveguide **404** and the coupling waveguide **408** shown in FIG. 4A may be a first waveguide section and a first coupling section respectively.

The optical gain medium **410** may include a stack arrangement having an InP slab **464**, a multiple quantum well (MQW) region **460** with an arrangement of (but not limited to)  $8 \times \text{In}_{0.653}\text{Al}_{0.055}\text{Ga}_{0.292}\text{As}$  well/ $9 \times \text{In}_{0.45}\text{Al}_{0.089}\text{Ga}_{0.461}\text{As}$  barriers, a separate confinement heterostructure (SCH) layer **462** (e.g. a  $\text{In}_{0.528}\text{Al}_{0.131}\text{Ga}_{0.341}\text{As}$  layer), and an InP cladding layer **466**.

The a-Si coupling waveguide **408** may be in contact with at least a portion of the SiN waveguide **404**, as shown in FIG. 4A, or may be spaced apart from the SiN waveguide **404**. The optical gain medium **410** may be in contact with at least a portion of the a-Si coupling waveguide **408**, as shown in FIG. 4A, or may be spaced apart from the a-Si coupling waveguide **408**.

In various embodiments, coupling between different layers or waveguides may be realized by design of inverse tapers, for inverse taper coupling. As shown in FIG. 4A, the a-Si waveguide **408** may have a tapering region, at an end region of the a-Si waveguide **408**, where a width of the tapering region of the a-Si waveguide **408** may increase in a direction away from the end region of the a-Si waveguide **408**. The optical gain medium **410** may have a tapering region, at an end region of the optical gain medium **410**, where a width of the tapering region of the optical gain medium **410** may increase in a direction away from the end region of the optical gain medium **410**. The InP cladding layer **466**, the SCH layer **462** and the MQW region **460** may have at least substantially similar tapering configuration or dimension. The InP slab **464** may have a different tapering configuration or dimension compared to the other layers of the optical gain medium **410**.

As would be appreciated, each of the optical light source **200** (FIG. 2) and the optical light source **300** (FIG. 3A) are illustrated as employing a stack-layered structure.

FIG. 4B shows a partial perspective view and a partial cross-sectional view of an optical light source **430** having a waveguide-embedded structure, according to various embodiments. The optical light source **430** may include similar features as those for the optical light source **400** and may be as described in the context of the optical light source **400**, except that the a-Si waveguide **408** is embedded inside the SiN waveguide **408**. The a-Si waveguide **408** may be embedded in the SiN waveguide **408**, to be coplanar with the SiN waveguide **408**. It should be appreciated that the different partial views of the optical light source **430** shown in FIG. 4B may correspond to one half of the optical light source **430**. For example, this may mean that the waveguide **404** and the coupling waveguide **408** shown in FIG. 4B may be a first waveguide section and a first coupling section respectively.

For verification of the vertical structures of various embodiments, the intensity coupling between the stacked layers was calculated for both the stack-layered structure and the waveguide-embedded structure. FIG. 5A shows a plot **500** of the calculated intensity transitions between the different waveguide layers of the embodiment of FIG. 4A, while FIG. 5B shows a plot **510** of the calculated intensity transitions between the different waveguide layers of the embodiment of FIG. 4B. It should be appreciated that shown in FIGS. 5A and 5B are respective halves of the optical light sources **400**, **430**.

For both structures, as may be observed, light may be gradually coupled from the SiN waveguide **404** to the gain medium stacked arrangement **410** strongly. The obtained coupling losses from the SiN waveguide **404** to the InP waveguide for the optical light source **400** with the stack-layered structure and the optical light source **430** with the waveguide-embedded structure may be respectively approximately  $-1.3$  dB and approximately  $-2.5$  dB. It should be appreciated that no optimization was done for both calculations. By optimizing the vertical coupling structure, such as in terms of at least one of the a-Si waveguide thickness, the coupling length, or the InP cladding layer thickness, the coupling loss may be further reduced.

As described above, various embodiments may provide a structure for hybrid Si lasers, e.g. a multi-layer stacked structure for hybrid Si lasers. Various embodiments may employ a low-loss SiN or SiON waveguide as the laser cavity. Various embodiments may employ a chirped DBR design in the SiN or SiON layer for the formation of the laser cavity. Using chirped DBRs for the laser cavity may avoid the process of low-production surface polishing. Various embodiments may employ amorphous silicon (a-Si) as an intermediate layer for enhanced vertical coupling, for example for coupling

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between the SiN or SiON waveguide and the optical gain medium having a III-V material.

Various embodiments may enable a cost effective implementation and CMOS compatible fabrication of the Si devices of various embodiments. Further, the optical light sources of various embodiments may be ready for photonic integration for optical transceivers.

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.

While the preferred embodiments of the devices and methods have been described in reference to the environment in which they were developed, they are merely illustrative of the principles of the inventions. The elements of the various embodiments may be incorporated into each of the other species to obtain the benefits of those elements in combination with such other species, and the various beneficial features may be employed in embodiments alone or in combination with each other. Other embodiments and configurations may be devised without departing from the spirit of the inventions and the scope of the appended claims.

The invention claimed is:

1. An optical light source comprising:
  - a waveguide comprising two reflectors arranged spaced apart from each other to define an optical cavity therebetween;
  - an optical gain medium; and
  - a coupling structure arranged to couple light between the optical cavity and the optical gain medium, wherein the coupling structure comprises an additional waveguide, the additional waveguide being arranged in contact with the optical gain medium, wherein the waveguide comprises a first waveguide section and a second waveguide section spaced apart from the first waveguide section, and wherein the coupling structure comprises:
    - a first coupling section arranged to couple light between the first waveguide section and the optical gain medium; and
    - a second coupling section spaced apart from the first coupling section, the second coupling section arranged to couple light between the second waveguide section and the optical gain medium.
2. The optical light source as claimed in claim 1, wherein the coupling structure is arranged spaced apart from the optical cavity.
3. The optical light source as claimed in claim 1, wherein the waveguide comprises a material capable of inducing a propagation loss of less than 2 dB/cm.
4. The optical light source as claimed in claim 1, wherein the waveguide comprises at least one of a silicon nitride-based material or silicon oxynitride-based material.
5. The optical light source as claimed in claim 1, wherein the coupling structure is embedded in the waveguide.

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6. The optical light source as claimed in claim 1, wherein the coupling structure has a refractive index in between respective refractive indices of the waveguide and the optical gain medium.

7. The optical light source as claimed in claim 1, wherein the coupling structure has a thickness between about 50 nm and about 500 nm.

8. The optical light source as claimed in claim 1, wherein the coupling structure comprises amorphous silicon or polycrystalline silicon.

9. The optical light source as claimed in claim 1, wherein the optical gain medium comprises a multiple quantum well region.

10. The optical light source as claimed in claim 1, wherein the optical gain medium comprises a cladding layer.

11. The optical light source as claimed in claim 10, wherein the cladding layer has a thickness between about 0.1  $\mu\text{m}$  and about 1.5  $\mu\text{m}$ .

12. The optical light source as claimed in claim 1, wherein a section of the optical gain medium is configured as a saturable absorber section.

13. The optical light source as claimed in claim 1, wherein the optical gain medium comprises a III-V material.

14. The optical light source as claimed in claim 1, wherein at least one of the two reflectors comprises a Bragg reflector.

15. The optical light source as claimed in claim 1, wherein at least one of the coupling structure or the optical gain medium comprises a tapering region.

16. The optical light source as claimed in claim 1, wherein the first waveguide section and the first coupling section are arranged spaced apart from each other, and wherein the second waveguide section and the second coupling section are arranged spaced apart from each other.

17. The optical light source as claimed in claim 1, wherein the optical gain medium is arranged spaced apart from the first coupling section and the second coupling section.

18. An optical light source comprising:
  - a waveguide comprising two reflectors arranged spaced apart from each other to define an optical cavity therebetween;
  - an optical gain medium; and
  - a coupling structure arranged to couple light between the optical cavity and the optical gain medium; wherein the waveguide comprises a first waveguide section and a second waveguide section spaced apart from the first waveguide section, and wherein the coupling structure comprises:
    - a first coupling section arranged to couple light between the first waveguide section and the optical gain medium; and
    - a second coupling section spaced apart from the first coupling section, the second coupling section arranged to couple light between the second waveguide section and the optical gain medium.

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