



(19) **United States**

(12) **Patent Application Publication**

Abeles

(10) **Pub. No.: US 2001/0030985 A1**

(43) **Pub. Date: Oct. 18, 2001**

(54) **MASTER OSCILLATOR VERTICAL EMISSION LASER**

(57) **ABSTRACT**

(76) Inventor: **Joseph H. Abeles**, Highland Park, NJ (US)

Correspondence Address:
Steve Mendelsohn, Mendelsohn & Associates, P.C.
Suite 715
1515 Market Street
Philadelphia, PA 19102 (US)

(21) Appl. No.: **09/788,713**

(22) Filed: **Feb. 20, 2001**

Related U.S. Application Data

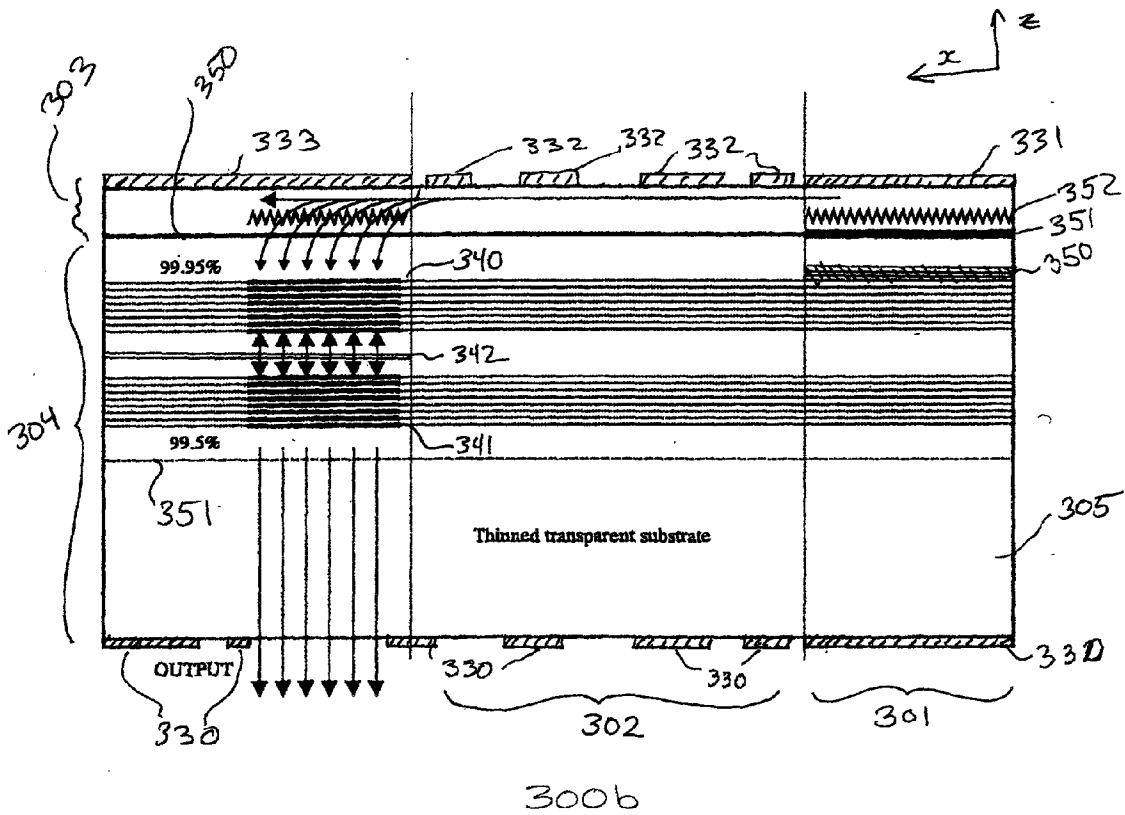
(63) Non-provisional of provisional application No. 60/184,334, filed on Feb. 23, 2000.

Publication Classification

(51) **Int. Cl.⁷ H01S 5/00**

(52) **U.S. Cl. 372/43**

A master oscillator, vertical emission (MOVE) laser includes an oscillator, a coupling region, and vertical-cavity amplifier region formed on a common substrate. The coupling region may include separately defined expansion and grating regions. Single-mode radiation of the oscillator passes through the expansion region, which is a passive region that provides spatial expansion of the propagating single-mode radiation wavefront with little or no gain. The expanded single-mode radiation from the expansion region passes through the grating region, which provides coupling of the relatively broad wavefront from the expansion region into the cavity of the vertical-cavity amplifier. The expansion and grating regions may be configured to reduce or eliminate reflection of single-mode radiation propagating within the vertical-cavity amplifier back toward the oscillator. The cavity of the vertical-cavity amplifier is relatively broad when compared to the cavity of the oscillator. The vertical-cavity amplifier operates as a low-gain-per-pass amplifier for incident single-mode radiation generated by the oscillator. Thus, radiation of relatively low optical power emitted from the oscillator controls single-mode radiation of relatively high optical power emitted by the vertical-cavity amplifier.



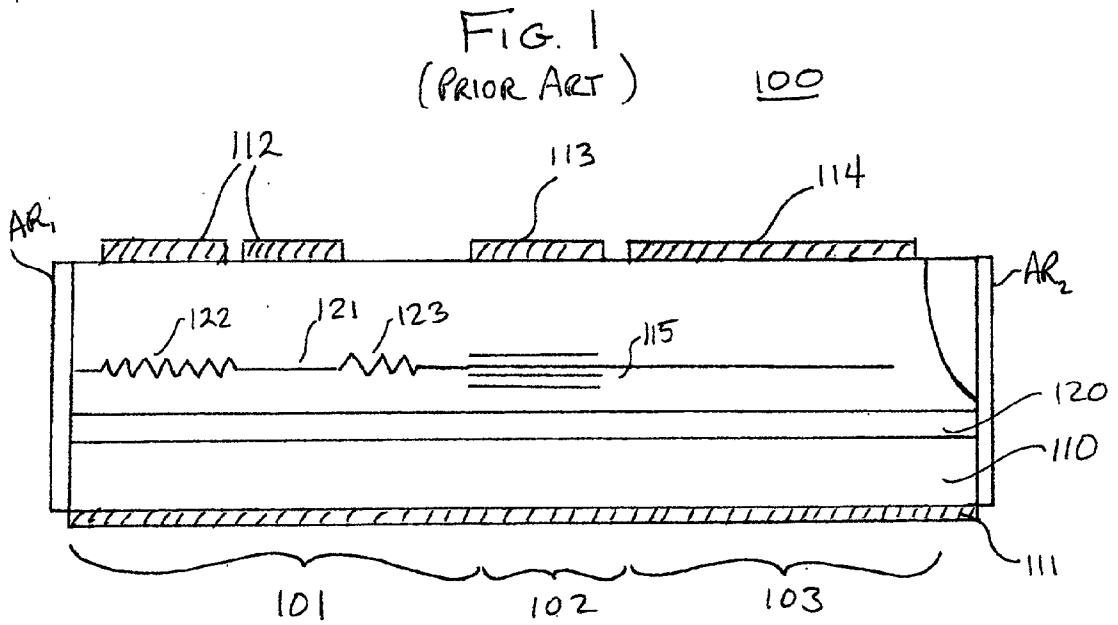
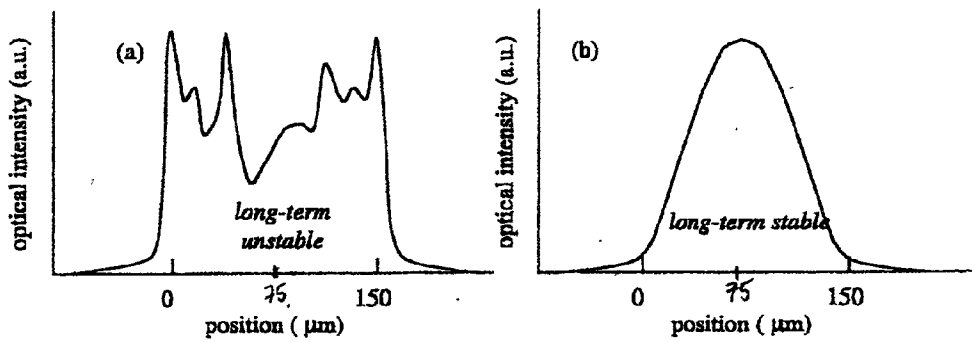
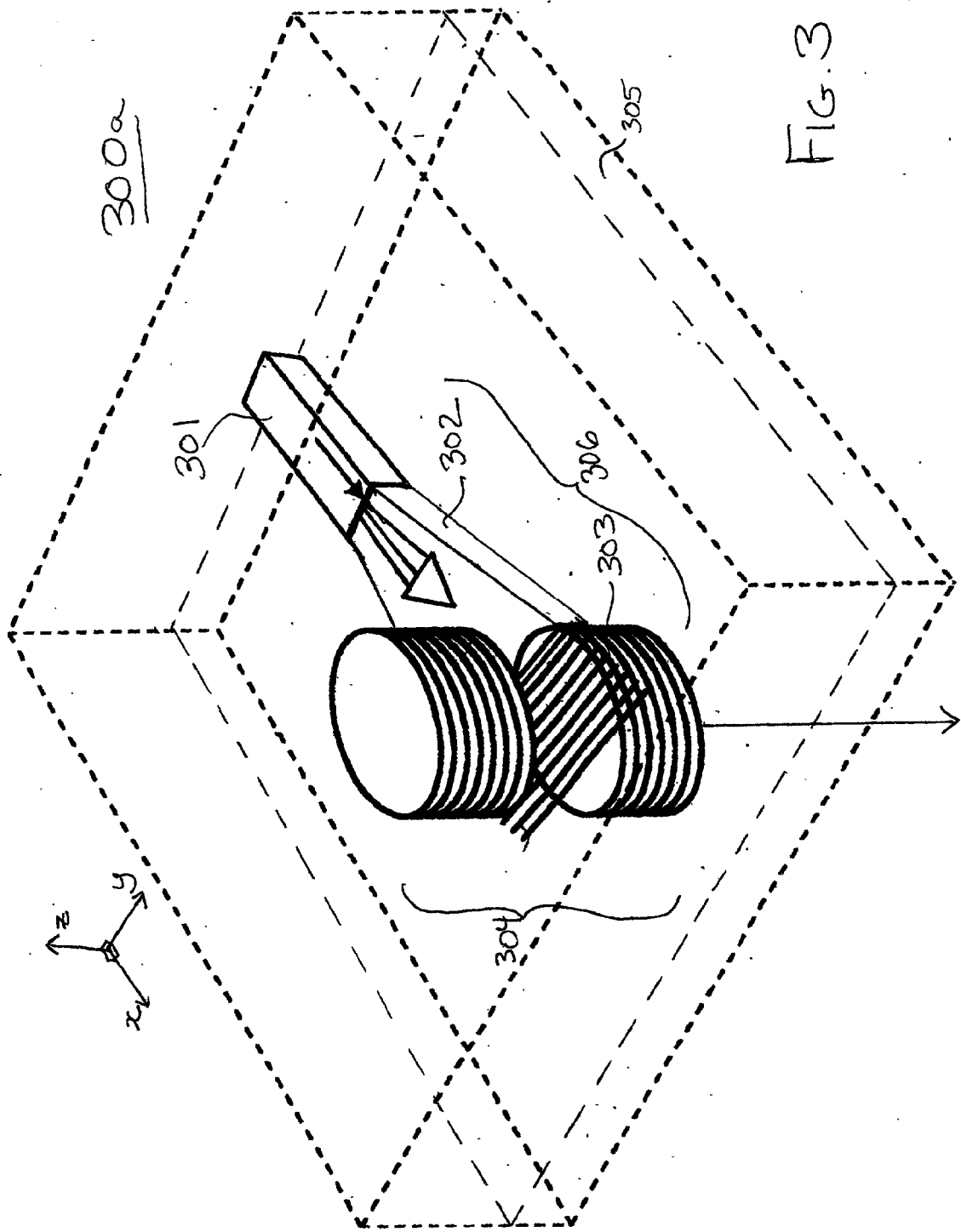
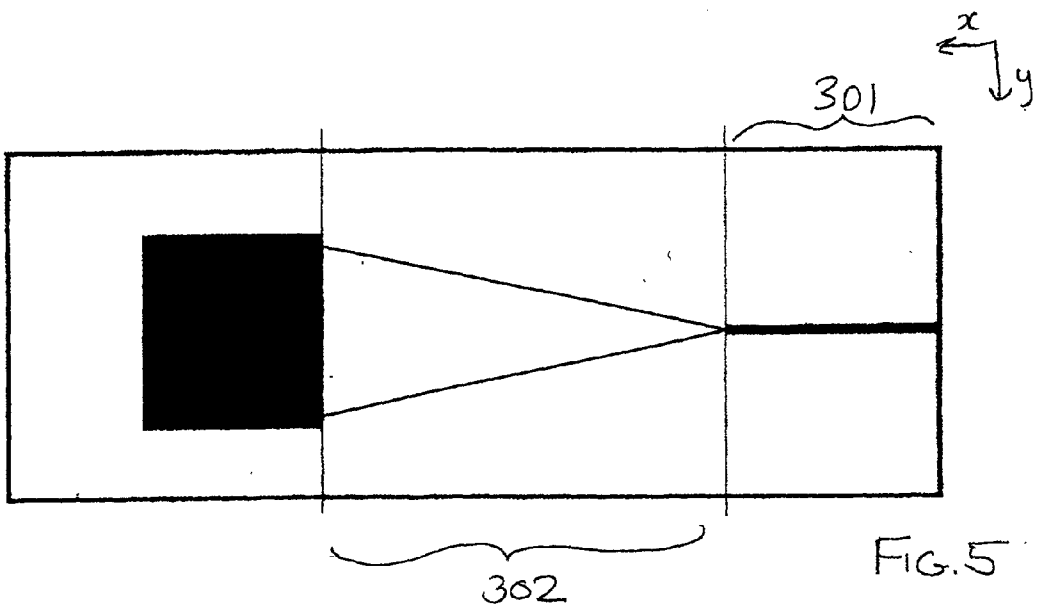
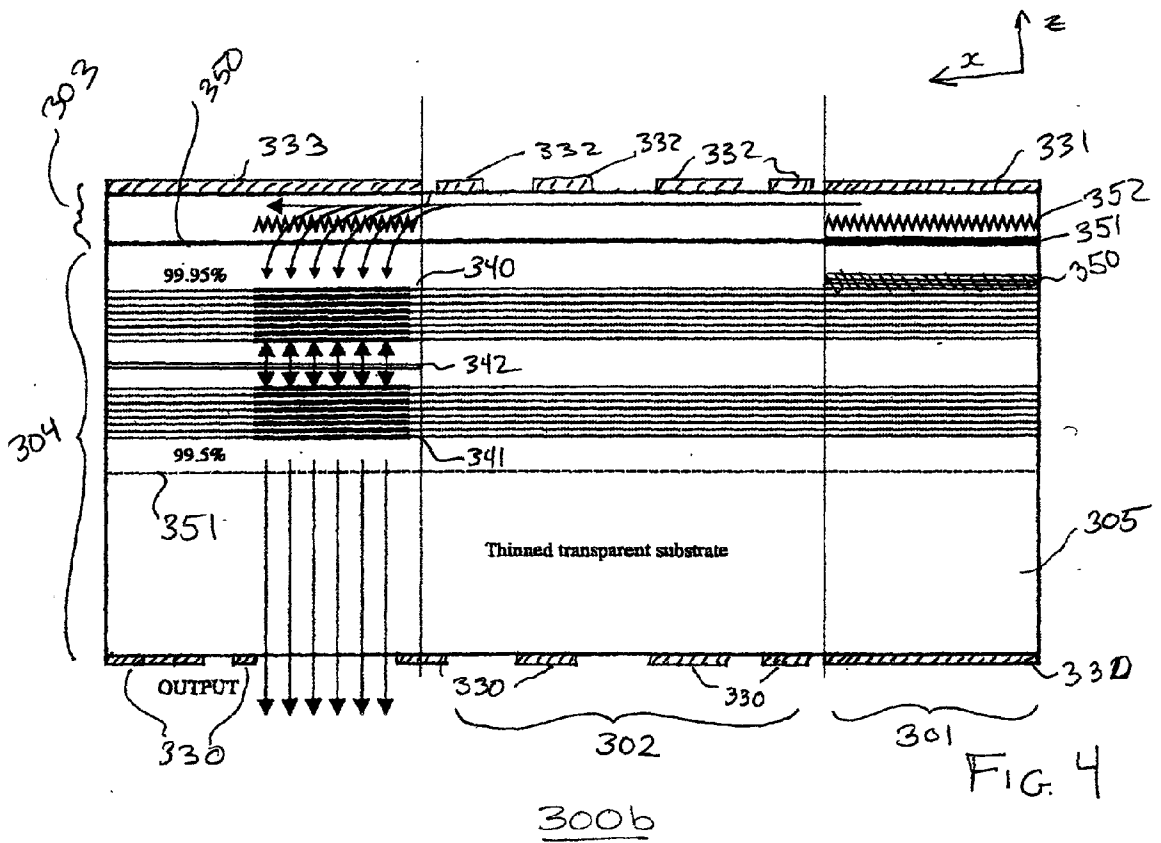


FIG. 2a (PRIOR ART)

FIG. 2b (PRIOR ART)







MASTER OSCILLATOR VERTICAL EMISSION LASER

RELATED APPLICATIONS

[0001] This application claims the benefit of the filing date of U.S. provisional application No. 60/184,334, filed on Feb. 23, 2000, as attorney docket no. SAR 13897 P.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The present invention relates to integrated semiconductor lasers.

[0004] 2. Description of the Related Art

[0005] High-power, single-mode laser diode sources are employed in a wide variety of applications, such as medical sensing devices and high-speed, optical telecommunication network components. For example, Raman amplifier components for optical networks typically require pump powers of 1 Watt and above.

[0006] A variety of laser diode structures exist in the prior art, including edge-emitting stripe, tapered stripe, broad stripe, grating-surface-emitting, master oscillator power amplifier, grating-stabilized broad stripe, surface-emitting distributed feedback, and antiguidded array structures. Important features of any given laser diode structure include: high output power, single near-Gaussian spatial mode, short- and long-term lasing mode stability over time, long-term reliability, compact packaging, manufacturability, and ease of coupling to an external waveguide such as an optical fiber. However, no single laser diode structure of the prior art adequately possesses all of these features.

[0007] Obtaining relatively high output power with single-mode emission by a laser diode is difficult. Structures having greater output power tend to produce either (a) multi-mode emission or (b) low long-term stability and reliability. For example, linear stripe lasers, typically including either buried heterostructure or ridge waveguide lateral index guiding, have attained emitted powers of up to 700 mW in reports dating to 1992. However, these devices typically suffer from a high optical power density of 10-20 MW/cm² at the diode's output facet, which tends to degrade performance.

[0008] Some high-power, semiconductor laser diodes utilize a device structure with a light source (termed "master oscillator") and other components, all integrated onto a common semiconductor substrate. For example, a master oscillator power amplifier (MOPA) laser includes an oscillator and a high-gain optical amplifier that are monolithically integrated.

[0009] FIG. 1 shows an exemplary structure for a tapered-amplifier MOPA laser 100 of the prior art. MOPA laser 100 comprises single-mode laser diode oscillator 101, optional pre-amplifier 102, and optical power amplifier 103 that are formed on a common substrate 110. Single-mode laser diode oscillator 101 includes active region 120 and a gain region 121 that, along with the adjacent layers above and below them, form a transverse waveguide (i.e., a waveguide with direction parallel to the plane of the active region 120). However formed, MOPA laser 100 includes a light emitting region (e.g., active region 120) near a p-n-junction. Pump current applied to electrodes 111 and 112 greater than the

lasing threshold current causes lasing (i.e., generation of amplified lightwaves) in active region 120 and gain region 121. MOPA laser 100 includes facets AR₁ and AR₂ that have antireflective coatings to minimize residual reflection of lightwaves within MOPA laser 100.

[0010] If a distributed Bragg reflector (DBR) laser is employed for the single-mode laser diode oscillator 101, gain region 121 is bounded by first- and second-order gratings 122 and 123. Gain region 121 may be formed by a lateral real refractive index waveguide material structure. Optional pre-amplifier 102 may be employed to optimize signal level and adjust beam shape of the lightwave produced by single-mode laser diode oscillator 101 that is subsequently applied to the following optical power amplifier 103. Pre-amplifier 102 typically includes a single-mode waveguide region that may be tapered. The single-mode waveguide region is formed from layers 115 adjacent to the active region 120, may be electrically isolated from single-mode laser diode oscillator 101, and is energized with pump current applied to electrodes 111 and 113.

[0011] Optical power amplifier 103 is coupled to pre-amplifier 102. Optical power amplifier 103 generally includes a transverse waveguide region about active region 120. In the transverse waveguide region, active region 120 is sandwiched between adjacent higher-bandgap, lower-refractive-index layers. Optical power amplifier 103 is electrically isolated from optical preamplifier 102 and is energized with pump current applied to electrodes 111 and 114.

[0012] A drawback of the MOPA laser structure of FIG. 1 is that the amplification of the beam emitted from the oscillator occurs when the beam passes through a relatively high-gain amplifier (e.g., optical power amplifier 103). The high-gain amplifier may have a typical single-pass gain in the neighborhood of 15 to 30 dB. In contrast, in solid-state lasing media supporting large, high-power optical modes (e.g., Nd:YAG rod external cavity lasers), the single-pass gain is relatively low (e.g., on the order of 0.1 dB per pass).

[0013] In a high-gain amplifier, a semiconductor region that supports multiple, propagating optical modes exhibits non-linearities associated with the optical amplification process. The non-linearities of the amplification process result from saturation of gain and cause beam distortions, including both those known as "self-focusing" which is related to the phenomenon known as "filamentation" that tends to distort the wavefront of the propagating radiation in an uncontrolled fashion. Self-focusing and filamentation arise in large part and are related to the Kramers-Kronig relationship between imaginary and real parts of the refractive index in the amplifier regions of the semiconductor. Self-focusing exists in many semiconductor laser structures, and is particularly pronounced in those structures that support more than one waveguide mode under pumped-cavity conditions. Unstable resonator lasers and surface-emitting, distributed-feedback lasers similarly exhibit distortion from self-focusing.

[0014] FIG. 2a illustrates the broad-area gain section optical intensity profile for a high-gain, high non-linearity gain section affected by self-focusing and filamentation. As shown in FIG. 2a, a plot of optical intensity versus wavelength position indicates that the wavefront exhibits an irregular shape about the center position 75 μ m, and is thus long-term unstable. FIG. 2b illustrates the broad-area gain

section optical intensity profile for a low-gain, low non-linearity gain section not affected by self-focusing. As shown in FIG. 2b, a plot of optical intensity versus wavelength position indicates that the wavefront exhibits a smooth roll-off shape about the center position 75 μm , and is thus long-term stable.

[0015] Most laser diodes are edge emitting and are so called because the light beam emits from the cleaved edge of the processed laser diode semiconductor chip (e.g., through facet AR₂ of FIG. 1). These types of laser diodes are commonly termed Fabry-Perot (FP) laser diodes since the laser diode cavity is similar to that of a conventional gas or solid state laser, but the cavity is formed inside the semiconductor laser diode chip itself. Mirrors may be formed by the cleaved edges of the chip, or one or both of the cleaved edges may be anti-reflection (AR) coated and external mirrors are added.

[0016] A vertical-cavity, surface-emitting laser (VCSEL), on the other hand, emits its beam from the top surface, and potentially the bottom surface, of the semiconductor chip. The cavity comprises a hundred or more layers of mirrors and active regions formed epitaxially on a bulk (inactive) substrate.

[0017] VCSEL devices exhibit the characteristics of low threshold current and low power when compared to other semiconductor laser diode devices that emit single-mode radiation. Lower lasing threshold and drive current results in lower electrical power requirements, potentially faster modulation, simpler drive circuitry, and reduced radio frequency interference (RFI) emission. VCSEL devices are also more tolerant of fluctuations in power supply drive. Directly controlling current for continuous operation is generally sufficient without requiring an optical feedback path, such as a feedback signal generated from a monitor photodiode mounted near one of the facets.

[0018] Although VCSEL devices that exhibit higher power are known in the prior art, these devices emit multi-mode radiation. In general, the broad cavity structure of VCSEL devices does not contain an alignment mechanism for lightwaves propagating through the cavity to produce single-mode radiation. VCSEL devices operated under external cavity, optically pumped conditions may provide higher power while maintaining single-mode emission, but these devices are relatively complex and require unwieldy external optical elements to support the single-mode emission. Such external components generally comprise specially designed mirrors to provide the necessary alignment mechanism.

SUMMARY OF THE INVENTION

[0019] The present invention relates to a master oscillator, vertical emission (MOVE) laser including an oscillator, coupling region, and vertical cavity amplifier region formed on a common substrate. The coupling region may include separately defined expansion and grating regions. The emitted single-mode radiation of the oscillator passes through the expansion region, which is a substantially passive region that provides spatial expansion of the propagating single-mode radiation wavefront with little or no gain. The expanded single-mode radiation from the expansion region passes through the grating region, which provides coupling of the relatively broad wavefront into the cavity of the

vertical-cavity amplifier from the expansion region. The expansion and grating regions may be configured to reduce or eliminate reflection back toward the oscillator of single-mode radiation propagating within the vertical-cavity amplifier. The cavity of the vertical-cavity amplifier is relatively broad in cross-sectional area and relatively short in length when compared to the cavity of the oscillator. The vertical-cavity amplifier operates as a low-gain-per-pass amplifier for incident single-spatial-mode radiation generated by the oscillator. Thus, radiation of relatively low optical power emitted from the oscillator controls single-mode radiation of relatively high optical power emitted by the vertical-cavity amplifier.

[0020] In accordance with an exemplary embodiment of the present invention, an integrated semiconductor laser includes an oscillator having a cavity and capable of generating single-mode radiation; a vertical-cavity amplifier having a cavity broader than the oscillator cavity; and a coupling region having a narrow end coupled to the oscillator cavity and a wide end coupled to the vertical-cavity amplifier. When operating, single-mode radiation received from the oscillator is expanded by the coupling region and coupled into the vertical-cavity amplifier, and the vertical-cavity amplifier emits single-mode radiation at an optical power greater than that of the single-mode radiation generated by the oscillator.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] Other aspects, features, and advantages of the present invention will become more fully apparent from the following detailed description, the appended claims, and the accompanying drawings in which:

[0022] FIG. 1 shows an exemplary master oscillator, power amplifier (MOPA) structure of the prior art;

[0023] FIG. 2a illustrates the broad-area gain section optical intensity profile for a high-gain, high non-linearity gain section affected by self-focusing and filamentation;

[0024] FIG. 2b illustrates the broad-area gain section optical intensity profile for a low-gain, low non-linearity gain section not affected by self-focusing;

[0025] FIG. 3 shows relative positioning of elements for a master oscillator, vertical emission, (MOVE) laser diode in accordance with embodiments of the present invention;

[0026] FIG. 4 shows a cross-sectional view of a MOVE laser diode in accordance with an embodiment of the present invention; and

[0027] FIG. 5 shows a top view of the MOVE laser diode of FIG. 4.

DETAILED DESCRIPTION

[0028] Referring to FIGS. 3, 4, and 5, there is shown a master oscillator, vertical emission (MOVE) laser in accordance with an embodiment of the present invention. MOVE laser 300 includes oscillator 301, coupling region 306, and vertical cavity amplifier 304 all formed on a common substrate 305. Grating region 303 may be positioned either within vertical-cavity amplifier 303 (as shown in FIG. 3), or above or below the vertical-cavity amplifier 304 (as shown in FIG. 4). FIG. 3 shows relative positioning of elements for MOVE laser 300a. Single-spatial-mode radiation propa-

gates from oscillator **301** to vertical cavity amplifier **304** through coupling region **306** comprising expansion region **302** and grating region **303**. As used herein, the terms “single-spatial-mode” and “single-mode” are used interchangeably to refer to single-spatial-mode radiation as light-waves propagating within the elements of MOVE laser.

[0029] In accordance with embodiments of the present invention, oscillator **301** provides single-mode radiation of relatively low power from its cavity over a relatively small (facet) surface area. Coupling region **306** expands the single-mode radiation spatially with little or no gain, thereby providing radiation with a relatively broad wavefront while avoiding effects that tend to cause self-focusing. Coupling region **306** further reflects the broad wavefront radiation into the cavity of the vertical-cavity amplifier, while mitigating reflection of radiation back toward oscillator **301**. Vertical-cavity amplifier **304** operates as a low-gain-per-pass amplifier for incident single-spatial-mode radiation from oscillator **301**, thereby further avoiding effects that tend to cause self-focusing. Vertical-cavity amplifier **304** provides single-mode output power over a relatively broad area, thus acting as an optical power amplifier.

[0030] FIGS. 4 and 5 show cross-sectional and top views, respectively, of MOVE laser **300b** in accordance with an exemplary embodiment of the present invention having common electrode **330** formed on the bottom of substrate **305**, and electrodes **331**, **332**, and **333** formed on the top of MOVE laser **300b**. MOVE laser **300b** may be formed either as a homostructure, single/double heterostructure, or multiple heterostructure. Material composition for MOVE laser **300b** is typically a combination of Group III-V compound semiconductors. Substrate **305** is made of any suitable semiconductor material, and preferred embodiments of the present invention employ GaAs to facilitate epitaxial growth of subsequent GaAs compound layers and their derivatives. Epitaxial growth may be by any suitable technique, such as metal organic chemical vapor deposition, molecular beam epitaxy, or chemical beam epitaxy. As would be apparent to one skilled in the art, other common semiconductor materials may be employed, such as Ge, Si, InAs, InP, and GaSb.

[0031] Oscillator **301** is a laser diode emitting single-mode radiation at a single frequency, and the laser diode is employed as a source of single-mode, coherent optical power for subsequent amplification. The frequency of the single-mode radiation is tailored to the characteristics of vertical-cavity amplifier **304**, and the optical power of the radiation emitted by oscillator **301** is set to optimize injection of coherent power into vertical-cavity amplifier **304**. The cavity of oscillator **301** is relatively narrow when compared to the cavity width of vertical-cavity amplifier **304**. For example, the oscillator cavity would be approximately 3 microns in width, whereas the vertical-cavity amplifier would be between 25 and 500 microns in diameter.

[0032] Oscillator **301** may be embodied as a distributed-feedback Bragg reflector (DFBR) laser diode. In general, any number of different laser diode structures may be employed for oscillator **301** that may be integrated into a semiconductor substrate to provide a source of single-mode, coherent optical power. Other types of laser diode structures include: edge-emitting stripe, tapered stripe, broad stripe, grating-surface-emitting, grating-stabilized broad stripe, and surface-emitting distributed feedback structures. In general,

oscillator **301** includes light-emitting active and gain regions near a pn-junction and within a transverse waveguide **351**. The active region may be formed in any number of ways known in the art, such as by disposing layers of ternary or quasi-ternary compounds (e.g., AlGaAs, InGaAs, InGaAs(Sb)) with one or more quantum wells bounded by barrier regions. Pump current applied to electrodes **330** and **331** greater than the lasing threshold current causes oscillator **301** to generate a single-spatial-mode radiation. The transverse waveguide is coupled to a grating **352** that has a reflection response that peaks at the frequency of the light-wave in the waveguide region. The output single-mode radiation from the grating is directed to expansion region **302**. An optional isolation layer **350** may be employed to isolate the oscillator **301** from the remaining layers of the integrated semiconductor during formation of expansion region **302** and vertical-cavity amplifier **304**.

[0033] Expansion region **302** is a passive, low-gain mode expansion region coupling oscillator **301** to grating region **303**. Expansion region **302** is substantially isolated electrically from oscillator **301**, grating region **303**, and vertical-cavity amplifier **304**. Little or no net gain is provided to the optical signal passing through expansion region **302**, which behaves as an optical waveguide for the propagating light-wave. A split contact **332** is formed on top of expansion region **302**. Current may be injected between electrodes **330** and **332** in a manner sufficient to cause the material of expansion region **302** to be optically transparent to the propagating radiation. The current may be pump current and the expansion region may be formed with an active region if slight gain is required to offset optical signal losses within the material as the lightwave propagates through it.

[0034] As the radiation passes through expansion region **302** toward grating region **303**, the radiation wavefront is expanded laterally as it passes to grating region **303**. Here, “lateral” refers to the direction in the plane of the active region of oscillator **301** perpendicular to the direction of propagation of lightwaves, and perpendicular to the vertical direction (e.g., along the y axis of FIGS. 3, 4, and 5). The direction of emitted radiation (emitted lightwave) propagating from oscillator **301** is referred to herein as the longitudinal direction (e.g., along the x axis of FIGS. 3, 4, and 5). Light is emitted from MOVE laser **300a** and **300b** in the vertical direction, shown in FIGS. 3, 4, and 5 as the axis perpendicular to the top and bottom of MOVE laser **300a** and **300b** (e.g., along the z axis of FIGS. 3, 4, and 5).

[0035] Expansion region **302** operates in similar manner to a pre-amplifier region of a tapered master oscillator, power amplifier (MOPA) of the prior art, but differs in that preferably little or no net gain is provided as the single-mode radiation wavefront expands. When the expanded mode wavefront reaches the vertical-cavity structure, it has expanded to a lateral width significantly wider than that of the output radiation from oscillator **301**. Without significant gain or loss in expansion region **302**, the single-mode radiation beam enlarges laterally in a manner that is free from distortion due to non-linearities and other self-focusing effects that may result from gain. Thus, the width at the beginning of expansion region **302** (i.e., the side coupled to oscillator **301**) is similar to the width of the oscillator waveguide, while the end of expansion region **302** (i.e., the side coupled to grating region **303**) is significantly wider than the width of the oscillator waveguide. The width may

also be significantly wider than that of a single-mode vertical-cavity laser. Consequently, the width at the larger end may be as small as $10\ \mu\text{m}$, or up to $250\ \mu\text{m}$ or more. The typical width of the narrow end is 3 microns.

[0036] Reflected radiation that passes through expansion region **302** toward oscillator **301** is substantially attenuated as it propagates in the direction opposite to lateral expansion. Thus, expansion region **302** acts as a spatial, optical filter to reduce or eliminate incident radiation to oscillator **301**.

[0037] The expansion region **302** and grating region **303** are configured so as to provide radiation from oscillator **301** either perpendicularly (along z axis) to or at a tilted angle (within x-z plane) into vertical-cavity amplifier **303**. Grating region **303** may be positioned either within vertical-cavity amplifier **303** (as shown in FIG. 3) near a, or above or below the stacks of Bragg reflectors **340** and **341** at a port of vertical-cavity amplifier **304** (as shown in FIG. 4).

[0038] Grating region **303** may be formed between two adjacent semiconductor layers having different indices of refraction. Grating region **303** is formed so that, when MOVE laser **300** is operating, a lightwave in grating region **303** may interact with a lightwave propagating in layers of vertical-cavity amplifier **304**. For coupling, the degree of optical lightwave overlap depends on the reflectivity of the grating structure. In general, forming grating region **303** with more teeth and/or deeper teeth results in a greater reflectivity. In addition, spacing between the teeth and the pitch of the spacing tends to effect reflectivity. Preferred embodiments may involve a second order grating structure for grating region **303** that is periodic, satisfies the well-known Bragg condition, and has a reflection response that peaks at the frequency of the lightwave emitted by oscillator **301**. Since grating region **303** has an out-coupling and reflection response tailored to coupling radiation from expansion region **302** to vertical-cavity amplifier **304**, grating region **303** tends not to pass reflected radiation back from vertical-cavity amplifier **304** to expansion region **302**.

[0039] Vertical-cavity amplifier **304** is formed of at least two stacks of Bragg reflectors **340** and **341** disposed about an active region **342**. Active region **342** may be formed in a number of ways known in the art, and for the preferred embodiment may comprise one or more quantum wells bounded by barrier regions adjacent to corresponding Bragg reflectors **340** and **341**. For a preferred embodiment, vertical-cavity amplifier **304** may generally be made of layers of AlGaAs. Each stack of Bragg reflectors **340** and **341** comprises multiple, high-reflectivity dielectric mirror layers formed by alternating the relative concentration of compound elements in each layer of the stack. Various techniques are known in the art for forming the multiple, high-reflectivity dielectric mirror layers in Bragg reflectors **340** and **341**. In addition, one of the stacks of Bragg reflectors **340** and **341** is generally doped with a p-type dopant, while the other stack is generally doped with an n-type dopant. Vertical-cavity amplifier **304** operates as a low-gain-per-pass amplifier because of a relatively short propagation distance between mirrors, which may be approximately $2\ \mu\text{m}$ in the described embodiment.

[0040] Electrode **333** is formed on the top of vertical-cavity amplifier **304**, and portions of electrode **330** are formed under a corresponding area of substrate **305** on the

bottom of vertical-cavity amplifier **304**. In order to allow light to pass through the bottom of MOVE laser **300b**, this area of substrate **305** is preferably a thinned, optically transparent substrate. In addition, portions of electrode **330** that are formed on this area of substrate **305** allow for emission of single-mode output optical power through the bottom of MOVE laser **300b** using techniques known in the art. These techniques may include depositing the electrode material onto substrate **305** and then photo-etching areas, and/or depositing thinned, optically transparent conductor material between the portions of electrode **330** and substrate **305**. Vertical-cavity amplifier **304** is formed such that current injected or pumped into vertical-cavity amplifier **304** preferably does not flow through stacks of Bragg reflectors **340** and **341**. Current flowing through stacks of Bragg reflectors **340** and **341** may generate heat, material dislocation, or other degradation because of electrical impedance of each stack. Vertical-cavity amplifier **304** is substantially isolated electrically from grating region **303**, expansion region **302**, and oscillator **301**.

[0041] Vertical-cavity amplifier **304** operates in a manner similar to that of vertical-cavity surface-emitting lasers (VCSEL) of the prior art. Pump current applied to electrodes **330** and **333** greater than the lasing threshold current causes lasing within the cavity. A broad-cavity VCSEL generally emits radiation having multi-spatial-mode beams. However, in accordance with embodiments of the present invention, injecting a lightwave of single-spatial-mode radiation causes single-mode emission from the broad-area cavity of vertical-cavity amplifier **304**. Thus, vertical-cavity amplifier **304** tends to operate as a regenerative amplifier, in sharp contrast to behavior of an in-plane optical gain amplifier as used in MOPA lasers of the prior art (e.g., MOPA laser **100** of FIG. 1).

[0042] In an integrated semiconductor laser, the master oscillator (e.g., oscillator **301**) may become destabilized due to feedback from the vertical-cavity power amplifier. When destabilized, the master oscillator may cease operation, or change from emitting a single-mode radiation to emitting multi-mode radiation. To reduce the possibility of destabilizing oscillator **301**, preferred embodiments position the grating region **303** outside of (above or below in the vertical axis) the vertical-cavity amplifier **304**, and on the opposite side from which power is extracted. As shown in FIG. 4, grating region **303** couples the radiation into the vertical-cavity amplifier at the base of stack **340**, rather than between stacks as shown in FIG. 3. Single-mode optical radiation from grating region **303** impinges on the vertical-cavity amplifier through a port **350** having higher reflectivity than port **351**. Port **351** is opposite to port **350** and is utilized for the output light beam, as shown in FIG. 4. This structure of FIG. 4, in addition to the spatial filtering of expansion region **302**, attenuates or removes reflected radiation that may propagate in the feedback path back to oscillator **301**.

[0043] For the preferred embodiment of FIG. 4, the stack of Bragg reflectors **340** has a reflectivity (in the absence of operation under the Fabry-Perot cavity and amplification) of about 99.95% at port **350**, while the stack of Bragg reflectors **341** has a reflectivity under the same conditions of about 99.5% at port **351**. Thus, significantly more optical power is emitted through the bottom at port **351** when operating than from the top port **350** of the structure. Under bias, however, the cavity of the vertical-cavity amplifier **304** becomes

significantly more transparent at resonance due to the Fabry-Perot effect, which effect is further enhanced by the presence of optical gain in the cavity. Thus, a relatively small level of optical power injected into the cavity from the master oscillator controls a relatively large level of optical power emitted by the vertical-cavity amplifier in a manner similar to that of the well-known injection-locking effect.

[0044] In comparison to in-plane optical amplifiers such as those used in the prior art, non-linearities are sharply reduced in a vertical optical amplifier because of the low gain of the vertical cavity medium per pass. The gain of each quantum well is quite low, but the gain need only offset slightly the loss caused by the cavity/reflector media for each pass. The real part of the refractive index of the vertical-cavity medium is generally uniform across the medium in two-dimensions. The real part of the refractive index of the vertical-cavity medium is highly uniform because the losses of the vertical cavity medium are quite small and, therefore, may be overcome with low-gain quantum wells within the vertical cavity.

[0045] The embodiments shown and described with respect to **FIGS. 3 and 4** may be preferred because of manufacturing or other specific implementation concerns. However, the present invention is not so limited. Embedding oscillator **331** closer to the substrate, placing grating region below port **351**, and reversing the relative reflectivity of the stacks of Bragg reflectors **340** and **341** may form a MOVE laser having its output light beam through the top of the laser. Such structure may allow for reduced optical power loss and better output coupling of the lightwave by avoiding a relatively long path through the semiconductor substrate. In addition, one skilled in the art would realize that the present invention may be extended to other types of vertical-cavity amplifier structures. For example, a vertical-cavity amplifier with only one stack of Bragg reflectors may be formed and coupled to grating region, possibly having a mirror in between the grating region and stack.

[0046] Thus, there is provided an integrated master oscillator, vertical emission laser in accordance with embodiments of the present invention. It will be further understood that various changes in the details, materials, and arrangements of the parts which have been described and illustrated in order to explain the nature of this invention may be made by those skilled in the art without departing from the principle and scope of the invention as expressed in the following claims.

What is claimed is:

1. An integrated circuit having a semiconductor laser comprising:

- an oscillator having a cavity and capable of generating single-mode radiation;
- a vertical-cavity amplifier having a cavity broader than the oscillator cavity; and
- a coupling region having a narrow end coupled to the oscillator cavity and a wide end coupled to the vertical-cavity amplifier, wherein:

when operating, single-mode radiation received from the oscillator is expanded by the coupling region and coupled into the vertical-cavity amplifier, and the vertical-cavity amplifier emits single-mode radiation at an optical power greater than that of the single-mode radiation generated by the oscillator.

2. The invention of claim 1, wherein the coupling region comprises an expansion region and a grating region.

3. The invention of claim 2, wherein the expansion region allows for lateral spatial expansion of the single-mode radiation between the oscillator and the grating region.

4. The invention of claim 2, wherein the grating region couples the single-mode radiation from the oscillator to the vertical-cavity amplifier.

5. The invention of claim 1, wherein the oscillator is a laser diode.

6. The invention of claim 5, wherein a structure for the laser diode is either edge-emitting stripe, tapered stripe, broad stripe, grating-surface-emitting, grating-stabilized broad stripe, or surface-emitting distributed feedback.

7. The invention of claim 1, wherein the cavity is formed from at least two stacks of reflectors formed about an active region.

8. The invention of claim 7, wherein each stack comprises multiple, high-reflectivity dielectric mirror layers.

9. The invention of claim 8, wherein each stack comprises a plurality of Bragg reflectors.

10. The invention of claim 7, wherein the cavity includes a port at each opposing end of the vertical-cavity amplifier.

11. The invention of claim 10, wherein the grating region is positioned between each of the two stacks of reflectors.

12. The invention of claim 10, wherein:

one of the two stacks has less reflectivity than the other stack, and

the coupling region is positioned 1) adjacent to the port adjacent to the stack having less reflectivity, and

the cavity emits the single-mode light beam from the port at the other end of the vertical cavity amplifier.

13. The invention of claim 1, wherein the oscillator, grating region, and vertical-cavity amplifier are integrated on a common semiconductor substrate.

14. The invention of claim 3, wherein:

the oscillator, grating region, and vertical-cavity amplifier are formed from a plurality of layers,

a material for the common semiconductor substrate is selected from the group consisting of germanium, silicon, gallium arsenide, indium arsenide, indium phosphide, and gallium antimonide, and

the plurality of layers comprises materials selected from Group III-V compounds based on the material selected for the substrate.

15. The invention of claim 1, wherein the vertical-cavity amplifier exhibits a low-gain-per-pass characteristic.

* * * * *