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(54) **MONOLITHICALLY INTEGRATED MODE-LOCKED VERTICAL CAVITY SURFACE EMITTING LASER (VCSEL)**

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(51) **Int. Cl.**^{7} **H01S 3/08**

(52) **U.S. Cl.** **372/96**; 372/92

(58) **Field of Search** 372/43, 45, 46, 372/49, 75, 96, 98, 99, 101, 103, 50, 47, 18

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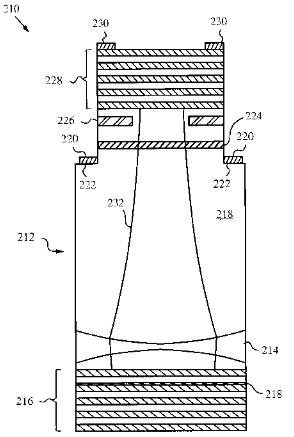
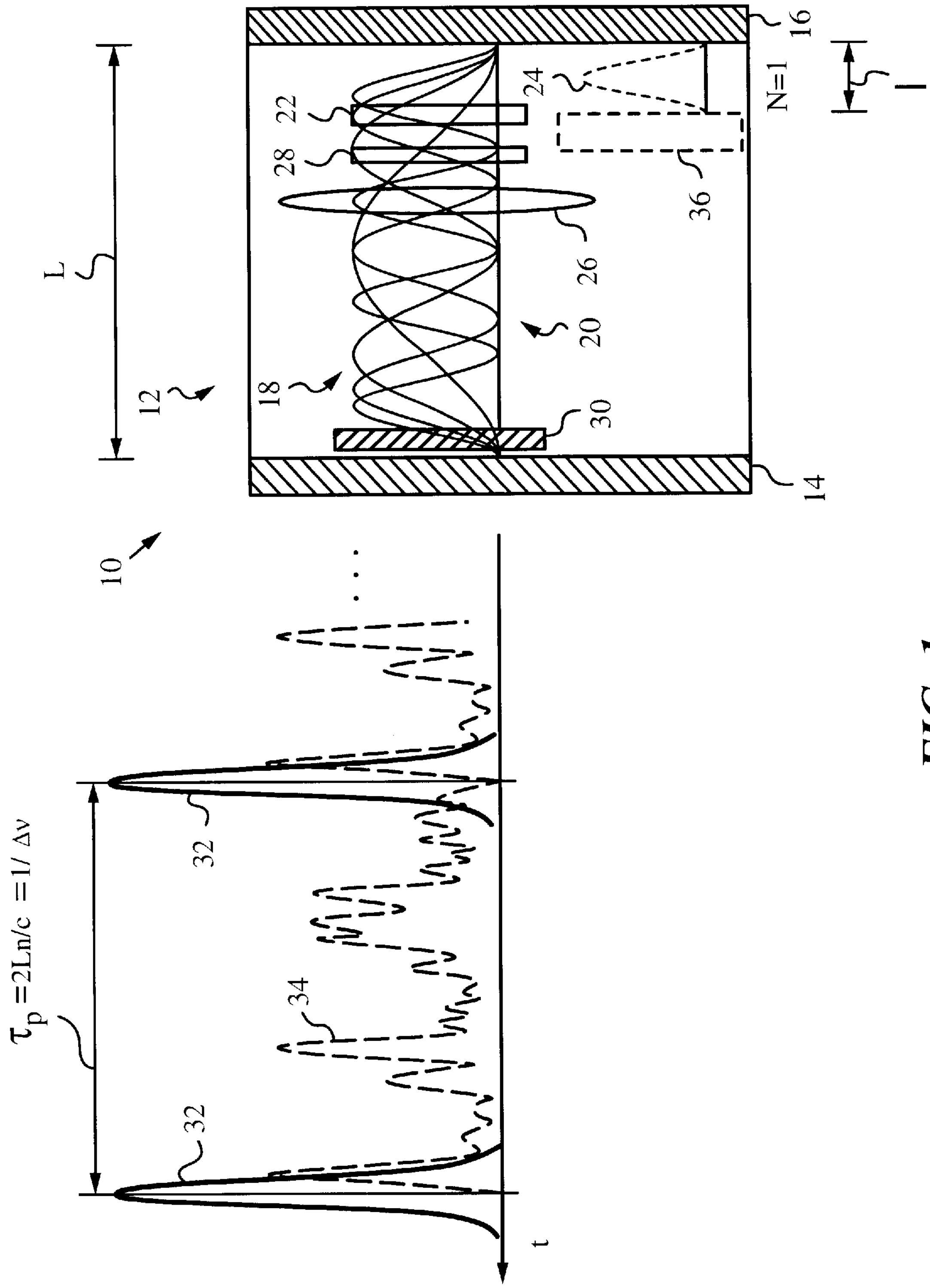
(57) **ABSTRACT**

A monolithically integrated, mode-locked vertical cavity surface emitting laser (VCSEL) for emitting ultrafast high power pulses. The resonator of the VCSEL has an active medium for emitting a radiation, a spacer for extending the resonator to a length L at which a significant number N of axial modes of the radiation are supported in the resonator and a saturable absorber for mode-locking. The VCSEL has an arrangement for stabilizing the resonator such that one transverse mode of the radiation is supported within the resonator. The VCSEL also has an arrangement for compensating dispersion of the radiation occurring in the resonator.

18 Claims, 6 Drawing Sheets

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N=1
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FIG. 1

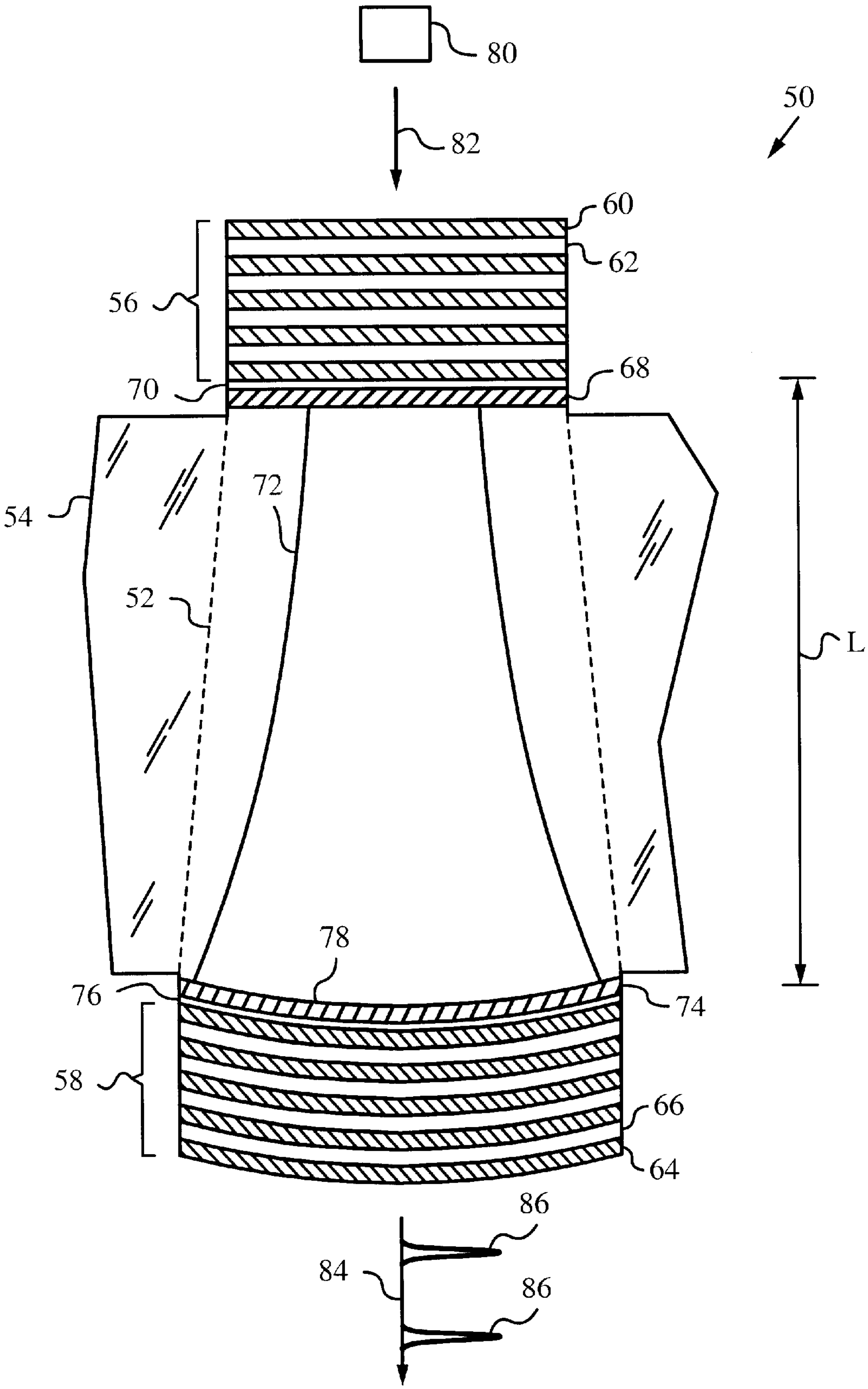


FIG. 2

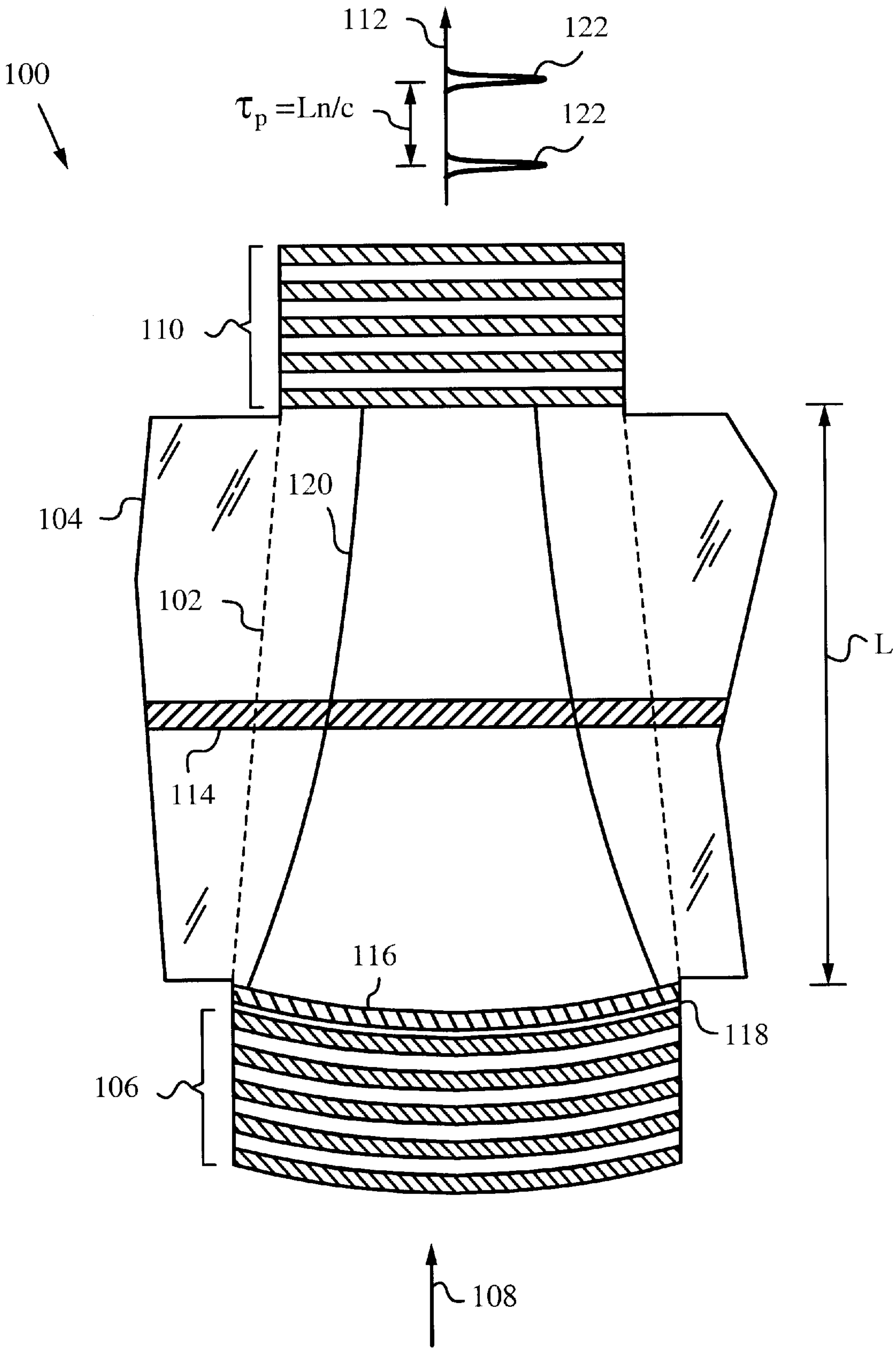
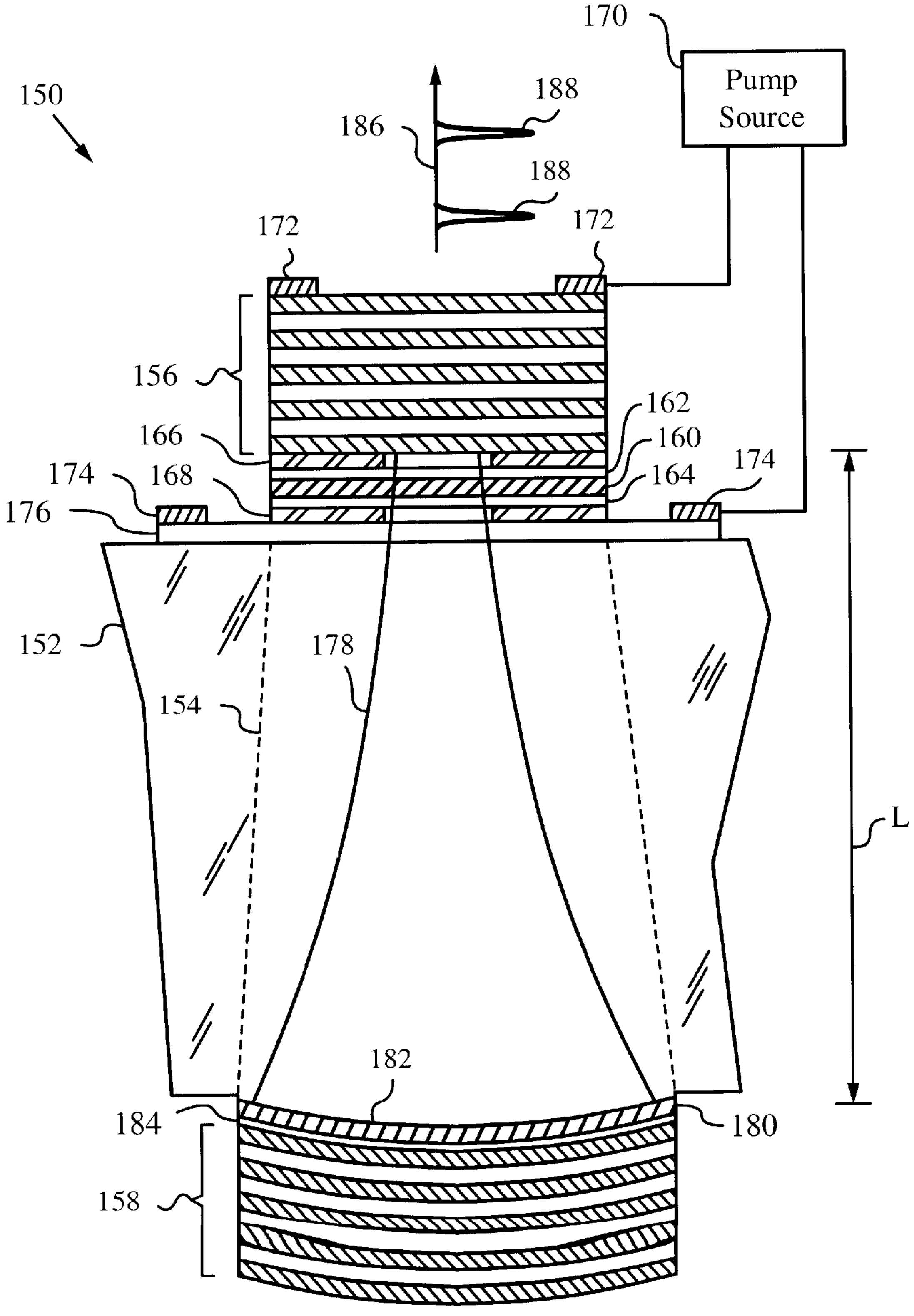


FIG. 3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Pump Source
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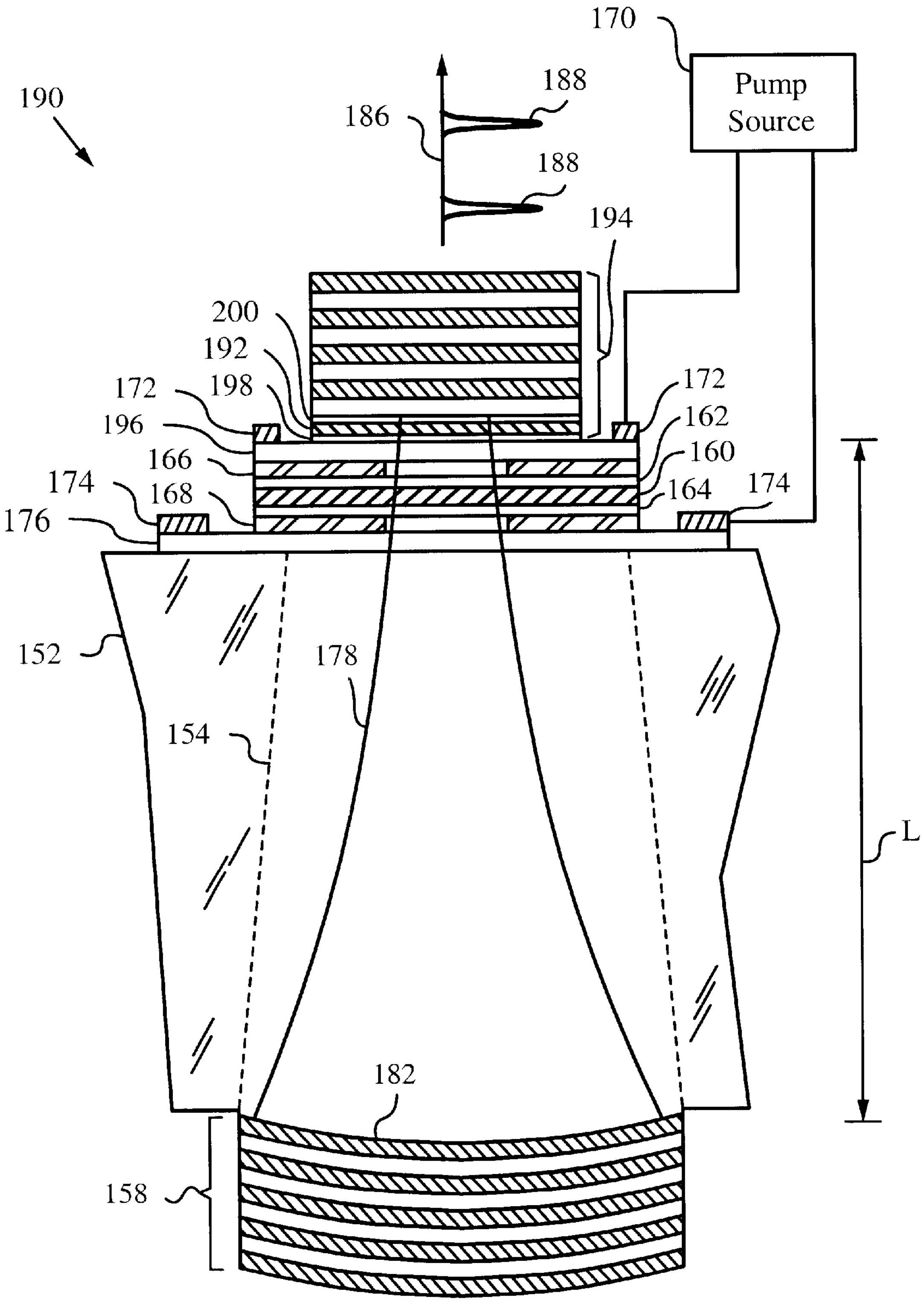
FIG. 4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Pump Source
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FIG. 5

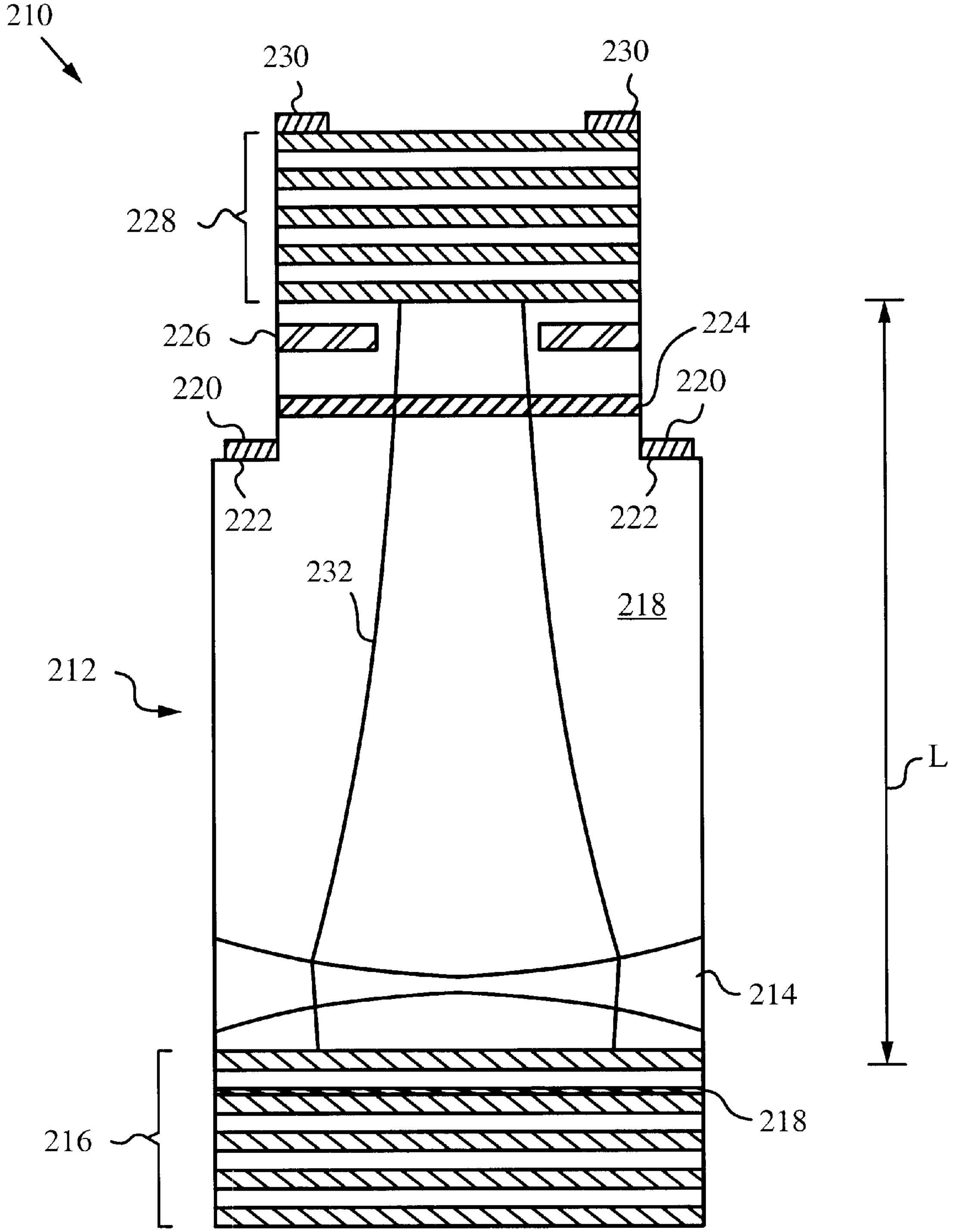

FIG. 6

MONOLITHICALLY INTEGRATED MODE-LOCKED VERTICAL CAVITY SURFACE EMITTING LASER (VCSEL)

RELATED APPLICATIONS

This application is based on the Provisional Patent Application No. 60/362,839 filed on Mar. 7, 2002 and herein incorporated by reference.

FIELD OF THE INVENTION

The present invention relates generally to vertical cavity surface emitting lasers (VCSELs), and in particular to a monolithically integrated VCSEL whose resonator cavity is designed for mode-locking.

BACKGROUND OF THE INVENTION

The vertical cavity surface emitting laser (VCSEL) is a well-known type of semiconductor laser. Its advantages include compactness, single axial mode emission, high quality circular beam shape, ease of mass production, and simple testability. Most VCSELs have a short resonator cavity, which limits their longitudinal or axial lasing modes to one.

Mode-locking is a known method capable of delivering short and high power pulses of radiation. Lasers with sufficiently long resonator cavities to support a significant number of axial lasing modes take advantage of mode-locking to produce a superposition of the axial modes yielding ultrashort pulses with very high peak powers. For more information on the theory of mode-locking and fundamental mode-locking techniques the reader is referred to Orazio Svelto, Principles of Lasers, translated by David C. Hanna, 4th edition, Plenum, pp. 330–364. A number of mode-locking techniques rely on a shutter or saturable absorber to mode-lock a number of the axial modes supported by the resonator cavity. Specifically, passive mode-locking takes advantage of the high peak power of the pulses as criteria for the saturable absorber to force the laser to run in mode-locked condition.

Because mode-locking is capable of generating a train of ultrashort pulses with high peak powers and low jitter it has many applications in a variety of fields. Short optical pulses have a large spectral bandwidth and can be used to generate multiple wavelength channels for telecommunication systems such as wavelength-division-multiplexed (WDM) and dense WDM (DWDM) optical communications networks. A high pulse repetition rate can also be utilized as a source for optical time-division-multiplexed (TDM) signals or for timing control signals in sampling applications. High repetition rate and low jitter mode-locked pulses can also be used for clock distribution in electronic systems.

It has been recognized that combining the advantages of VCSEL lasers with mode-locking would be of great benefit. In fact, the prior art teaches various structures and methods for using VCSELs in an external cavity mode-locking arrangement. For example, Jiang W., et al., "Femtosecond Periodic Gain Vertical-Cavity Lasers", IEEE Photonics Technology Letters, Vol. 5, No. 1, January 1993, pp. 23–25 discloses an external cavity actively mode-locked VCSEL. This device is optically pumped by a mode-locked Ti:Sapphire laser. Jiang W., et al., "Electrically pumped mode-locked vertical-cavity semiconductor laser", Optics Letters, Vol. 18, No. 22, November 1993, pp. 1937–1939 also teach an externally mode-locked VCSEL which is electrically rather than optically pumped. Hoogland S., et al., "Passively Mode-Locked Diode-Pumped Surface-Emitting Semiconductor Laser", IEEE Photonics Technology Letters, Vol. 12, No. 9, September 2000, pp. 1135–1137 also teach an optically pumped VCSEL which is mode-locked using a saturable absorber mirror forming a part of an external cavity. For further examples the reader is referred to Dowd P., et al., "Mode-Locking of an InGaAs VCSEL in an External Cavity", LEOS 1995, IEEE, 8Th Annual Meeting Conference Proceedings, Vol. 2, pp. 139–140; Haring, R., et al., "Passively Mode-Locked Diode-Pumped Surface-Emitting Semiconductor Lasers", CLEO 2000, Technical Digest (IEEE Cat. No. 00CH37088), pp. 97–98.

The disadvantages of using VCSELs in external cavity arrangements include large size, alignment problems and poor scalability. In fact external mode-locking is incompatible with one of the major advantages of VCSELs, namely the ability to manufacture them in dense arrays or integrate them into optoelectronic chips. Therefore, VCSELs that are mode-locked with an external cavity cannot be used in most of the desired applications that stand to gain the most from short, stable and high power pulses.

In accordance with another approach, it has also been proposed to lengthen the VCSEL structure and filter transverse modes that tend to naturally arise in long resonator cavities. This approach is discussed, e.g., by Nikolajeff F., et al., "Spatial-mode control of vertical-cavity lasers with micromirrors fabricated and replicated in semiconductor materials", Applied Optics, Vol. 38, No. 14, May 1999, pp. 3030–3038. This reference teaches the fabrication of micromirrors on substrates to spatially filter transverse modes in the far field for external cavity lasers and suggests ways of implementing the idea on monolithic cavities.

U.S. Pat. No. 5,574,738 to Morgan teaches yet another approach to derive high frequency pulses from a VCSEL. Specifically, Morgan teaches a GHz-range frequency-modulated laser using a VCSEL with a saturable absorber contained within the VCSEL's distributed Bragg reflector to self-pulsate the VCSEL in the GHz regime. The repetition frequency is modulated with current, saturable absorber biasing or cavity design. The principles of self-pulsation are similar to those of Q-switching or spiking in which a build-up of population inversion while saturable absorber losses are high causes a high power laser pulse to develop when the saturable absorber losses drop. Thus, the self-pulsation technique taught by Morgan is implemented with a single axial mode in a short VCSEL.

In contrast with the phenomenon of self-pulsation used by Morgan, mode-locking requires a large number of axial modes to be supported by the VCSEL. In mode-locking the function of the saturable absorber is to absorb slow and low power components of the superposition produced the randomly phased axial modes. Meanwhile, fast and high power components of the superposition will saturate the absorber and pass through it. Thus, during mode-locking the saturable absorber induces the laser to yield high power mode-locked pulses.

The operation of the absorber in mode-locking is also in stark contrast with its operation in Q-switching, where it is used to prevent lasing in all modes while a population inversion is being build up. A drop in the absorption of the absorber upon saturation causes the laser to produce a pulse also referred to as giant pulse. The giant pulse is not a result of any particular superposition of axial modes. A Q-switched laser with a saturable absorber has build up times, as well as rise and fall times that depend on the cavity design and never reach mode-locking. In Q-switching the laser is not continuously on; lasing action is being turned on and off. In a mode-locked laser, on the other hand, all the modes are lasing continuously. It should also be noted that the repetition rates in mode-locking are determined by the cavity length while in Q-switching is determined by how fast can inversion be reached.

In fact, none of the prior art teachings can be used to devise a monolithically integrated mode-locked VCSEL, i.e., a VCSEL that is integrated in one device and does not require the use of an external cavity for mode-locking operation. That is because simply increasing the cavity size of a conventional VCSEL introduces significant problems related to resonator stability and dispersion. An additional problem relates to the bulk associated with the addition of mode-locking components, and associated loss of compactness. Therefore, it would be a major advance in the art of semiconductor lasers to provide a new type of VCSEL that combines the compactness and ease of mass production of conventional VCSELs with the advantageous properties of mode-locked lasers.

OBJECTS AND ADVANTAGES

In view of the above shortcomings of the prior art, it is a primary object of the invention to provide a monolithically integrated VCSEL that can be mode-locked to deliver high frequency and high power ultrafast pulses. In particular, it is the object of the invention to ensure resonator stability in VCSELs with extended cavities and to compensate for dispersion to thus enable further pulse compression.

It is another object of the invention to provide for monolithically integrated mode-locked VCSELs, which are compact and easy to mass-produce.

These and numerous other advantages of the present invention will become apparent upon reading the following description.

SUMMARY

The objects and advantages of the invention are achieved by a monolithically integrated, mode-locked vertical cavity surface emitting laser (VCSEL) in accordance with the invention. The resonator of the VCSEL has an active medium for emitting a radiation, a spacer for extending the resonator to support a significant number of axial modes of the radiation and a saturable absorber for establishing a certain phase condition between these modes to mode-lock them. The VCSEL has an arrangement for stabilizing the resonator such that diffraction losses are minimized and furthermore, only one transverse mode of the radiation is supported within the resonator. Additionally, the VCSEL is provided with an arrangement for compensating dispersion of the radiation occurring in the resonator.

The resonator is defined between a first reflector and a second reflector. Conveniently, at least one of these reflectors is a distributed Bragg reflector (DBR). In one embodiment of the invention the arrangement for stabilizing the resonator includes a specific curvature of the at least one DBR. In addition, the aperture of the at least one DBR is defined to ensure single transverse mode operation. Furthermore, the arrangement for stabilizing the resonator can include a resonator length as a geometric limitation. In fact, it is preferred that the length of the resonator be equal to twice the radius of curvature of the DBR reflector such that the resonator is a half confocal resonator. In the same embodiment or in a different embodiment the arrangement for compensating dispersion can be a chirp introduced into the at least one DBR reflector.

The arrangement for stabilizing the resonator can also include a lensing element. The lensing element can be provided independent of whether the resonator does or does not have a curved reflector. Preferably, the lensing element is a layered microlens embedded inside the resonator between the reflectors.

The monolithically integrated VCSEL and all of its components including the arrangements for stabilizing the resonator and dispersion compensation can be built on a single substrate. Preferably, the substrate is used as the spacer in this case. Any suitable pumping device can be used to pump the active medium residing in the resonator. The pumping device can be an electrical pumping device delivering a suitable current to the active medium. Alternatively, the pumping device can be an optical pumping device injecting pump radiation into the resonator to pump the active medium. When using an optical pumping device it is advantageous to place the saturable absorber at an opposite end of the resonator opposite from where the active medium is located. Also, the pump radiation should preferably be delivered through the reflector at the end where the active medium is located. The active medium can be any suitable lasing medium including a medium with quantum wells.

The invention further provides for a method of mode-locking the monolithically integrated VCSEL. Specifically, the resonator is preferably extended to support a significant number of axial modes of the radiation emitted by the active medium. The more axial modes are available, the more modes become available for mode-locking and producing the mode-locked output pulse. In some situations **5** or even fewer axial modes may be sufficient to obtain satisfactory pulses of output radiation.

A detailed description of the invention and the preferred and alternative embodiments is presented below in reference to the attached drawing figures.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** is a diagram illustrating the principles of a mode-locked vertical cavity surface emitting laser (VCSEL) in accordance with the invention.

FIG. **2** is a cross sectional view of an optically pumped mode-locked VCSEL in accordance with the invention.

FIG. **3** is a cross sectional view of another optically pumped mode-locked VCSEL in accordance with the invention.

FIG. **4** is a cross-sectional view of an electrically pumped mode-locked VCSEL in accordance with the invention.

FIG. **5** is a cross-section of another electrically pumped mode-locked VCSEL.

Fig. **6** is a cross sectional view illustrating the use of a microlens for stabilizing a resonator in a mode-locked VCSEL in accordance with the invention.

DETAILED DESCRIPTION

The invention will be best understood by initially referring to the diagram in FIG. **1** illustrating the general principles of a monolithically integrated, vertical cavity surface emitting laser **10** (VCSEL) in accordance with the invention. VCSEL **10** has a resonator cavity or resonator **12** of length L delimited by a first reflector **14** and a second reflector **16**. Length L is sufficiently large to support a significant number N of longitudinal or axial modes **18** of a radiation **20** under the gain bandwidth of active medium **22** located in resonator **12**. In this diagram axial modes **18** are indicated by their field intensities related to the square of the electric field (E^2).

The specific number N of axial modes **18** required for mode-locking will depend on the application and may range from 5 or even fewer to hundreds of modes, as will be appreciated by one skilled in the art.

Although a significant number of axial modes **18** are necessary for effective mode-locking, it is not desirable for resonator **12** to support many transverse modes. In fact, it is preferred that resonator **12** support only one transverse mode, i.e., the fundamental TEM_{00} mode. Thus, to prevent resonator **12** from supporting numerous transverse modes made possible by extended length L, VCSEL **10** has a device **26** for stabilizing resonator **12**. In this case, device **26** is schematically designated as a lens, but other elements including apertures and/or curved reflector geometries can be used as well, as described below. Lens **26** focuses radiation **20** near the axis of resonator **12** to suppress transverse modes beyond the fundamental TEM_{OO}. Additionally, a device **28** for preventing dispersion of radiation **20** is provided in cavity **12**. In this case device **28** is a chirped wavelength-dependent retarder, but it can be another dispersion compensating device, as described below.

Resonator **12** also contains a saturable absorber **30** for establishing a certain phase relationship between modes **18**. For example, a constant phase difference ϕ may be set up between successive modes **18** by saturable absorber **30**. Alternatively, absorber **30** can be used to establish a linearly or even non-linearly varying phase difference between successive modes **18**, as will be appreciated by those skilled in the art.

The phase difference ϕ brings about output of mode-locked pulses **32** obtained from a superposition of modes **18** at phase difference ϕ. The typical superposition of modes **18** output by resonator **12** without mode-locking is indicated by the dashed line **34** for comparison purposes. The period τ_p between pulses **32** is equal to:

$$\tau_p = \frac{2Ln}{c} = \frac{1}{\Delta f},$$

where c is the speed of light, n is the index of refraction of resonator **12** and Δf is the free spectral range or separation between axial modes **18**.

The spacing of modes **18** in frequency is given by:

$$\Delta f = \frac{c}{2Ln},$$

which is the same as the repetition rate of the pulses or the inverse of period τ_p between pulses **32**. The mode spacing in wavelength can be calculated as:

$$\Delta\lambda = \frac{\lambda^2}{2Ln}$$

The number of modes **18** depends on how much bandwidth VCSEL **10** is able to mode-lock. Typical bandwidths in edge emitters are around 5 nm, however this could vary by a few nm. When resonator **12** has a length L=500 μm then at 980 nm center wavelength the wavelength spacing is 2.72 Å and the total number N of modes **18** is around 18 (N=18). If pulses **32** are transform-limited, meaning that dispersion has been controlled, then pulses **32** can be as short as 640 fs. On the other hand, if resonator **12** has a much shorter length, e.g., L=136 μm, then the wavelength spacing could be up to 1 nm and mode-locking the same bandwidth of 5 nm to obtain the same pulse duration of 640 fs requires only 5 modes **18** (N=5). Thus, the actual number N of modes **18** required to achieve mode-locking and generate the desired pulses **32** will vary substantially, typically from 5 or even less to several hundred or even more. Meanwhile, length L of resonator **12** can be varied from about 100 μm at which the repetition rate of pulses **32** is about 426 GHz to hundreds of μm.

For comparison purposes, a prior art resonator of length l is indicated between reflector **16** and a dashed reflector **36**. Length l is short in comparison to length L and only sufficient to support one axial mode **24**, N=1, of radiation under the gain spectrum. The presence of only one axial mode **24** precludes the phenomenon of mode-locking from occurring altogether.

The above principles can be employed to produce a large variety of VCSELs in accordance with the invention. One particular embodiment of a monolithically integrated, mode-locked VCSEL **50** is illustrated in FIG. **2**. VCSEL **50** has a resonator **52** of length L defined in a substrate **54** between a top or first reflector **56** and a bottom or second reflector **58**. First reflector **56** is a flat distributed Bragg reflector (DBR) built up of a number of alternating layers **60**, **62**. Second reflector **58** is a curved DBR built up of a number of alternating layers **64**, **66**. DBR **56** and DBR **58** can be fabricated by epitaxial semiconductor growth or deposition of dielectrics. DBR **56** and DBR **58** may have different numbers of layers, and many different materials and compositions can be chosen for their fabrication. Preferably, however, alternating layers **60**, **62** and **64**, **66** are alternating AlGaAs/GaAs epitaxial layers, or alternating SiO_2, Si_xN_y dielectric layers, each with an optical thickness of one-quarter wavelength of a radiation **72** to be reflected within resonator **52**.

An active medium **68** is positioned at top end of resonator **52** below first DBR **56** and is separated from DBR **56** by a spacing layer **70**. Active medium **68** is any suitable material providing optical gain in a wavelength range of interest and able to generate radiation **72** in that wavelength range. For example, active medium **68** is a material having defined therein one or more quantum wells using gain materials and barrier materials well-known to those skilled in the art. Preferably, medium **68** uses InGaAs quantum wells with GaAs well barriers (not shown). Other material, still within the GaAs system, such as GaInNAs(Sb) can be used to extend the design to longer wavelengths. Furthermore, the devices could also be implemented using other material systems such as InP with InGaAsP or InGaAlAs quantum wells.

A saturable absorber **74** is located at the bottom end of resonator **52** opposite from the end where active medium **68** is located. Absorber **74** is separated from bottom DBR **58** by a spacing layer **76**. Absorber **74** can be a layer of semiconductor material. Such materials are well-known to exhibit saturable absorption. Preferably, the material is grown in such a way as to reduce the time scale of absorption saturation recovery or carrier lifetime. Known methods for such reduction include low-temperature growth of GaAs, proton implantation, or incorporation of absorber **74** in a reverse-biased diode. Quantum well materials are also known to have desirable absorption saturation behavior and can be used as absorber **74**.

In the present embodiment absorber **74** is grown on a curved surface **78** of substrate **54**. In fact, the radius of curvature of surface **78** determines a radius of curvature of absorber **74** as well as a radius of curvature R of curved DBR **58**. Curved surface **78** in substrate **54** can be fabricated by any known method including techniques such as diffusion-limited etching or reflow and shape-transfer etching. For more information on the technique of diffusion limited wet etching the reader is referred to Y. Kim, et al., "Semiconductor Microlenses Fabrication by One-Step Wet Etching", IEEE Photonics Technology Letters, Vol. 12, No. 5, 2000, pp. 507–509.

Substrate **54** is selected from materials that are transparent at the wavelength of radiation **72**. In most wavelength ranges, GaAs is a suitable material for substrate **54**. Semi-insulating GaAs substrates are preferred to reduce free-carrier absorption losses. A person skilled in the art will appreciate that other materials can be used as substrate **54**.

An optical pumping device **80** that emits a pump radiation **82** is provided for optically pumping active medium **68** of VCSEL **50** to induce generation of radiation **72**. Device **80** is any suitable optical source such as a laser, e.g., a diode laser. In order to admit pump radiation **82** into resonator **52** first DBR **56** is transparent at the wavelength of pump radiation **82**. At the same time, DBR **56** is highly reflective at the wavelength of radiation **72** generated by active medium **68**. Curved DBR **58** is adjusted to be reflective at the wavelength of radiation **72** but allow a sufficient amount of radiation **72** to be coupled out of resonator **52** in the form of output radiation **84**.

In accordance with the above-mentioned principles of the invention, length L of resonator **52** is set to be sufficient to support a significant number of axial modes of radiation **72**. In setting length L substrate **54** is used as a spacer that extends resonator **52** to desired length L. In other words, the thickness of substrate **54** should be selected based on desired length L of resonator **52**.

The material of substrate **54** tends to disperse radiation pulses traveling inside resonator **52**. The dispersion of radiation **72** and decreased stability of resonator **52**, i.e., increase of diffraction losses and generation of multiple transverse modes of radiation **72**, arising due to extended length L are mitigated by providing an arrangement for compensating dispersion and an arrangement for stabilizing resonator **52**. In the present case, the arrangement for compensating dispersion is a chirp in one or both DBRs **56**, **58**. Appropriate chirp in DBRs **56**, **58** is obtained by setting different thicknesses (chirping) of adjacent layers **60**, **62** and **64**, **66**. The amount of group velocity dispersion (GVD) and chirp DBR design necessary to compensate for the dispersion in radiation **72** is calculated from the bandwidth of radiation **72** and the dispersive properties of substrate **54** in accordance with well-known methods. For additional information the reader is referred to Kärtner F., et al., "Design and fabrication of double-chirped mirrors", Optics Letters, Vol. 22, No. 11, June 1997, pp. 831–833.

In general, curved reflectors and lenses can be used to minimize diffraction losses or stabilize resonator **52** such that most of the energy of radiation **72** is confined within resonator **52**. Furthermore, in conjunction with defining appropriate apertures by limiting the size of reflectors **56**, **58** one achieves a high level of discrimination between transverse modes of radiation **72**. That is because fundamental transverse mode TEM_{00} diffracts less than higher order transverse modes. If the apertures defined by reflectors **56**, **58** are smaller than the higher modes, the latter will experience high losses while TEM_{00} will experience smaller losses.

The arrangement for stabilizing resonator **52** in the present embodiment is the radius of curvature R and aperture of DBR **58**. Specifically, the aperture of DBR **58** is chosen to be sufficiently small to prevent the establishment of transverse modes beyond the fundamental TEM_{00} mode of radiation **72** in resonator **52**. Preferably, radius R of DBR **58** is also equal to twice the length L of resonator **52**. In this case resonator **52** forms a half confocal resonator. In addition to controlling transverse modes of radiation **72**, half confocal geometry of resonator **52** is advantageous because it increases alignment tolerances between DBRs **56**, **58**.

During operation, pump device **80** delivers pump radiation **82**, which enters resonator **52** through first DBR **56**. Pump radiation **82** pumps active medium **68**, which generates radiation **72** in accordance with the principles of stimulated emission. The length L of resonator **52** allows radiation **72** to resonate within resonator **52** in a significant number of axial modes. At the same time, the half confocal geometry of resonator **52** stabilizes resonator **52** such that radiation **72** resonates in only the fundamental transverse mode TEM_{00} . Radiation **72** experiences dispersion due to substrate **54**. The effects of this dispersion are compensated by the chirp of DBRs **56** and **58**.

Saturable absorber **74** determines the phase difference between the modes of radiation **72**. Since absorber **74** is positioned at the end of resonator **52**, it defines a constant phase difference ϕ between successive modes that leads to so-called fundamental mode-locking. Under fundamental mode-locking conditions output radiation **84** is made up of pulses **86** separated by a duration equal to 2Ln/c. In one specific case length L of resonator **52** is set by 500 μn thick substrate **54** and active medium **68** is made up of InGaAs a multiple quantum well (MQW) material. Under these conditions, when VCSEL **50** is pumped by pump radiation **82** to excite the 980 nm transition, active medium **68** emits radiation **72** at 980 nm at a repetition rate of 85.7 GHz. In general, when resonator **52** is extended such that it supports a large number of axial modes of radiation **72**, for example more than 50 axial modes, the peak power of pulses **86** can reach levels of several Watts with pulse durations of less than a picosecond and repetition rates in the tens of GHz range.

Monolithically integrated and mode-locked VCSEL **50** is stable and overcomes the limitations of the prior art. All components of VCSEL **50** including the arrangements for stabilizing resonator **52** and dispersion compensation built into DBRs **56**, **58** are produced on single substrate **54**. This enables mass production of a large number of VCSELs **50** side-by-side, e.g., in a compact array format.

A person skilled in the art will appreciate that the principles of invention can be used to design a large variety of monolithically integrated, mode-locked VCSELs. In one alternative embodiment, the VCSEL can be designed to operate in a harmonic mode-locking condition that is achieved by placing saturable absorber **74** at various locations within resonator **52**, e.g., in the middle of substrate **54**. Alternatively, absorber **74** can be placed between alternating layers **64**, **66** of DBR **58** to set up yet another fundamental mode-locking condition in which the saturation intensity of absorber **74** is increased. Also, it should be noted that controlling certain parameters of the quantum wells of active medium **68** within cavity **52** allows for spectral shaping of radiation **72** generated by medium **68**. Specifically, the gain region in medium **68** can be tuned by tuning the gain peak of each quantum well using different well widths, by independently biasing the quantum wells, and by weighting the gain effects by placing the wells at proper points within the standing wave pattern of radiation **72** within resonator **52**. A person skilled in the art will be familiar in how these principles can be applied, e.g., in order to obtain a flat spectrum of radiation **72**.

FIG. **3** illustrates another embodiment of a monolithically integrated, mode-locked VCSEL **100** with a resonator **102** whose length L is determined by a substrate **104**, which is used as a spacer, analogous to the embodiment of FIG. **1**. VCSEL **100** has a curved DBR **106** for in-coupling a pump radiation **108** into resonator **102** and a flat DBR **110** for out-coupling output radiation **112**. A saturable absorber **114** is embedded inside substrate **104** in the middle of resonator **102**. An active medium **116** is located next to DBR **106** and separated from it by a spacing layer **118**. In accordance with the invention, length L is set sufficiently long to support within resonator **102** a significant number of axial modes of a radiation **120** generated by active medium **116** when pumped by pump radiation **108**. As in the previous embodiment, the aperture of curved DBR **106** is limited and the radius of curvature of curved DBR **106** is preferably set to twice length L to render resonator **102** a half confocal resonator.

During operation VCSEL **100** receives pump radiation **108** through curved DBR **106**. Pump radiation **108** induces active medium **116** to generate radiation **120**. Resonator **102** designed in accordance with the invention supports a significant number of axial modes but only a single transverse mode, i.e., the fundamental TEM_{00} mode of radiation **120**. The location of saturable absorber **114** establishes a harmonic mode-locking condition (also called colliding-pulse condition). As a result, output radiation **112** exiting through DBR **110** consists of pulses **122** separated by a duration τ_p equal to Ln/c.

A person skilled in the art will recognize that the embodiments described above can be adapted to use the same DBR for in-coupling pump radiation and for out-coupling output radiation. In fact, either the curved or flat DBRs can serve this dual purpose. In addition, the pump beam may be delivered from the side (side-pumping) in an alternative geometry and with appropriate placement of the active medium. In all embodiments, the exact placement of the saturable absorber should be selected such that it does not interfere with the optical pumping. In other words, it is preferable that the pump radiation in-coupled into the resonator is incident primarily or at least first on the active medium rather than the saturable absorber.

Yet another embodiment of a VCSEL **150** n accordance with the invention is designed for direct electrical pumping, as shown in FIG. **4**. VCSEL **150** is built on a substrate **152** and has a resonator **154** of length L. Resonator **154** has a first DBR **156** that is flat and a second DBR **158** that is curved for stabilizing resonator **154**. DBR **156** is selected to have appropriate reflectivity to act as an output coupler. DBR **158** is chirped to compensate for dispersion and is selected to have appropriate reflectivity to act as a high reflector.

An active medium **160**, preferably containing a number of quantum wells placed within the intrinsic region of a PIN diode, is positioned below DBR **156**. Medium **160** is sandwiched between two contact layers **162**, **164** and oxide apertures **166**, **168**.

An electrical pumping device or pump source **170** is connected to a top contact **172** and a bottom contact **174**. Bottom contact **174** is located on a current spreading layer **176**. Current spreading layer **176** is in electrical contact with medium **160**. Pump source **170** is designed to produce current flow between contacts **172** and **174** and through medium **160**. The passage of current through medium **160** causes generation of a radiation **178**. In accordance with the invention, length L is extended by substrate **152** to be of sufficient length to support a significant number of axial modes of radiation **178** in resonator **154**.

A saturable absorber **180** is grown next to DBR **158** on top of a curved surface **182** of substrate **152**. A spacing layer **184** separates absorber **180** from DBR **158**. Absorber **180** is located on opposite end of resonator **154** from medium **160** in order not to interfere with the pumping.

During operation medium **160** is pumped by source **170** by applying a current between contacts **172** and **174**. The positioning of contacts **172** and **174** apart from each other, preferably far apart, ensures good uniformity of current flow across the horizontal extent of medium **160**. Oxide apertures **162**, **164** guide the current through the center of medium **160**. Current spreading layer **176** distributes the current homogeneously across medium **160**.

In response to the current, medium **160** generates radiation **178** in a number of axial modes. Absorber **180** mode-locks radiation **178** in the fundamental mode-locking condition. An output radiation **186** containing pulses **188** issues from VCSEL **150** through DBR **156**, which acts as the output coupler.

VCSEL **150** is compact and independent. Electrically pumped VCSEL **150** may be preferable to the optically pumped VCSELs in certain applications, as will be appreciated by those skilled in the art. Of course, many conventional VCSEL design techniques can be implemented to improve the efficiency of VCSEL **150** and/or adapt VCSEL **150** to any particular application. For example, in an alternative embodiment, contact **174** can be provided at the bottom of VCSEL **150** near DBR **158**. In another embodiment the positions of medium **160** and absorber **180** can be swapped. In yet another embodiment, the reflectivities of the DBRs can be adjusted such that DBR **158** is the output coupler and DBR **156** is the high reflector.

Yet another embodiment of VCSEL **190** is shown in FIG. **5**, where medium **160** and a saturable absorber **192** are located at the same end of resonator **154**. In this drawing parts corresponding to those in FIG. **4** are labeled with the same reference numbers.

Resonator **154** is defined between a first flat DBR **194** and curved DBR **158**. DBR **194** is grown on top of an additional current spreading layer **196**. Top contact **172** is also located on top of current spreading layer **196** around DBR **194**. Absorber **192** is integrated into DBR **194**. Specifically, absorber **192** is sandwiched between two separating layers **198**, **200** within DBR **194**.

During operation source **170** applies a current between top contact **172** located on current spreading layer **196** and bottom contact **174** on current spreading layer **176**. Thus, current flows uniformly through the layers containing medium **160**, but does not flow through absorber **192** placed within DBR **194**. In this manner interference between electrical pumping of medium **160** and the action of absorber **192** is prevented. The substrates used in any of the above embodiments can be made of unmodified substrate material with the corresponding structures including the reflectors, absorbers, and active media grown or deposited on both sides. Alternatively, the structures can be modified by growth, re-growth, etching and bonding. These techniques can be used to achieve a variety of objectives, including a reduced substrate absorption, thickness adjustability and lower wavelength dispersion.

In yet another embodiment a mode-locked VCSEL **210** has a stable resonator **212** designed by replacing curved DBR by an optically equivalent combination of a lensing element **214** followed by a flat mirror or reflector **216**, as shown in the cross-sectional view in FIG. **6**. Preferably, lensing element **214** is a microlens formed by a side oxidation technique known in the art. For example, refractive microlens **214** can be a layered microlens fabricated by depositing a stack of layers with different compositions, etching through the stack to expose the outer layer edges, and then selectively oxidizing certain layers inwardly from the outer edges, thereby obtaining a lateral index profile that acts as an optical lens. Using alternating layers of GaAs and high-aluminum concentration AlGaAs, and selectively oxidizing the AlGaAs layers using elevated temperatures in an oxygen-rich environment is a preferred embodiment of this concept.

In this embodiment reflector **216** is a flat DBR and a saturable absorber **218** is integrated into DBR **216**. DBR **216** is chirped to provide for dispersion compensation.

VCSEL **210** is built on a substrate **218** and is designed for electrical pumping of an active medium **224**. A bottom contact **220** is provided on a ledge **222** in substrate **218**. Medium **224**, in the present case an InGaAs MQW, is provided above contact **220**. An aluminum oxide aperture **226** is located above medium **224** for current guidance. A second flat reflector **228**, also in the form of a DBR, is located above aperture **226**. A top contact **230** is deposited on top of DBR **228**.

Resonator **212** of VCSEL **210** has a length L sufficient to support a significant number of axial modes of a radiation **232**. Radiation **232** is generated by medium **224** when a current is applied between contacts **230** and **220** by a pump source (not shown). Microlens **214** in combination with reflector **216** stabilize resonator **212** such that only the fundamental TEM_{00} transverse mode of radiation **232** is supported in resonator **212**. The chirp in DBR **216** compensates for wavelength dispersion occurring to radiation **232** in resonator **212**. Meanwhile, absorber **218** enforces the fundamental mode-locking condition such that the output radiation of VCSEL **210** contains pulses separated by a duration 2Ln/c (not shown).

Monolithically integrated, mode-locked VCSELs fabricated in accordance with the invention can be used in many applications requiring compact, subpicosecond pulses. For example, large bandwidth short pulses produced by the VCSELs of the invention can be used for wavelength division multiplexed (WDM) applications and systems. The high repetition rates achievable with the VCSELs of invention also render them useful for optical time domain multiplexed (OTDM) systems and sampling applications. The low jitter of the pulses enables the use of the VCSELs in timing applications, such as providing clock signals for integrated circuits.

Other techniques, in conjunction with passive mode-locking, can be utilized to achieve better performance of VCSELs according to the invention in optical systems. Hybrid mode-locking uses an external signal to synchronize the pulses and reduce jitter. Arrays of mode-locked VCSELs emitting pulses in phase can be implemented using this technique. Subharmonic mode-locking is another hybrid technique that synchronizes the output of a mode-locked laser to a reference signal of lower frequency. Subharmonic mode-locked VCSELs can be used for OTDM and clock distribution systems where higher frequency clocks with low jitter need to be generated from slower signals.

The high peak powers of the ultrafast pulses obtained with mode-locked VCSELs of the present invention are also interesting for non-linear optics and bio applications. Many of the non-linear effects are only seen at high electric fields. A compact mode-locked VCSEL used as source can be easily coupled into fibers and enable the utilization of such effects in telecommunication systems or research. Two-photon absorption microscopy relies on the peak powers of mode-locked lasers to excite specific transitions in biological samples with higher signal to noise ratio detection while preserving the integrity of the sample. A low-cost, compact mode-locked VCSEL in accordance with the invention will produce sufficiently high beam quality to be attractive for these applications.

It will be clear to one skilled in the art that the above embodiments may be altered in many ways without departing from the scope of the invention. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.

What is claimed is:

1. A multimode vertical cavity surface emitting laser (VCSEL), the VCSEL comprising:

an active medium for emitting radiation at a lasing wavelength;

a resonator, within which the active medium resides, the resonator including a semi-insulating substrate, the resonator having a first end and a second end with a length therebetween set to support the multimode;

a first reflector at the first end of the resonator;

a second reflector at the second end of the resonator;

a saturable absorber coupled to the resonator, whereby the saturable absorber is able to absorbing slow and low power components of the multimode such that only high power mode-locked pulses pass therethrough; and

a means for stabilizing the resonator to reduce diffraction losses.

2. A multimode vertical cavity surface emitting laser (VCSEL), the VCSEL comprising:

an active medium for emitting radiation at a lasing wavelength;

a resonator, within which the active medium resides, the resonator including a substantially electrically insulating substrate, the resonator having a first end and a second end with a length therebetween set to support the multimode;

a first reflector at the first end of the resonator;

a second reflector at the second end of the resonator;

a saturable absorber coupled to the resonator, whereby the saturable absorber is able to absorbing slow and low power components of the multimode such that only high power mode-locked pulses pass therethrough; and

a means for stabilizing the resonator to reduce diffraction losses.

3. A multimode vertical cavity surface emitting laser (VCSEL), the VCSEL comprising:

an active medium for emitting radiation at a lasing wavelength;

a resonator, within which the active medium resides, the resonator including a transparent substrate, the resonator having a first end and a second end with a length therebetween set to multimode;

a first reflector at the first end of the resonator;

a second reflector at the second end of the resonator;

a saturable absorber coupled to the resonator, whereby the saturable absorber is able to absorbing slow and low power components of the multimode such that only high power mode-locked pulses pass therethrough; and

means for stabilizing the resonator includes a lensing element.

4. The VCSEL, according to claim **3**, wherein:

the first reflector is a distributed Bragg reflector that is made integral with the substrate.

5. The VCSEL, according to claim **4**, wherein the saturable absorber is made integral with the substrate.

6. The VCSEL, according to claim **5**, wherein the second reflector is a distributed Bragg reflector that is deposited on the substrate.

7. The VCSEL, according to claim **4**, wherein the distributed Bragg reflector is produced by epitaxial growth on the substrate.

8. The VCSEL, according to claim **3**, wherein the lensing element is a microlens.

9. The VCSEL, according to claim **3**, wherein:

the radiation includes a fundamental transverse mode and

the VCSEL further comprises at least one aperture to limit all transverse modes but the fundamental transverse mode.

10. The VCSEL, according to claim **3**, wherein the means for stabilizing the resonator comprises a curvature of the first reflector.

11. The VCSEL, according to claim **10**, wherein the curvature is defined by a radius of curvature and the length of the resonator is equal to twice the radius of curvature.

12. The VCSEL, according to claim **11**, wherein:

the radiation includes a fundamental transverse mode and

the VCSEL further comprises at least one aperture to limit all transverse modes but the fundamental transverse mode.

13. The VCSEL, according to claim **3**, further comprising a means for compensating for dispersion of the radiation in the resonator.

14. The VCSEL, according to claim **13**, wherein the first reflector is a distributed Bragg reflector and the means for compensating for dispersion includes the introduction of a chirp in the distributed Bragg reflector.

15. The VCSEL, according to claim **3**, further comprising a pumping device for pumping the active medium.

16. The VCSEL, according to claim **15**, wherein:

the active medium is disposed near to the first end of the resonator;

the saturable absorber is disposed nearto the second end of the resonator; and

the pumping device has the capability for optical pumping.

17. The VCSEL, according to claim **15**, wherein:

the pumping device has the capability for electrical pumping.

18. The VCSEL, according to claim **17**, wherein:

the pumping device is disposed nearto the first end of the resonator;

the pumping device is coupled to first and second electrical contacts;

and both first and second electrical contacts are disposed nearer to the first end of the resonator than the second end of the resonator.

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