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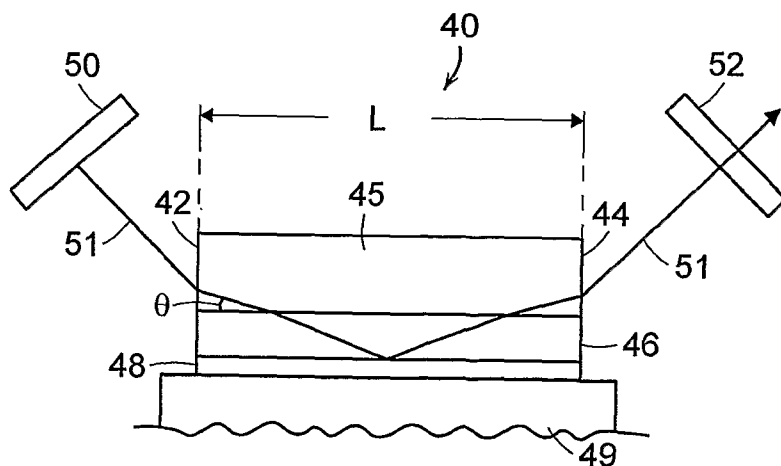
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(54) Title: GRAZING INCIDENCE SLAB SEMICONDUCTOR LASER SYSTEM AND METHOD



(57) Abstract: A semiconductor laser system is disclosed for providing a laser output signal along a first output path responsive to an excitation signal being applied to a planar semiconductor gain medium. The semiconductor gain medium includes quantum wells within a cavity path, and the cavity path extends at least through the semiconductor gain medium, is reflected by an interface that provides substantially total internal reflection and that is substantially parallel to the gain medium, back through the semiconductor gain medium, enters the semiconductor substrate, and then exits the semiconductor substrate.

WO 2007/100341 A2

GRAZING INCIDENCE SLAB SEMICONDUCTOR
LASER SYSTEM AND METHOD

This application claims priority to U.S. Patent Application Serial No. 11/118,233 filed on April 29, 2005.

5 The present invention was developed, at least in part, under a grant from the United States Air Force under Contract No. FA19628-00-C-0002. The United States government has certain rights to this invention.

BACKGROUND

10 The invention relates to semiconductor lasers, and particularly relates to high power, high brightness semiconductor lasers in which the output power contained within a single spatial optical mode is high.

Semiconductor lasers typically include edge emitting semiconductor lasers (e.g., in-plane semiconductor lasers) and surface emitting semiconductor lasers (e.g.,
15 vertical cavity semiconductor lasers).

Figure 1 shows an in-plane semiconductor laser in which the optical mode is defined by an optical waveguide. In particular, the in-plane semiconductor laser of Figure 1 includes a substrate 10, and cladding layers 12 and 14 on either side of a semiconductor gain layer 16. The cladding layers and gain layer are typically grown
20 epitaxially onto the substrate using well-known techniques. Modern gain layers comprise one or more quantum wells. The gain layer 16 may be pumped along a pump stripe 18 by either optical or electrical pumping, producing a laser beam 20 in a direction A as shown. Typically, cleaved facets of the semiconductor form the mirrors that comprise the optical resonator. As such, the laser beam propagates in a

direction that is substantially normal to these facets. For stable propagation of a single spatial-mode, the refractive index fluctuations (Δn) within the waveguide, as defined by the stripe width and gain region thickness, should be sufficiently small.

The allowed magnitude of index fluctuations to maintain single-mode operation varies
5 as $\Delta n \propto (\lambda/d)^2$ where λ is the free-space wavelength and d is the mode size.

Otherwise, it is observed that the optical mode degrades as the beam propagates along the pump stripe. If the optical mode itself causes the index fluctuations, the optical mode is found to degrade in a process called filamentation. In-plane lasers exhibit a strong tendency to filament because of the long interaction length of the optical mode
10 with the gain layer. In near-IR laser diodes, it has generally been observed that the filamentation caused by carrier-induced and temperature-induced refractive index fluctuations limit the mode size to roughly $d \approx 5 \lambda$. The slab coupled optical waveguide laser concept has realized this mode size in both transverse dimensions.

See "Slab-coupled 1.3- μm semiconductor laser with single-spatial large-diameter
15 mode," J.N. Walpole, et al., IEEE Photonics Technology Letters, vol.14, p.756 (2002). Given the limits on transverse mode size for in-plane lasers, the single-mode output power will be limited by either catastrophic optical damage (COD) or by thermal roll-over. The COD limit in GaAs-based lasers is about 10 – 40 MW/cm².

Given a mode size of about 5λ with λ approximately equal to 1 μm , this translates to
20 a maximum single-mode output power of about 2 - 10 W. Thermal roll-over refers to a reduction in device efficiency when the gain region over-heats. The output power at which thermal roll-over occurs can be increased by reducing the heat load per unit area. For a given transverse mode size, the device area can be increased by making longer devices. This, however, requires very low waveguide losses.

25 Figure 2A shows a vertical external cavity surface emitting laser (VECSEL) in

which the gain layer is pumped optically. The VECSEL includes a multi-quantum-well gain layer 22a, a multi-layer Bragg mirror 24a, and an antireflective coating 28a. The laser is mounted on a heat sink 26a, and is optically pumped by a pump beam 30a, generating a laser output beam 32a. The optical resonator is formed between the

5 Bragg mirror 24a and an output mirror 34a that is external to the semiconductor. As compared to the in-plane laser, a larger mode size is stable in the VECSEL because the laser beam traverses a shorter distance in the semiconductor. It accumulates, therefore, only a small optical path difference (OPD) across its wavefront on each bounce through the cavity. This OPD can generally be compensated in the external

10 cavity. Filamentation is also greatly reduced because of the short interaction length with the gain region. Furthermore, any tendency toward filamentation is suppressed by spatial filtering in the external cavity. As a result, the mode size in VECSELs can be several 100's of microns in diameter. The COD-limit is then >1 kW and does not limit the average output power. In practice, the single-mode output power from

15 VECSELs has been limited by thermal rollover to less than 30 W. If the pump spot size is increased to reduce the power dissipation per unit area, then in-plane parasitic amplified spontaneous emission can become problematic. See for example, "High-power optically pumped semiconductor lasers", J. Chilla, et al., Proceedings of the International Society for Optical Engineering (SPIE), vol. 5332, p. 143 (2004).

20 Another difficulty with the VECSEL is that the total thickness of the multi-quantum-wells that comprise the gain region is so thin that the gain per bounce is small. This requires a low-loss optical cavity to achieve lasing, and even small optical losses degrade the power efficiency. A higher single-bounce gain is desirable for increased power efficiency and robustness against thermal roll-over.

25 Figure 2B shows a vertical external cavity surface emitting laser (VECSEL) in

which a multi-quantum well gain sheet is pumped electrically. Similar to the device shown in Figure 2A, this device typically includes a multi-quantum-well gain layer 22b, a multi-layer Bragg mirror 24b and a heat-sink (not shown). The electrically pumped VECSEL also includes a substrate 28b and two electrical contacts 36b and 38b. The top electrical contact 36b is attached to the substrate 28b and includes a hole 37b to allow the generated laser beam 32b to exit the semiconductor through an optional frequency converter 31b before exiting via an output mirror 33b. The electric pumping signal is applied to nodes 30b and 34b of contacts 36b and 38b respectively. To allow electrical pumping along a current path as indicated at 39b, the substrate must be doped to be electrically conductive. Doping of the substrate leads to optical absorption losses for the laser beam. As a result, there is a trade-off between electrical and optical efficiency. For VECSELs, this optical absorption is especially detrimental to its optical efficiency because the gain per pass through the active region is small. Certain prior art devices, for example, employ an intermediate mirror to shield a laser gain region from the lossy substrate. See, for example, Published PCT Patent Application No. WO US01/67563. Furthermore, the hole in the top electrical contact that is needed to allow the laser beam to exit the semiconductor, requires that the electrical current flow laterally in a direction normal to the light propagation. This causes the edges of the pumped gain volume to experience higher current flow than the center. This non-uniformity in current flow, or current crowding, limits the size of the optical mode. For all of the above reasons, single mode output power in electrically pumped VECSELs is significantly below that of optically pumped lasers and has typically been limited to less than about 0.5 W. See "High-brightness 980-nm pump lasers based on the Novalux extended cavity surface-emitting laser (NECSEL) concept", J.G. McInerney, Proceedings of the

International Society for Optical Engineering (SPIE), vol. 4947, p. 240 (2003).

There is a need therefore, for a semiconductor laser that provides improved power and brightness and which is amenable to both optical and electrical pumping.

5 SUMMARY

In accordance with an embodiment, the invention provides a semiconductor laser system for providing a laser output signal along a first output path responsive to an excitation signal being applied to a planar semiconductor gain medium. The semiconductor gain medium includes quantum wells within a cavity path, and the
10 cavity path extends at least through the semiconductor gain medium, is reflected by an interface that provides substantially total internal reflection and that is substantially parallel to the gain medium, back through the semiconductor gain medium, enters the
5 semiconductor substrate, and then exits the semiconductor substrate.

In accordance with another embodiment, the laser signal extends through the
15 semiconductor gain layer, is reflected by a reflective interface back through the semiconductor gain layer, into the semiconductor substrate, and out of the semiconductor substrate. The cavity path approaches the reflective interface at an angle between about 1 degree and about 20 degrees.

In accordance with another embodiment, the planar semiconductor gain
20 medium has a first surface thereon within a cavity path, and the cavity path extends through the semiconductor gain medium, is reflected by a reflective interface back through the semiconductor gain medium, into the substrate, and out of the semiconductor substrate. The cavity path passes through the semiconductor gain
medium at an angle of between about 1 degree and about 20 degrees with respect to
25 the first surface of the semiconductor gain medium.

In accordance with another embodiment, the invention provides a semiconductor laser that includes first and second reflectors, a gain layer, a total internal reflection interface, a substrate on which the gain layer and total internal reflective interface are attached, and an energy source. The first and second reflectors
5 define a resonant cavity, and the resonant cavity defines a fundamental cavity mode of an associated laser beam. The gain layer comprises one or more quantum wells disposed within the resonant cavity. The total internal reflective interface is substantially parallel with the gain layer. The energy source is for energizing the gain layer within a first volume. The energy source causes optical energy emission to
10 propagate such that the optical energy emission is reflected by the total internal reflective interface at an angle that provides total internal reflection of the optical energy emission and enters the substrate at an angle of between 1 and 20 degrees with respect to the gain layer.

15 BRIEF DESCRIPTION OF THE ILLUSTRATED EMBODIMENTS

The following detailed description may be further understood with reference to the accompanying drawings in which:

Figure 1 shows an illustrative diagrammatic side view of an in-plane semiconductor laser in accordance with the prior art;

20 Figure 2A shows an illustrative diagrammatic side view of an optically pumped vertical external cavity surface emitting semiconductor laser in accordance with the prior art;

Figure 2B shows an illustrative diagrammatic side view of an electrically pumped vertical external cavity surface emitting semiconductor laser in accordance
25 with the prior art;

Figure 3 shows an illustrative diagrammatic side view of a semiconductor laser system in accordance with an embodiment of the invention;

Figure 4 shows an illustrative diagrammatic side view of a semiconductor laser system in accordance with an embodiment of the invention being used in a ring-cavity configuration;

Figure 5 shows an illustrative diagrammatic side view of a semiconductor laser system in accordance with an embodiment of the invention that includes reflective surfaces on the end facets to form a resonator;

Figure 6 shows an illustrative diagrammatic side view of a semiconductor laser system in accordance with an embodiment of the invention that includes a partial reflector;

Figure 7 shows an illustrative diagrammatic side view of a semiconductor laser system in accordance with an embodiment of the invention being optically pumped either through the substrate or through the heat-sink;

Figure 8 shows an illustrative diagrammatic side view of a semiconductor laser system in accordance with an embodiment of the invention being electrically pumped;

Figure 9 shows an illustrative diagrammatic side view of multiple devices in accordance with an embodiment of the invention that are connected in series; and

Figure 10 shows an illustrative diagrammatic side view of multiple devices in accordance with an embodiment of the invention that are connected in parallel.

The drawings are shown for illustrative purposes only and are not to scale.

DETAILED DESCRIPTION OF THE ILLUSTRATED EMBODIMENTS

Applicant has discovered that a grazing incidence slab semiconductor laser

may be formed that provides efficient, high power and high brightness output that overcomes the COD limitations of in-plane lasers and the thermal limitations of VECSELS. Moreover, as compared with VECSELS, lasers in accordance with certain embodiments of the invention provide a laser geometry that is amenable to achieving
5 high output power levels with electrical pumping.

A benefit of semiconductor lasers is that gain materials may be designed to provide specific wavelengths for a variety of applications, that the efficiency may be high, and that electrical pumping may be used for the excitation. It is also known, however, that semiconductor lasers generally have a large thermo-optic coefficient
10 (dn/dT). The large dn/dT indicates strong thermal lensing, and hence degradation of laser beam quality in applications where it is known that dn/dT presents limitations.

It is also known that certain solid state lasers such as disclosed in U.S. Patent No. 5,315,612, may provide a slab geometry with a shallow, grazing angle of incidence with total internal reflection to permit optical gain to be accessed near the
15 pump face of a laser material (e.g., Nd:YVO₄). The optical path difference (OPD) however, varies with respect to dn/dT , and it is known that semiconductor materials generally have a thermo-optic coefficient that is on the order of ten times larger than solid-state laser materials (e.g., Nd:YVO₄). A large OPD gives rise to distortions in the spatial properties of the laser beam, which degrade the beam quality and, hence,
20 the brightness. This generally indicates that a similar geometry is not suitable for semiconductor lasers.

At this point, a distinction should be made between solid-state laser materials (e.g., Nd:YVO₄) and semiconductor materials. Solid-state laser materials are generally those in which activated ions are incorporated into oxide and fluoride hosts.
25 A comprehensive review of solid-state laser materials is given in A. A. Kaminskii,

Laser Crystals: Their physics and properties (Springer-Verlag, New York, 1990). It is not known to be able to electrically pump these solid-state laser materials and hence they are limited to being optically pumped. The optical absorption depth in these materials at the pump wavelength depends on the concentration of activated ions and can be as shallow as a few hundred microns as in the case of Nd:YVO₄. On the other hand, the semiconductor materials of interest here are crystalline compounds taken from columns III and V of the periodic table (e.g., GaAs, InP, GaP, GaN, GaSb) or from columns II and VI of the periodic table (e.g., ZnS, ZnSe). Well known techniques such as molecular beam epitaxy (MBE) and organo-metallic vapor phase epitaxy (OMVPE) allow for dissimilar, but nearly lattice-matched, semiconductor materials to be grown in layers with atomic layer control. These techniques allow for the fabrication of the very thin layers called quantum wells that provide the optical gain in most modern semiconductor lasers. Semiconductors have an electrical conductivity which can be increased to useful levels by doping with appropriate ions. This allows optical gain to be excited within the quantum well, for instance, by electrical pumping. When optically pumped with photons having energy greater than the semiconductor's energy bandgap, the absorption depth can be as shallow as a few microns. This is several orders of magnitude shallower than for a solid-state laser material and is highly beneficial for a particular embodiment of the invention as discussed below.

In the case of the slab geometry, applicant has discovered that factors other than the thermo-optic coefficient contribute to the OPD and may be minimized in semiconductor lasers as compared to solid state lasers, permitting semiconductor lasers to be created using the grazing incidence geometry. In particular, the OPD

varies as $OPD_{\max} \propto P_{\text{diss}} \rho_{\text{th}} \frac{dn}{dT} L_p$ where P_{diss} is the power dissipated per unit area,

ρ_{th} is the thermal resistance, and L_P is the depth of the gain region from the heatsink.

With a large thermo-optic coefficient (dn/dT) that is on the order of ten times larger than Nd:YVO₄, the above equation would indicate that the OPD variation would be prohibitive for semiconductor lasers. The cross-section thickness of semiconductor
5 lasers, however, is typically on the order of 100 times smaller than that of solid state lasers. This may more than compensate for the larger thermo-optic coefficient (dn/dT), particularly for optically pumped semiconductor lasers for which there is negligible heat generation within the substrate.

The invention provides the use of a semiconductor gain chip that utilizes a
10 gain layer and total internal reflection (TIR) in an external cavity configuration to create a semiconductor laser that overcomes limitations of both in-plane and vertical cavity semiconductor lasers to achieve high power, high-brightness emission. The process of total internal reflection occurs when light propagates in a medium having a refractive index n_{high} and is incident onto an interface with a second material having a
15 lower refractive index n_{low} . Specifically, total internal reflection occurs when the angle of incidence, relative to the plane of the interface, is less than the critical angle where $\cos(\theta_{critical}) = n_{low}/n_{high}$. In this case, the light wave decays exponentially with distance within the lower index material. If the lower index material is relatively thick, then the incident wave is fully reflected. If the lower index material is
20 sufficiently thin, being sandwiched between two materials of higher refractive index, then a portion of the optical energy can be transmitted through the low index material even though the angle of incidence is less than $\theta_{critical}$. In this case, the optical energy is said to tunnel through the low index material in a process called frustrated total internal reflection. In addition to the process of total internal reflection, other

methods are often used to create reflectors of optical energy. These include, for instance, the use of metal mirrors and distributed Bragg reflectors.

In accordance with an embodiment of the present invention, a semiconductor chip 40 including a substrate 45 is cleaved to a length L and the facets 42, 44 are anti-reflection (AR) coated for the laser wavelength as shown in Figure 3. A gain layer 46 may include quantum well semiconductor material, and may be either optically or electrically pumped. A low refractive index material 48 is placed between the gain layer 46 and the heat-sink 49. The total internal reflection is provided at the interface between the low index material 48 and the gain layer 46. An external cavity is built around the gain chip that includes a highly reflective back mirror 50 and front output coupler 52. The laser mode enters the substrate through the AR-coated facet of the laser, traverses the gain layer at an internal angle, θ , experiences total internal reflection at the interface 48 between the gain layer and a low index layer, re-enters the substrate, and finally exits from the opposite facet of the laser as shown at 51. The laser sample is mounted to a heat-sink 49 in proximity to the low index layer.

The optical mode size at the semiconductor facet in the horizontal dimension (in the plane of Figure 3) is limited by the thickness of the substrate and can be $>100 \mu\text{m}$. Since the mode can be so large, the COD limit is much greater than for in-plane lasers and will not limit the average output power. For a given laser mode size, the beam intercepts the gain region in a footprint that is $1/\sin\theta$ times larger than the VECSEL case. Choosing an internal angle of $\theta = 0.1$ radian results in a footprint that is larger by approximately a factor of ten. This reduces the thermal load per unit area proportionately. The optical mode size in the vertical dimension (into the page) may be $> 100 \mu\text{m}$, further decreasing the thermal load. The gain per bounce of the laser beam is also larger than the VECSEL by the factor $1/\sin \theta$. Choosing $\theta = 0.1$ radian

increases the gain per bounce by a factor of ten for a fixed number of quantum wells and pump intensity. This makes the cavity more tolerant to excess loss. On the other hand, the interaction length of the laser mode with the gain region is increased by the factor $1/\sin \theta$ as compared to VECSELS. This increased interaction length enhances
5 the tendency toward filamentation as compared to VECSELS. However, this interaction length is still much shorter than for in-plane lasers and it is expected that the beam quality will be limited by thermal lensing in the substrate rather than filamentation. Similar to the VECSEL, it is expected that any tendency toward multi-mode operation or filamentation can be counteracted in the external cavity.

10 Other advantages of the invention with respect to VECSELS are as follows. The large aspect ratio of the beam footprint on the gain layer is a better match to the emission pattern of diode lasers that are used for optical pumping. Also, this geometry is amenable to electrical pumping because the electrical contacts do not obscure the laser beam path. This overcomes issues related to current crowding.
15 Finally, reflection from the bottom surface of the gain chip depends on TIR and hence does not require thick multilayer Bragg reflectors as in the case of a VECSEL. This eases material growth considerably.

In accordance with another embodiment, the system may be employed with mirrors 54 and 56 to form a ring cavity configuration in which the laser output from
20 the semiconductor is cycled back through the device as shown at 55 in Figure 4. In accordance with another embodiment, the system may include a semiconductor gain chip that includes a substrate 58, a gain layer 60 and a low index material 62 that provides a TIR interface with the gain layer 60 as shown in Figure 5. The system of Figure 5 further includes mirrors that are formed in the semiconductor and coated
25 with a reflective material 64, 66 as shown to provide a resonator cavity within the

chip for the laser path as shown at 65. Although the figure shows two mirrors being formed in the semiconductor, one mirror could be formed in the semiconductor while others are external to the semiconductor.

When it is desirable to increase the gain per bounce through the gain layer, a partial reflector may be included between the gain layer and the substrate as shown in Figure 6. Similar to Figure 3, a semiconductor chip is cleaved to a length L and the facets 72, 74 are anti-reflection (AR) coated for the laser wavelength and comprises a gain layer 76, low index material 77, and a heat-sink 78. The gain layer 76 may include a plurality of layers of gain material as shown. In addition, a partial reflector 80 is placed between the gain layer and the substrate 82. The purpose of this partial reflector is to form an optical resonator comprising the partial reflector, gain layer, and low index material. This causes the laser beam 73 that is incident onto the partial reflector to bounce back-and-forth through the gain layer several times, in a process called resonant enhancement, prior to exiting the gain layer and re-entering the substrate. It should be noted, however, that resonant enhancement occurs only for a limited range of internal angles and laser wavelengths. Under resonance conditions, the gain can be several times greater than in the case of no resonant enhancement. The operation of the partial reflector can be based on frustrated total internal reflection in which it provides interfaces that are capable of total internal reflection, but whose layer is too thin to provide complete reflection. As such, the partial reflector may be composed of a material having a refractive index that is lower than that of the substrate or gain layer. The reflectivity of this partial reflector then depends on its thickness and refractive index as well as the internal angle of the laser beam. Typically, the reflectivity of this partial reflector will be chosen to fall in the range 10% – 80%. Since the partial reflector will generally be composed of a material

having a larger energy bandgap than found in the gain layer, it can also accomplish the dual purpose of confining electronic carriers to the gain layer.

Various pumping configurations are shown in Figures 7 and 8. In Figure 7, the optically pumped semiconductor laser is mounted epi-side down onto a heatsink 84 that may, for example, be a copper heat-spreader. The device includes a substrate 45, a gain layer 46, a low index layer 48, and a TIR interface between the gain layer 46 and the low index layer 48. The device substrate is substantially transparent to the wavelength of the pump source 86 and the pump light is transmitted through the substrate. The laser path is shown at 81. In other embodiments, if the substrate 45 is not transparent to the wavelength of the pump source 86, the device may be bonded epi-side down to a heat-sink 84 that is transparent to the pump light (for example, diamond) and optical pumping can be provided using pump source 88. The system may also include an optional non-linear crystal 53 for frequency conversion.

In Figure 8, the electrically pumped semiconductor laser is mounted epi-side down onto a heatsink 90 (e.g., a copper heat spreader), and includes a substrate 45, a gain layer 46, a low index layer 94, end facets 42 and 44, and electrical contact layers 92 and 95 that are coupled to nodes for electrically pumping the laser. The laser path is shown at 83. No hole in the contact layer 92 (such as shown in Figure 2B) is required as the output beam is provided through the end facet 44 as shown. The system also includes a highly reflective mirror 50, an output mirror 52, and an optional non-linear crystal 53 for frequency conversion.

In various embodiments, the gain layer and low index layers discussed above are grown epitaxially onto a semiconductor substrate such as GaAs, InP, GaSb, GaN and others. In this case, the semiconductor substrate must be substantially optically transparent to the laser output. For optical pumping in a system as shown in Figure 7

(using the pump source 86), the substrate must also be transparent to the optical pump radiation. Alternatively, the gain layer and low index layers could be epitaxially grown on a semiconductor substrate, then transferred and bonded to another suitable substrate using techniques well known in the art. Furthermore, the low index layer
5 does not have to be epitaxially grown. It could, for instance, consist of an evaporated film or be bonded to the gain layer.

In accordance with further embodiments, the system may include a plurality of devices 100a, 100b, 100c that each include a substrate 102a, 102b, 102c, a gain medium 104a, 104b, 104c, a low index layer 106a, 106b, and 106c, and a heat-sink
10 108a, 108b, 108c that are connected together in series as shown in Figure 9 for providing a continuous laser path 101 through the devices. Any optical means known in the art may be used to optically connect devices in series.

In accordance with further embodiments, the system may include a plurality of devices 110a, 110b, 110c that each include a substrate 112a, 112b, 112c, a gain
15 medium 114a, 114b, 114c, a low index layer 116a, 116b, and 116c, and a heat-sink 118a, 118b, 118c that are connected together in parallel with their outputs 119a, 119b, 119c joined together into a single output beam 120 by appropriate optical elements including mirrors 124 and a collimating lens 126 as generally shown in Figure 10. The devices of Figures 9 and 10 need not be separate from each other, but may be all
20 part of a single substrate.

Any number of external cavity configurations may be employed with semiconductor gain chips of the present invention. Further, non-linear crystals could be incorporated into the cavity to allow for intracavity frequency conversion. Also, a semiconductor gain chip could be configured as an amplifier to amplify incident laser
25 radiation. Also, since the laser chip is resistant to COD because of the large mode

size, the gain chip is particularly suited for generating short-duration pulses of high peak power. This could be accomplished by using well-known techniques such as Q-switching and mode-locking. Also, since the laser beam exits the laser facet at a non-normal angle, for some embodiments, the modal reflectivity for the laser beam can be very low. This is advantageous for applications such as external cavity wavelength tuning and mode-locking. Also, it can be appreciated that arrays of lasers could be configured within a single gain chip for power scaling. Techniques such as coherent and incoherent beam combining could be applied to such arrays to further increase the brightness of sources based on this invention. Applications of such a laser source are numerous and could include printing, communications, medicine, laser radar, and optical pumping of other lasers and amplifiers.

Those skilled in the art will appreciate that numerous modifications and variations may be made to the above disclosed embodiments without departing from the spirit and scope of the invention.

15 What is claimed is:

1 1. A semiconductor laser system for providing a laser output signal along a first
2 output path responsive to an excitation signal being applied to a planar semiconductor
3 gain medium comprising quantum wells within a cavity path, said cavity path
4 extending at least through said semiconductor gain medium, being reflected by an
5 interface that provides substantially total internal reflection and that is substantially
6 parallel to the gain medium, back through said semiconductor gain medium, entering
7 the semiconductor substrate, and then exiting the semiconductor substrate.

1 2. The semiconductor laser system as claimed in claim 1, wherein said cavity
2 path approaches said total internal reflective interface at of angle between about 1
3 degree and about 20 degrees.

1 3. The semiconductor laser system as claimed in claim 1, wherein said
2 semiconductor laser system includes mirrors in said cavity path to form an optical
3 resonator.

1 4. The semiconductor laser system as claimed in claim 3, wherein said mirrors
2 are outside of a semiconductor slab that includes said semiconductor gain medium.

1 5. The semiconductor laser system as claimed in claim 3, wherein the optical
2 resonator includes a non-linear material that is capable of converting the lasing
3 frequency of the semiconductor laser to another frequency.

1 6. The semiconductor laser system as claimed in claim 1, wherein said cavity
2 path passes through said semiconductor gain medium at an angle of between about 1
3 degree and about 20 degrees.

1 7. The semiconductor laser system as claimed in claim 1, wherein said
2 semiconductor gain medium is optically pumped.

1 8. The semiconductor laser system as claimed in claim 1, wherein said
2 semiconductor gain medium is optically pumped through the semiconductor substrate.

1 9. The semiconductor laser system as claimed in claim 1, wherein said
2 semiconductor gain medium is electrically pumped.

1 10. The semiconductor laser system as claimed in claim 1, wherein said
2 semiconductor laser system is provided in a ring configuration.

1 11. The semiconductor laser system as claimed in claim 1, wherein said
2 semiconductor laser system includes a partial reflector that is placed between the gain
3 layer and the substrate, and where the partial reflector utilizes the process of frustrated
4 total internal reflection.

1 12. The semiconductor laser system as claimed in claim 1, wherein said
2 semiconductor substrate includes one or more mirrors formed on the surfaces of the
3 semiconductor.

1 13. The semiconductor laser system as claimed in claim 1, wherein said
2 semiconductor laser system includes a plurality of semiconductor gain mediums.

1 14. A semiconductor laser system for providing a laser output signal along a first
2 output path responsive to an excitation signal being applied to a planar semiconductor
3 gain layer within a cavity path, said cavity path extending through said semiconductor
4 gain layer, being reflected by a reflective interface back through said semiconductor
5 gain layer, into the semiconductor substrate, and out of the semiconductor substrate,
6 wherein said cavity path approaches said reflective interface at an angle between
7 about 1 degree and about 20 degrees.

- 1 15. The semiconductor laser system as claimed in claim 14, wherein said
2 reflective interface is a total internal reflective interface.
- 1 16. The semiconductor laser system as claimed in claim 14, wherein said
2 semiconductor laser system includes mirrors in said cavity path.
- 1 17. The semiconductor laser system as claimed in claim 16, wherein said mirrors
2 are outside of a semiconductor slab that includes said semiconductor gain medium.
- 1 18. The semiconductor laser system as claimed in claim 16, wherein said mirrors
2 are positioned to provide a ring configuration.
- 1 19. The semiconductor laser system as claimed in claim 14, wherein said
2 semiconductor laser system includes a partial reflector that is placed between the gain
3 layer and the substrate, and where the partial reflector utilizes the process of frustrated
4 total internal reflection.
- 1 20. The semiconductor laser system as claimed in claim 14, wherein said system
2 includes a plurality of individual laser devices that are coupled together in series with
3 one another.
- 1 21. The semiconductor laser system as claimed in claim 20, wherein said plurality
2 of individual laser devices are directly coupled together in series with one another.
- 1 22. The semiconductor laser system as claimed in claim 14, wherein said system
2 includes a plurality of individual laser devices that are coupled together in parallel
3 with one another.

1 23. The semiconductor laser system as claimed in claim 22, wherein said plurality
2 of individual laser devices are directly coupled together in parallel with one another.

1 24. The semiconductor laser system as claimed in claim 14, wherein said
2 semiconductor laser system includes a plurality of semiconductor gain mediums.

1 25. The semiconductor laser system as claimed in claim 14, wherein said
2 semiconductor gain medium is optically pumped.

1 26. The semiconductor laser system as claimed in claim 14, wherein said
2 semiconductor gain medium is electrically pumped.

1 27. A semiconductor laser system for providing a laser output signal along a first
2 output path responsive to an excitation signal being applied to a planar semiconductor
3 gain medium having a first surface thereon within a cavity path, said cavity path
4 extending through said semiconductor gain medium, being reflected by a reflective
5 interface back through said semiconductor gain medium, into the substrate, and out of
6 the semiconductor substrate, wherein said cavity path passes through said
7 semiconductor gain medium at an angle of between about 1 degree and about 20
8 degrees with respect to said first surface of said semiconductor gain medium.

1 28. A semiconductor laser comprising:
2 first and second reflectors defining a resonant cavity, said resonant cavity
3 defining a fundamental cavity mode of an associated laser beam;
4 a gain layer comprising one or more quantum wells disposed within said
5 resonant cavity;
6 a total internal reflective interface that is substantially parallel with said gain
7 layer;

8 a substrate on which the gain layer and total internal reflective interface are
9 attached; and

10 an energy source for energizing said gain layer within a first volume, said
11 energy source causing optical energy emission to propagate such that said optical
12 energy emission is reflected by said total internal reflective interface at an angle that
13 provides total internal reflection of said optical energy emission and enters the
14 substrate at an angle of between 1 and 20 degrees with respect to the gain layer.

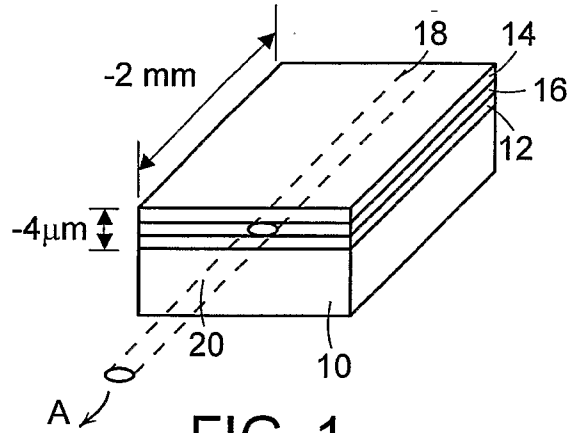


FIG. 1
PRIOR ART

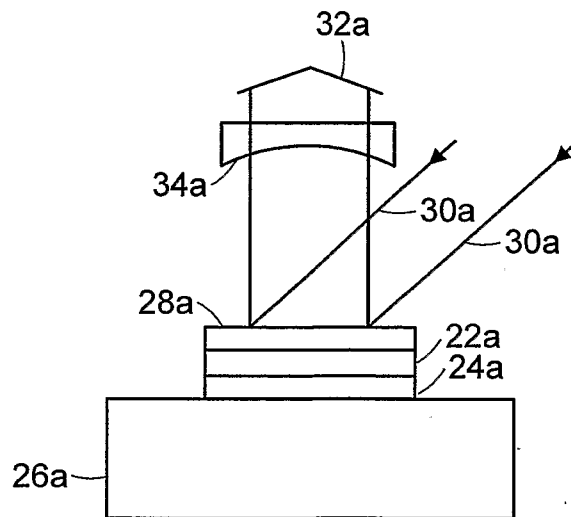


FIG. 2A
PRIOR ART

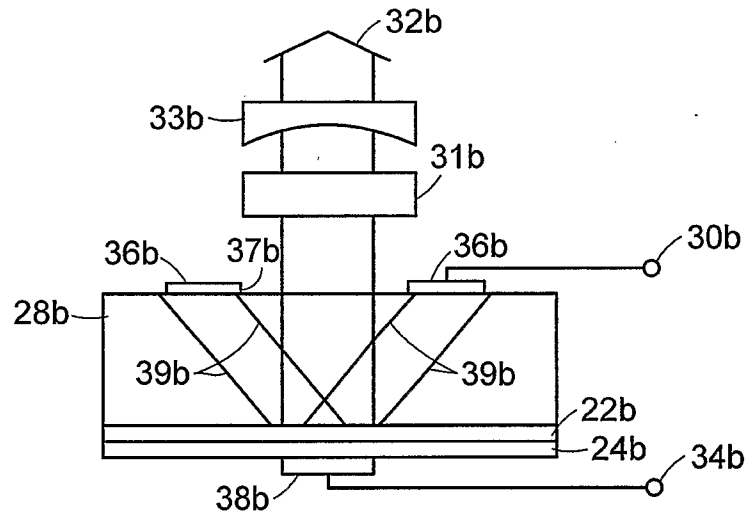


FIG. 2B
PRIOR ART

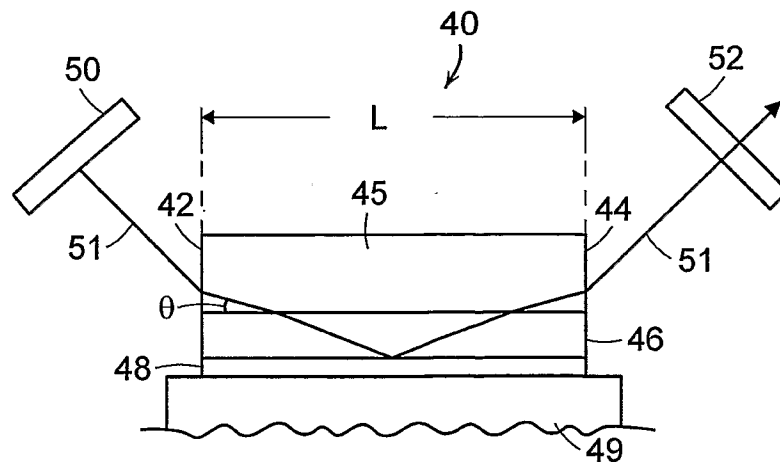


FIG. 3

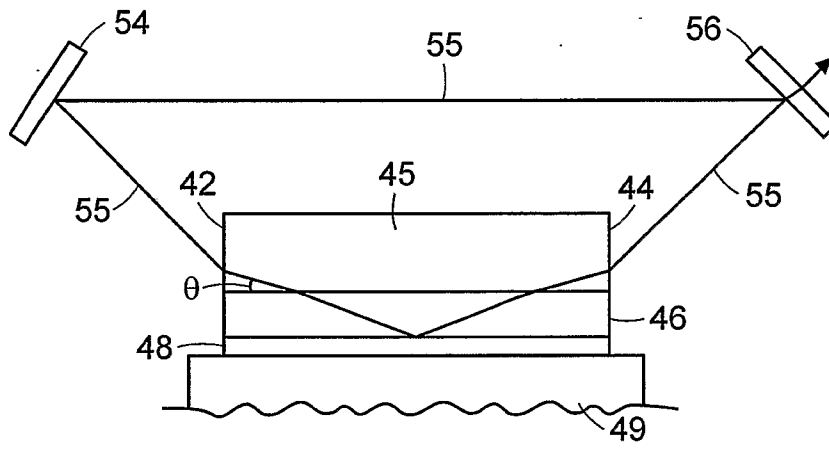


FIG. 4

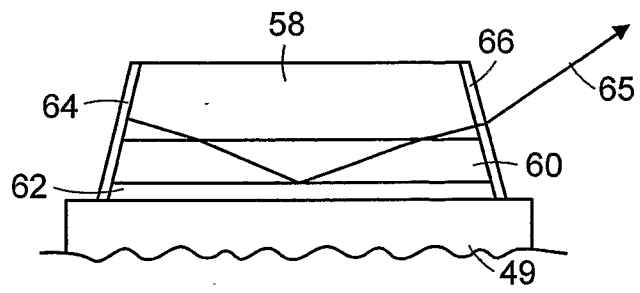


FIG. 5

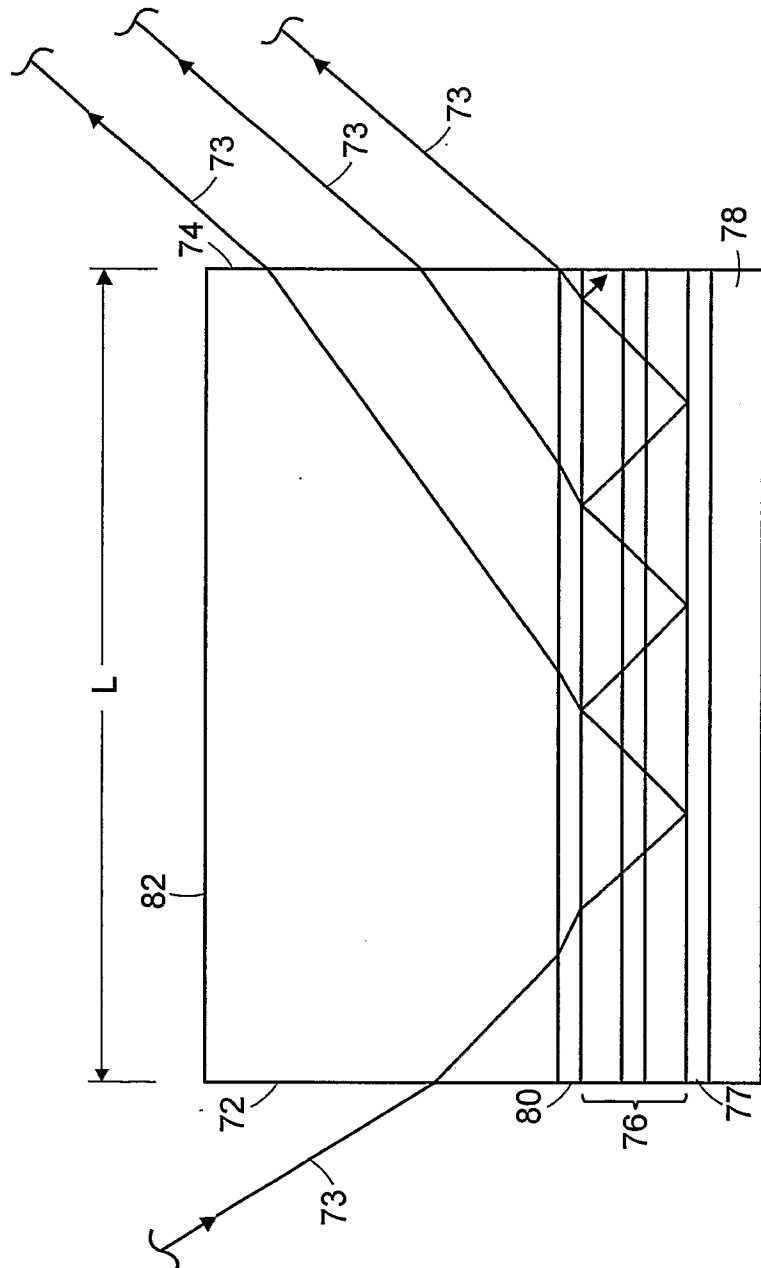


FIG. 6

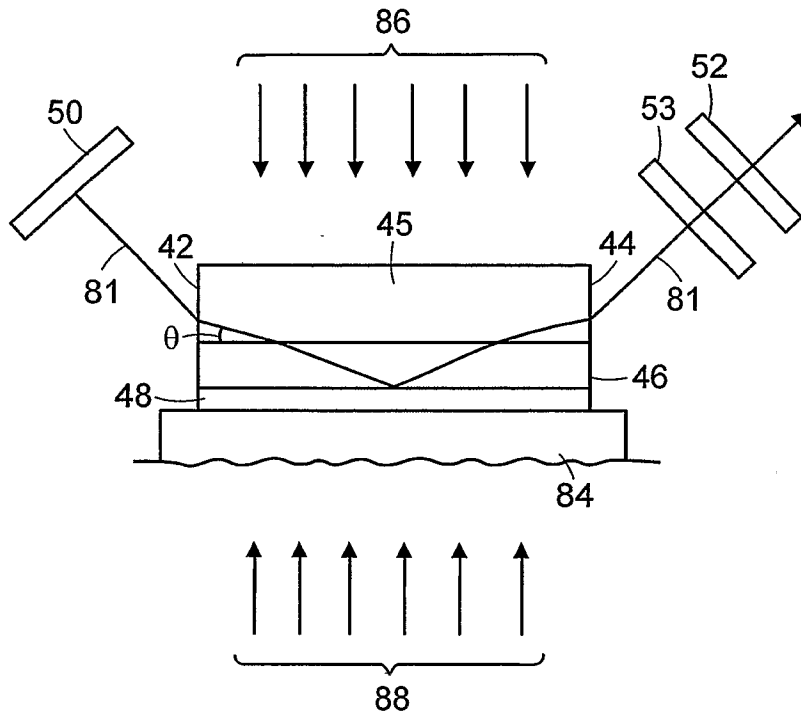


FIG. 7

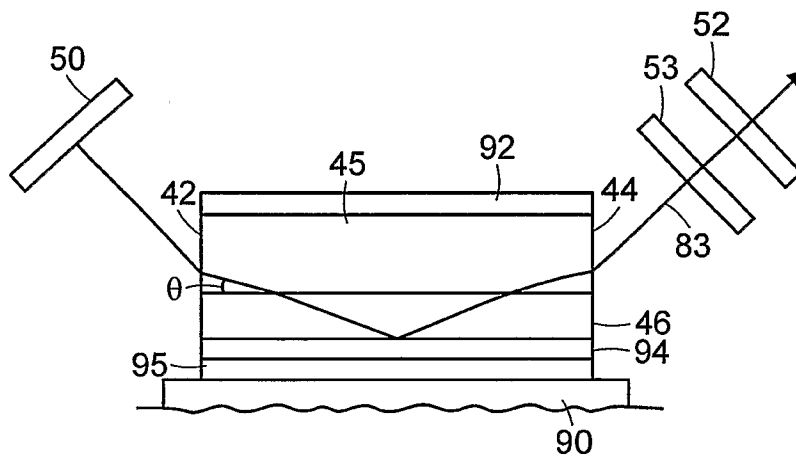


FIG. 8

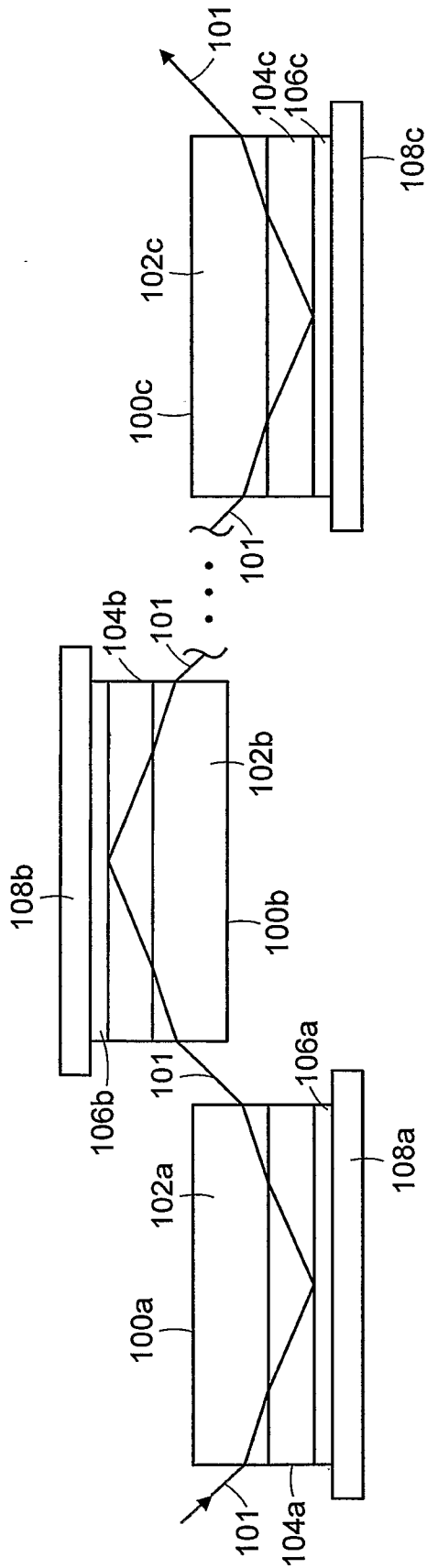


FIG. 9

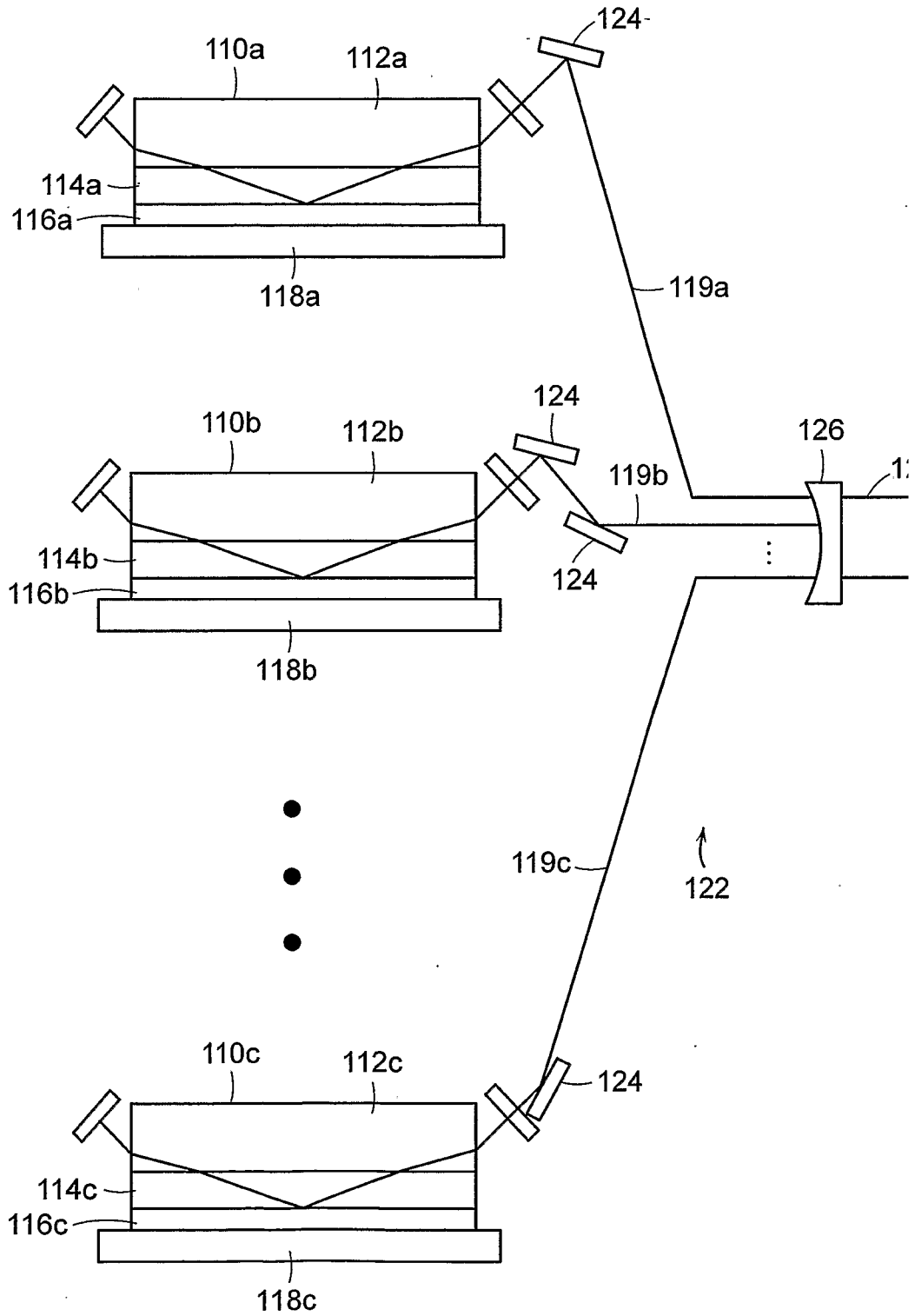


FIG. 10