

SEMICONDUCTOR OPTICAL AMPLIFIER

Area of Technology

The invention relates to quantum electronics, specifically to high-power multimode, monomode, and/or single-frequency radiation sources, and in particular to semiconductor optical amplifiers.

Prior Art

Traditionally, a semiconductor optical amplifier (hereinafter referred to as "SOA") consists of a master source of input radiation whose output is optically coupled by an optical system to the input of an amplifying component (hereinafter referred to as "AC") (S. O'Brien *et al.*, *IEEE J. of Quantum Electronics* (1993), Vol. 29, No. 6, pp. 2052–2057, and J. P. Donnelly *et al.*, *IEEE Phot. and Technology Letters* (1996), Vol. 8, pp. 1450–1452). The optical signals usually are spontaneous, superluminescent, or laser radiation. By virtue of the specific features of a SOA, such as small size, high gain per unit length, high efficiency, potentially low cost, integrability into optoelectronic circuits, etc., the SOA unquestionably has great prospects for use, both in the design of complex communications networks, particularly branched networks, and in the development of efficient high-power radiation sources.

A SOA in a discrete implementation is known (L. Goldberg *et al.*, *IEEE J. of Quantum Electronics* (1993), Vol. 29, No. 6, pp. 2028–2042) which includes a master source of input radiation that is input, when the amplifier is in operation, at an input angle δ into an AC optically coupled to the source. The AC is implemented on the basis of a semiconductor laser heterostructure that contains an active layer with a refractive index n_a and a bandgap E_a (eV) positioned between two cladding layers, in each of which there is at least one sublayer. The active gain region is implemented by using barrier regions to form a mesa strip that widens linearly from its initial width W_{in} of 10 μm at the input face of the active gain region, to a final width W_{out} of 160 μm at the output face of the active gain region. The length L_{AGR} of the SOA was 1500 μm . Note that the longitudinal axis of the active gain region, which lies in the active layer and is the optical gain axis of the AC, is located on the same optical axis as that of the master source and the optical system. The means of inputting the input radiation into the active gain region and of outputting radiation therefrom after amplification are the optical facet of the input face of the active gain region and the optical facet of the output face of the active gain region, which we conditionally call first optical facets, with antireflective coatings applied whose reflection coefficient R was in this case $R \sim 0.003$. The first optical facets are positioned at angles of inclination ψ_1 and ψ_2 to the plane perpendicular to the optical gain axis, which we call normal plane. In the prior art (L. Goldberg *et al.*, *IEEE J. of Quantum Electronics* (1993), Vol. 29, No. 6, pp. 2028–2042), the first optical facets of the AC are parallel to the normal plane. The sizes of the input and output apertures for the known AC (L. Goldberg *et al.*, *IEEE J. of Quantum Electronics* (1993), Vol. 29, No. 6, pp. 2028–2042) are:

$$S_{in} = d_{AGR} W_{in}, \quad (1)$$

and



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$$S_{\text{out}} = d_{\text{AGR}} W_{\text{out}}, \quad (2)$$

respectively, where d_{AGR} is the thickness of the active gain region, which usually does not exceed $1 \mu\text{m}$; therefore, for the AC of the known SOA (L. Goldberg *et al.*, *IEEE J. of Quantum Electronics* (1993), Vol. 29, No. 6, pp. 2028–2042) S_{in} is no more than $10 \mu\text{m}^2$ and S_{out} is no more than $160 \mu\text{m}^2$.

Antireflective coatings applied to the first optical facets of the active gain region are used as a means of suppressing spurious reflections and rereflections of the output signal (SPPI) in the known AC (L. Goldberg *et al.*, *IEEE J. of Quantum Electronics* (1993), Vol. 29, No. 6, pp. 2028–2042).

The known SOA (L. Goldberg *et al.*, *IEEE J. of Quantum Electronics* (1993), Vol. 29, No. 6, pp. 2028–2042) uses as its master source of input radiation a master laser diode with monomode radiation and a power P_{MSout} of 100 mW. The input radiation was focused by the optical system into a spot measuring $1 \times 4 \mu\text{m}$ on the first (input) optical facet. In addition, the input beams were input into the active gain region at different input angles δ . This resulted in the input into the amplifying component of an input power P_{in} in the AC of 25 mW into the initial face of the active gain region.

When an operating current I_{work} of 3 A was passed through a known AC with a length L_{AGR} of $1500 \mu\text{m}$ (L. Goldberg *et al.*, *IEEE J. of Quantum Electronics* (1993), Vol. 29, No. 6, pp. 2028–2042), 2.5 W of amplified output radiation power, P_{out} , was obtained. The input aperture was no larger than $1 \mu\text{m}$. In the vertical plane (this being a plane that passes through the longitudinal axis of the active layer and that is perpendicular to the layers of the laser heterostructure), the angle of divergence $\theta_{\perp}$, as with the usual injection-type emitters, was large, approximately 35° , and the output aperture was small, no more than $1 \mu\text{m}$. The effective angle of divergence $\theta_{\parallel}$ of the output radiation in the horizontal plane was 0.29° which corresponds to the diffraction-limited divergence for the indicated aperture size of $160 \mu\text{m}$. (The plane that is perpendicular to the vertical plane and that passes through the normal of the amplified output radiation front is called horizontal plane. In the known AC in question, this is the plane of the active layer.)

Disclosure of the Invention

Underlying the invention was the objective of creating a semiconductor optical amplifier (SOA) with increased areas of the input and output apertures, a reduced angle of divergence, and reduced astigmatism of the amplified output radiation, with the ability to obtain different directions of input and output of the amplified radiation relative to the optical gain axis in the active layer, and also with an increased effective gain-region length and increased resistance to the breakup mechanisms of the modal composition of the amplified input radiation. In the aggregate, the aforementioned factors result in the creation of a SOA with enhanced output power, efficiency, durability, and reliability, as well as high operational stability and steadiness. Simplification of the fabrication technology and the ability to implement a multibeam, multistage amplifier, as well of an amplifier in an integrated design, are thereby achieved.

In accordance with the invention, the stated objective is attained by virtue of the fact that in the semiconductor optical amplifier (SOA) including a master source of input radiation, and an amplifying component (AC) optically coupled to the source, the AC is

implemented on the basis of a semiconductor laser heterostructure that contains an active layer positioned between two cladding layers, in each of which there is at least one sublayer, ohmic contacts, where the amplifying component has at least one additional layer on at least one side of the heterostructure, so that the additional layer adjacent to the heterostructure is designated as the input–output region for radiation to which it is transparent, and is made of at least one sublayer and has refractive indices $n_{\text{IOR}q}$ of the sublayers and optical loss factors $\alpha_{\text{IOR}q}$ (cm^{-1}), where $q = 1, 2, \dots, p$ are defined as integers, which denote the sequential numbers of sublayers of the radiation input–output region, as counted from its boundary with the heterostructure; in the operating amplifier, the corresponding angle of input, δ , of input radiation and the net loss factor α_{OR} (cm^{-1}) for the amplified radiation emerging from the active layer and, the effective refractive index n_{eff} of the laser heterostructure, along with the radiation input–output region, and the refractive index $n_{\text{IOR}1}$ of the radiation input–output region satisfies the relations:

$$0 < \arccos \frac{n_{\text{eff}}}{n_{\text{IOR}1}} \leq \arccos \frac{n_{\text{eff-min}}}{n_{\text{IOR}1}}, \text{ such that } n_{\text{eff-min}} \text{ is greater than } n_{\text{min}},$$

where $n_{\text{eff-min}}$ is the minimum value of n_{eff} of all possible n_{eff} for the multiplicity of laser heterostructures, in aggregate with radiation input–output region, that are of practical value, and n_{min} is the smallest of the refractive indices in the layers of the heterostructure.

The distinction of the proposed SOA consists in the construction of the means of radiation input to and output from the AC proper, and also of the master source in a number of embodiments of the SOA. Consequently, there is a change in the directivity of the input and output radiation's inside and outside the AC relative to the plane of the active layer. In contrast to the device described by L. Goldberg *et al.* (*IEEE J. Of Quantum Electronics* (1993), Vol. 29, No. 6, pp. 2028–2042), we have proposed that the means of input of the input signal and the means of output of the amplifier radiation be unified, integrating all semiconductive layers of the heterostructure (hereinafter to be referred to as “laser heterostructure”) and radiation input–output regions (hereinafter to be referred to as “RIOR”), with radiation input and output through the corresponding optical facets arbitrarily called second, of the RIOR forming angles of inclination ψ_3 and ψ_4 , with the perpendicular plane, as well as with possible radiation input through the arbitrarily-called first optical facets limiting from the end sides the beginning and the end of the active region of amplification and forming angles of inclination, ψ_1 and ψ_2 .

Through the selection of the compositions and thicknesses of the semiconductive layers of the laser heterostructure and of the composition of the radiation input–output region, such conditions are created that a specified portion of the input radiation from the master source, which is input into the radiation input–output region under the appropriate conditions, flows into the active gain region and, after corresponding amplification therein, flows back into the very same radiation input–output region.

The conditions of outflow are realized when the following relationship is fulfilled: the refractive index n_{IOR} of the radiation input–output region exceeds the effective refractive index n_{eff} of the entire heterostructure with the adjacent radiation input–output region, that is:

$$n_{\text{IOR}} > n_{\text{eff}},$$

or, what is the same, the outflow angle φ exceeds zero, that is:

$$\varphi = \arccos(n_{\text{eff}}/n_{\text{IOR}}) > 0. \quad (4)$$

Relation (3) is a known condition (see, e.g., the *Handbook of Semiconductor Lasers and Photonic Integrated Circuits*, edited by Y. Suematsu and A. R. Adams, Chapman-Hill, London, 1994, pp. 58–65) upon whose fulfillment part of the radiation propagated in the optical waveguide of the laser heterostructure will flow from the active layer.

For our case of a multilayer heterostructure, in the design we have chosen, we proposed to use the principle, known in optics, of reversibility of the passage of rays in optical systems and hypothesized that universal condition (3) would be applicable not only for radiation outgoing into the radiation input–output region but also for radiation ingoing from the radiation input–output region. Further calculations and experiments confirmed the correctness of this hypothesis.

The task at hand can also be resolved by means of the fact that the input radiation of the operating amplifier, at the input of radiation through the second optical facet of the radiation input–output region, may be collimated. Then, the angle of input, δ , equal to the angle of incidence of the collimated input radiation to the surface of input (this device is unique, unlike the device of L. Goldberg *et al.* [*IEEE J. of Quantum Electronics* (1993), Vol. 29, No. 6, pp. 2028–2042]), is determined based on the selection of the equation between the angle of inflow, ξ , and the angle of outflow, φ , formed in the radiation input–output region, and consequently, by the perpendicular of the front of input inflowing radiation and by the perpendicular of the front of output amplified radiation with the plane of the active layer of the heterostructure, where $\xi = \arccos(r_{\text{eff}}/r_{\text{IOR1}})$; therefore the following formula is correct:

$$\xi = \varphi = \arccos(n_{\text{eff}}/n_{\text{IOR}}). \quad (5)$$

In this case, the input radiation from the radiation input–output region will be input into the active gain region of the proposed SOA and then, after the corresponding amplification therein, as stated previously, will flow back into the same radiation input–output region at an outflow angle φ (see relation (4)) to the plane of the active layer.

Conditions (4) and (5) determine the values of the refractive indices n_{IOR} , the inflow angle ξ , and the outflow angle φ , which depend on the ratios $n_{\text{eff}}/n_{\text{IOR}}$, at the bottom end of the values. The top bound of the angles ξ_{front} and φ_{front} is defined by the following relations proposed:

$$\arccos(n_{\text{eff}}/n_{\text{IOR}}) \leq \arccos(n_{\text{eff-min}}/n_{\text{IOR}}), \quad (6)$$

when

$$n_{\text{eff-min}} > n_{\text{min}}, \quad (7)$$

or

$$\xi_{\text{front}} = \varphi_{\text{front}} < \arccos(n_{\text{min}}/n_{\text{IOR}}), \quad (8)$$

where $n_{\text{eff-min}}$ is the minimum value of n_{eff} out of all possible n_{eff} for the multiplicity of laser heterostructures that are of practical value, with radiation input–output regions from which ACs of the proposed SOA can be made, and n_{min} is the smallest of the refractive

indices of the sublayers of the cladding layers. For real laser heterostructures the values of the angles ξ_{front} and φ_{front} may be approximately $30-40^\circ$, and accordingly the range of the angles ξ and φ varies over a range from greater than 0° to less than $30-40^\circ$.

Note that the presence of spectral dispersion (i.e., a dependence of r_{eff} and r_{IOR1} on the wave length of input radiation) leads to the possibility for the angle of outflow, φ (see (4) and (5)) varying depending on the spectral components of input radiation. The maximum variation of the angle φ may be within the range from $\varphi - \Delta\varphi/2$ to $\varphi + \Delta\varphi/2$, where $\Delta\varphi$ is the aperture angle of diversion of the out-flowing radiation determined by the complete width of the spectral band of amplification of the SOA. As a result of this, in accordance with (5), the maximum permissible deviation of the input angle of inflow ξ from the angle φ is determined by the above range from $\varphi - \Delta\varphi/2$ to $\varphi + \Delta\varphi/2$.

Note that the aforementioned relations (3)–(8) are also valid for cases where the radiation input–output region consists of several sublayers. In this case, in the aforementioned formulae, the refractive index n_{IOR} for a homogeneous radiation input–output region should be replaced with n_{IOR1} — refractive index for the first sublayer of the radiation input–output region that is adjacent to a sublayer of a cladding layer of the laser heterostructure. Hereinafter, unless otherwise stipulated, we shall consider the radiation input–output region to be homogeneous, and shall use n_{IOR} without the subscript “1” for the first sublayer.

In the case of satisfaction of the indicated characteristics of the invention, as well as in the case of transparency of the input–output region for the inflowing and outflow radiation, we obtained increased values of the capacity and efficiency of the SOA at effective lengths of radiation amplification significantly increased as compared to the usual. In addition, the areas of the input and output apertures of the device were also significantly increased; the angles of diversion and astigmatism of the output amplified radiation were significantly decreased and, as a result of the distributed input and output of amplified radiation along the entire active region of amplification, the stability of operation of the SAO with respect to the mechanisms of destruction of the modulator's composition of the amplified input radiation was increased.

The task at hand can be solved also through the fact that the net loss factor, α_{OE} , cm^{-1} , in the operating amplifier, for the amplified radiation flowing out of the active layer at the border between the sublayer of the cladding layer and the radiation input–output region, has been selected from the range of values limited at the lower end of the range, α_{ORmin} , cm^{-1} , by the minimum permissible value of the electrical power conversion efficiency supplied to the active region of amplification during the operation of the amplifier, to the power of amplified radiation, and limited at the upper end of the range, α_{ORmax} , cm^{-1} , by the maximum permissible value of the density of the current of operation. The increase in the permissible value of the operation current density j , A/cm^2 , in the AE leads, for example, to impermissible overheating of the AE. In other words, in order to ensure high efficiency of operation of the proposed amplifier, it is recommended that the value of the net loss factor, α_{OE} , cm^{-1} , of outflow radiation per unit of the length of the active region of amplification, be selected within the following range:

$$\alpha_{\text{ORmin}} < \alpha_{\text{OR}} < \alpha_{\text{ORmax}}, \quad (9)$$

It is advisable to introduce barrier regions in the various embodiments and to make the amplification element with at least one active region of amplification, with length L_{AO} , μm , W_{in} , μm , at its beginning, and W_{out} , μm , at its end, with first optical facets restricting from the ends the beginning and the end of the active region of amplification and forming angles of inclination, ψ_1 and ψ_2 , with the perpendicular plane, i.e., with the plane perpendicular to the longitudinal axis of the active layer.

In addition, in order to remove undesirable losses of injected current carriers, the amplification input-output region must be made with a width no lesser than the width of the active region of amplification, and the surface of the radiation input-output region bordering on the heterostructure, called inner, must be made with a length L_{IOR} , μm , no lesser than the length L_{AO} , μm .

The stated objective also is attained by virtue of the fact that the width W_{in} (μm) of the active gain region is selected equal to the width W_{out} (μm). Here, simplification of the fabrication technology for the device is achieved, as is, in contrast to ordinary SOAs, a sharp decrease in losses of injection currents in the unsaturated gain region on the input-radiation side. If the W_{out} of the active gain region is selected to be larger than W_{in} , a decrease in the diffraction-limited divergence of the output radiation is obtained in the plane parallel to the layers of the laser heterostructure.

Furthermore, it is proposed that the radiation input-output region be made of an optically homogeneous material with a spectral band of transparency to the wavelength λ (μm) of the radiation being amplified when the device is in operation.

The aforementioned requirement stems from the fact that when the ingoing and outgoing radiation's propagate in the sublayers of the radiation input-output region, the optical losses of these radiations (to absorption and scattering) therein must be small, and specifically, the optical loss factor α_{IORq} must be:

$$\alpha_{IORq} \ll 1/L_{IOR}, \quad (10),$$

where L_{IOR} is the maximum of the lengths L_{IOR-I} and L_{IOR-O} for the radiation input-output region.

Obviously, to satisfy relation (10), it is essential first of all that the sublayers of the radiation input-output region be optically homogeneous, and that the bandgap E_{IORq} of sublayers of the radiation input-output region be larger than the bandgap E_a of the active layer, which determines the spectral gain band of the SOA. Absorption losses decrease roughly exponentially as a function of the difference between E_{IORq} and E_a . Therefore, making the radiation input-output region from materials for which the wavelength λ (μm) falls within their transparency region results in a reduction of the optical losses α_{IORq} (cm^{-1}) and, hence in the attainment of one of the objective of this invention — an increase in the effective length of the radiation input-output region.

In the preferred embodiments of the device, the radiation input-output region may be made of a semiconductor with a bandgap width E_{IOR1} (eV) more than 0.09 eV larger than the bandgap width for the active layer E_a (eV).

In this case, if the concentration of carriers in the radiation input-output region does not exceed $1 \times 10^{18} \text{ cm}^{-3}$, the optical loss factor $\alpha_{IOR-abs}$ for absorption may reach values on the order of 0.1 cm^{-1} or less.

Note that in the general case the radiation input-output region may be made of not only semiconductive materials. It is only necessary that its characteristics, in particular the refractive index n_{IOR} and optical loss factor α_{IOR} for absorption and scattering, meet the necessary requirements (3) and (10).

Furthermore, we proposed that the thickness d_{IOR} of the radiation input-output region be selected from the range 5–50,000 μm . Here, the choice of the thickness d_{IOR} depends on the outflow angle φ , the length L_{AGR} , and the angles of inclination of the second optical facets in the AC. Naturally, the width W_{IOR} of the radiation input-output region must not be smaller than the width of the active gain region along the entire length of the AC.

In the preferred cases it is proposed that the median plane of the active layer be placed at a distance from the inner surface of the additional layer such that the intensity of the amplified radiation in the aforementioned median plane of the active layer that arises when the amplifier operates differs by no more than 20% from the maximum value.

This proposal is implemented by tailoring the composition (the refractive indices and absorption coefficients of the layers) and thicknesses of the layers of the laser heterostructure and the radiation input-output region. This leads to optimization of the operation of the AC, an increase in the gain for input radiation in the active layer, and consequently an increase in the efficiency and power of the output radiation.

In a number of cases, at least one of the sublayers of the cladding layers of the laser heterostructure is made to have a refractive index no lower than n_{IOR1} . This makes it possible to effect a controlled decrease in the values of the outflow angle φ (see relation (4)) of radiation and the related inflow angle ξ (see relation (5)), in the direction of a decrease in them. It is desirable that the inflow angle ξ and the outflow angle φ have small values — for example, for the purpose of building the proposed SOAs with a large gain length L_{AGR} but a limited thickness d_{IOR} .

It also is possible to make the layer of the laser heterostructure that adjoins the radiation input-output region of at least two introduced regions whose bordering surfaces are perpendicular to the plane of the active layer. In this case, either the refractive indices or the thicknesses of the neighboring regions of the sublayer are chosen to be different.

The region with the smaller thickness and/or larger refractive indices should be placed in direct proximity to the first optical facet. In this case the intensity of the outgoing radiation increases significantly in the indicated region, leading to a significant decrease in the intensity of the amplified radiation on the face of the active gain region, and hence to a corresponding decrease in the amount of spurious radiation reflected. Note that the aforementioned additional decrease in the intensity of the amplified radiation on the first optical facet will make it possible to increase the operating life and operational reliability of the device.

Furthermore, it is proposed that the outer additional layer be made of a material that absorbs the radiation being amplified. The purpose of this layer is to ensure that maximum absorption of possible spurious reflections and rereflections of amplified radiation, as for example through strong interband absorption, occurs in the layer. This results in more effective suppression of spurious radiations, and hence in the stabilization of the gain mode of the proposed SOA to high values of the amplified output power.

In the preferred cases, the radiation input-output region should be made electrically conductive, and if other additional layers are present, they too should be made electrically conductive. Here, an ohmic contact is formed with the surface of the electrically conductive radiation input-output region and, if other additional layers are present, an ohmic contact is formed with the free surface of the additional layers.

In a number of cases it is advisable to make the radiation input-output region from a material with an optical loss factor α_{IORq} of no more than 0.1 cm^{-1} . In some cases it is advisable to form the radiation input-output region from two sublayers; here, the first sublayer bordering the laser heterostructure must be electrically conductive, and the second sublayer must be made of a material with an optical loss factor α_{IORq} of no more than 0.1 cm^{-1} . Here, an ohmic contact is made with the first sublayer of the radiation input-output region.

The low values of α_{IORq} result in a corresponding increase (see relation (10)) in the effective length of the amplifier, and consequently in its output power and efficiency. If the second sublayer is not electrically conductive, then this brings about lower values for the factor α_{IOR2} . If the value of the refractive index n_{IOR2} is smaller for the second sublayer than for the first one, this leads to a decrease in the outflow angle φ as radiation propagates in the second sublayer, and consequently to a decrease in the total thickness of the radiation input-output region. Furthermore, this makes it possible to make second optical facets parallel to the normal plane, which results in the simplification of the fabrication technology for the product and in an increase in the effective length of the SOA and accordingly in its output power and efficiency.

In some cases an ohmic contact from the direction of the radiation input-output region can be formed with one of the electrically conductive sublayers of the cladding layer located between the active layer and the radiation input-output region. It is advisable that an ohmic contact be made with the electrically conductive layer that has the smallest value of the bandgap.

The proposed modifications for making ohmic contacts result in the simplification of the fabrication technology for the SOA.

The object that we posed is also attained by virtue of the fact that we proposed different designs of the radiation input-output region. These designs use laser heterostructures with the fullest possible ranges of inflow angles ξ and outflow angles φ , as determined by relations (4)–(8). Furthermore, we proposed radiation input-output regions with different angles of inclination ψ of the second optical facets, from the directions of both radiation input and output. (We stipulated that the angle of inclination of the optical facet is to be obtuse or acute, depending on what angle the optical facet subtends with the inner surface of the radiation input-output region.) What is proposed makes it possible to build a SOA with greater efficiency, output power, durability, and reliability, larger input and output apertures, and reduced angles of divergence of the output radiation for different directions of input and output of the amplified radiation, while simplifying the fabrication technology.

To effect radiation input through a second optical facet introduced to the radiation input-output region at the end of its input with an introduced anti-reflective coating made parallel to the normal plane, the input angle δ is made to satisfy the condition $\arcsin(n_{\text{IORq}} \sin \xi)$.

To effect radiation input through the outer surface of the radiation input-output region, the antireflective coating is formed on the part of the surface of the radiation input-output region that is determined by the size of the input aperture and that faces its inner surface and abuts on the second optical facet from the direction of radiation input, which forms an obtuse angle with the plane of the active layer and which is formed at an angle of inclination ψ_3 selected from the range:

$$[(\pi/4) - (\xi/2) - (\sigma/2)] \text{ to } [(\pi/4) - (\xi/2) + (\sigma/2)]$$

where π is equal to 3.1416 radians, while σ is the angle of complete inner reflection for the radiation flowing out in the radiation input-output region. If the input radiation is directed normally to the input surface, the angle of inclination ψ_3 is selected to be $[(\pi/4) - (\xi/2)]$.

To effect radiation input through a second optical facet with an antireflective coating that subtends an acute angle with the plane of the active layer, it is made at an angle of inclination ψ_3 selected from the range:

$$(\xi - \sigma) \text{ to } (\xi + \sigma).$$

If while the amplifier is in operation the input radiation is directed normally to the aforementioned optical facet, then the angle of inclination ψ_3 is selected to be equal to the inflow angle ξ .

To effect radiation input through a second optical facet—introduced in the radiation input-output region at the output end—with an anti-reflective coating that subtends an acute angle with the plane of the active layer, it is made with an angle of inclination ψ_4 selected from the range:

$$(\varphi - \sigma) \text{ to } (\varphi + \sigma).$$

To obtain output radiation directed normally to the output surface while the amplifier is in operation, the angle of inclination ψ_4 is selected equal to the outflow angle φ .

To effect radiation output through a second optical facet with an anti-reflective coating made parallel to the normal plane, the outflow angle φ is selected to be smaller than the angle of total internal reflection σ from the aforementioned surface.

To effect radiation input and output through one and the same second optical facet, it is proposed that an introduced reflective coating be made on one of the second optical facets, and that it be formed parallel to the normal plane, and that an antireflective coating be made on the other, opposite second optical facet; here, radiation input is provided for through one part of this surface, which is determined by the size of the input aperture and which is located, beginning with the boundary of the second optical facet with the inner surface of the radiation input-output region, at a distance of no more than $L_{AGR} \cdot \tan \varphi$, and radiation output is provided for through the same surface in a different part of it. In this particular case, it is proposed that a reflective coating be applied to the first optical facet adjacent to the second optical facet with the reflective coating, in order to increase the output power.

In such two-pass SOAs proposed by us, the input and output of the amplified radiation are spatially separated directly on the second optical facet.

To effect radiation output through the surface of the input-output region opposite the inner surface, the antireflective coating is made on a part of the surface, as determined by the size of the output aperture, of the radiation input-output region, which is opposite the inner surface of the latter and adjacent to the second optical facet from the direction of radiation output and which subtends an obtuse angle with the plane of the active layer and is formed at an angle of inclination ψ_4 selected to be in the range:

$$[(\pi/4) - (\varphi/2) - (\sigma/2)] \text{ to } [(\pi/4) - (\varphi/2) + (\sigma/2)].$$

For output in which the output radiation is directed normally to the output surface, the angle of inclination ψ_4 is selected to be $[(\pi/4) - (\varphi/2)]$.

To obtain a multibeam SOA, it is proposed that the radiation input-output region be made of at least two introduced subregions, the first of which is optically coupled to the master source, and the subregions are separated by second optical facets for radiation output from each subregion while the amplifier is in operation. The inclination of the faces forming the subregions may differ from the inclination of the second optical facet in the direction of radiation input. It is possible in this case to select different combinations of the angle of inclination ψ_3 and ψ_4 to effect radiation output, including such output normally to the plane of the active layer.

For example, to output radiation through the surface of the laser heterostructure opposite the position of the radiation input-output region, it is proposed that second optical facets in the direction of radiation output, subtending an acute angle with the plane of the active layer, be formed at an angle of inclination ψ_4 selected in the range:

$$[(\pi/4) + (\varphi/2) - (\sigma/2)] \text{ to } [(\pi/4) + (\varphi/2) + (\sigma/2)], \text{ and that}$$

antireflective coatings be made in the areas of their projections on the surface of the laser heterostructure opposite the position of the radiation input-output region.

To build a SOA with a multistage AC, it is proposed

- that at least two active gain regions with an identical inflow angle ξ and outflow angle φ for each gain region be formed on the surface of the radiation input-output region, or

- that at least two active gain regions be formed along a single line parallel to the surface of the radiation input–output region and to the plane of the active layer, with a spacing of $2d_{\text{IOR}}/\tan \varphi$ between the starts of the active regions, or
- that at least one active gain region with an identical inflow angle ξ and outflow angle φ for each gain region be formed on opposite surfaces of the radiation input–output region, or
- that at least one active gain region be formed along each of two lines that are parallel to each other and that are on opposite surfaces, with a shortest distance $d_{\text{IOR}}/\sin \varphi$ between the starts of the active gain regions on opposite sides.

We also proposed SOAs in both a discrete embodiment and an integrated embodiment, including the use of a nonstandard master source of input radiation, including a multistage AC.

In the discrete embodiment, it is proposed that the master source of input radiation be formed as a second amplifying component (AC). In this case the SOA is a source of superluminescent radiation with high directivity.

In the same discrete embodiment of the SOA, it is proposed that reflectors be incorporated in the active gain region of the second amplifying component. In this case the SOA is a source of highly directional laser radiation.

To obtain a SOA in the integrated embodiment with superluminescent radiation, it is proposed that the active gain region of the master source be placed in the radiation input–output region of the amplifying component so that the outflow angle φ of the active gain region of the master source is identical to the inflow angle ξ of the active gain region of the amplifying component.

To obtain a SOA in the integrated embodiment with laser radiation, it is proposed that reflectors be incorporated in the active gain region of the master source.

The amplified output radiation of such SOAs is distinguished by high output power with small angles of divergence in both the vertical and horizontal planes at low astigmatism.

The following modifications were proposed for the integrated embodiment:

- the active regions of the master source and amplifying component are on the same inner surface of the radiation input–output region;
- the active gain regions of the master source and amplifying component are on the same line parallel to the surface of the radiation input–output region and to the plane of the active layer, with a spacing $2d_{\text{IOR}}/\tan \varphi$ between the starts of the active regions;
- the active gain regions of the master source and amplifying component are disposed on opposite surfaces of the radiation input–output region; and
- the active gain regions of the master source and amplifying component are formed along each of two lines that are parallel to each other and that are on opposite surfaces, the shortest distance between the starts of the active gain regions on opposite surfaces being $d_{\text{IOR}}/\sin \varphi$.

For SOAs with a multistage AC, for both the discrete and the integrated embodiments, it is proposed that at least part of at least one surface of the radiation input–output region be made reflective.

By virtue of total internal reflection of radiation from the aforementioned reflective surfaces, those surfaces perform optical coupling between the active gain regions in the radiation input-output region common to them.

For SOAs with laser radiation in both discrete and integrated designs that are distinguished by different kinds of feedback, it is proposed that the reflectors of the active gain region of the second amplifying component — the master laser — and the reflectors of the active gain region of the AC be made, for example, in the form of:

- reflective coatings, or
- distributed Bragg reflectors, or
- distributed feedback reflectors along the entire length of the active gain region of the master source.

The essence of the present invention is a new, nonobvious proposal for distributed input of collimated input radiation into the amplifying component, and for distributed output of the amplified, diffraction-limited radiation with a small angle of divergence from the amplifying component. In the proposed SOAs the input of the input signal, like the output of the amplified radiation, occurs simultaneously along the entire length of the amplifying component, which is equal to the length of the active gain region, which is several times greater than its thickness. This is attained by virtue of the nonobvious aggregate of all the essential features, including the input of input radiation by using a collimated beam incident at specified angles on the input surface from the master source, the incorporation in the amplifying component of the SOA of the new, nonobvious means of radiation input proposed by us, which is originally combined into a unified (integrated) means of input/output that includes the entire laser heterostructure and an additionally introduced region of radiation input/output bounded on the end faces by additionally introduced second optical facets, and a set of original, nonobvious requirements formulated by us for the characteristics of the laser heterostructure used, the material of the input-output region itself, and the inclination of its optical facets.

The essence of the present invention is also the new SOA designs proposed, with multibeam radiation output and a multistage amplifying component, in an integrated embodiment with a master source of input superluminescent or laser radiation in the form of an analogous amplifying component.

When compared with the SOAs currently in use, including the device described by L. Goldberg *et al.* (*IEEE J. of Quantum Electronics* (1993), Vol. 29, No. 6, pp. 2028–2042), the advantages of the proposed SOAs are as follow.

The areas of the input and output apertures have been increased because of the increase in the size of the aforementioned apertures in the vertical plane. In comparison with the prior art, the aforementioned increase, which is defined by the ratio $d_{\text{IOR}}/d_{\text{AGR}}$, may amount to a factor of hundreds, thousands, or more.

The increase in the area of the input aperture allows not only for a reduction of losses of the input signal when it is fed into the active region and, accordingly, for the input of higher input power into the AC and an increase in the its input efficiency, which is important for building high-efficiency, powerful SOAs and high-sensitivity optical preamplifiers, but also allows for a significant simplification of the labor-intensive precision process of injecting the input radiation directly into the active gain region.

The increase in the area of the output aperture makes possible a decrease in the angle of divergence $\theta_{\perp}$ in the vertical plane of the amplified diffraction-limited output radiation, a reduction of its astigmatism, and a significant decrease (by a factor of approximately $d_{\text{IOR}}/d_{\text{AGR}}$) in the intensity of the amplified output [radiation] on the second optical facet during extraction from the SOA [3]. At the same time, in comparison with the design of the prior art [3], the radiation intensity on the first optical facet has been reduced on the side where the radiation is extracted.

The SOA designs proposed by us make possible not only the realization of different directions of radiation input into and output from the radiation input-output region, but also the expansion of the range of SOAs with large values of the outflow angles φ that are distinguished by higher efficiency and larger input and output apertures.

The decrease in the intensities of output radiation on the first and second optical facets on the radiation-output side makes it possible to obtain high levels of output radiation power, without approaching, as is the case in the prior art, the extreme breakup intensities; this makes it possible to assure increased operating life and reliability of the proposed SOAs, even at high power levels.

The corresponding selection of the values of α_{MS} , α_{AGR} , and α_{IOR} makes possible a significant increase in the effective gain length of the device, and thus an increase in the volume of the active gain region, and consequently an increase in the efficiency and output power of high-quality laser radiation with diffraction-limited divergence in two mutually perpendicular planes.

Increasing the effective length makes it possible to realize the promising designs proposed by us for multibeam SOAs and SOAs with a master source of input radiation in the form of an amplifying component and with a multistage amplifier, including those with an integrated embodiment.

Another important advantage of the proposed SOAs is their high operational stability and steadiness at high output-radiation levels, which are determined by the proposed fundamentally new mechanism of distributed radiation input-output [to-]from the active gain region.

Let us draw attention to the fact that the technical implementation of the proposed SOA is based on known basic production processes, which by now have been worked out quite well and are used extensively in the fabrication of typical SOAs.

Brief Description of Drawings

Hereafter, the invention is explained by specific embodiments of it, with references to the attached drawings. The examples of SOA design presented are not the only ones, and assume the existence of other embodiments whose particulars are reflected in the aggregate of the features in the claims.

Figure 1 schematically depicts a longitudinal section (along the optical gain axis in the active layer) of the design of the amplifying component of the proposed SOA with radiation input and output through second optical facets positioned at acute angles to the plane of the active layer, and with an ohmic contact with the outer surface of the optically homogeneous input-output region.

Figure 2 gives a top view of the design depicted in Fig. 1.

Figure 3 schematically depicts a longitudinal section of a specific laser heterostructure with the radiation input-output region, each of whose cladding layers contains one sublayer with refractive indices of n_{IOR} .

Figure 4 schematically depicts the change in the refractive index in the direction perpendicular to the layers of the laser heterostructure depicted in Fig. 3.

Figure 5 graphically shows the distribution of the near-field intensity of the amplified radiation (calculated data), with the superposed change in the refractive indices in the corresponding layers of the laser heterostructure shown in Figs. 3 and 4.

Figure 6 graphically depicts the far-field distribution of the intensity of the amplified radiation in the normal plane (calculated data).

Figures 7–9 schematically depict longitudinal sections of the designs of heterostructures for different embodiments of the amplifying component of the proposed SOA:

- Figure 7 shows the sublayer of the cladding layer of the laser heterostructure that is adjacent to the radiation input-output region, and consists of two regions with different values of the refractive indices;
- Figure 8 shows the radiation input-output region, which is made of two sublayers of different electrical conductivity; and
- Figure 9 shows that a second additional absorption layer has been made on the outside of the radiation input-output region.

Figures 10–12 schematically depict cross-sections of designs of the AC of the proposed SOA for different implementations of the ohmic contact, specifically:

- Figure 10 — with the electrically conductive additional layer (the radiation input-output region, which is the substrate);
- Figure 11 — with the electrically conductive sublayer that has the smallest bandgap among the sublayers of the cladding layer adjacent to the radiation input-output region; and
- Figure 12 — with the electrically conductive sublayer of the radiation input-output region that is adjacent to the laser heterostructure.

Figures 13–16 schematically depict longitudinal sections of different AC designs with one subregion of the radiation input-output region:

- Figure 13 — with radiation input and output through second optical facets parallel to the normal plane;
- Figure 14 — with radiation input through a second optical facet parallel to the normal plane, and without radiation output through a second optical facet positioned at an acute angle to the plane of the active layer;
- Figure 15 — with second optical facets positioned at obtuse angles to the plane of the active layer and with radiation input and output through the outer surface of the radiation input-output region; and
- Figure 16 — with radiation input and output through a second optical facet parallel to the normal plane, with a single reflection of amplified radiation in the radiation input-output region from the second optical facet.

Figures 17–18 schematically depict longitudinal sections of the proposed SOA with radiation input-output regions separated by second optical facets into several subregions, with radiation input through the first subregion and multibeam radiation output through:

- Figure 17 — the outer surfaces of each subregion, the second optical facets of each subregion being positioned at obtuse angles to the plane of the active layer, except the input surface, which is positioned at an acute angle; and
- Figure 18 — the second optical facets, which are positioned at acute angles to the plane of the active layer and which intersect at the boundary of the radiation input-output region with the laser heterostructure.

Figure 19 schematically depicts a longitudinal section of the design of a proposed discrete SOA with superluminescent radiation, in which the master element is implemented as an amplifying component.

Figure 20 schematically depicts a longitudinal section of the design of a proposed discrete SOA in which the master component is implemented as an injection laser with a radiation-output region.

Figures 21–24 schematically depict various integrated SOA designs:

- Figure 21 — the amplifying active regions of a SOA with superluminescent radiation are placed on one side of the radiation input-output region (longitudinal section);
- Figure 22 — the lasing and amplifying active regions are positioned on one side of the radiation input-output region (longitudinal section);
- Figure 23 — the lasing and amplifying active regions are positioned on one side of the radiation input-output region (top view); and
- Figure 24 — the lasing and amplifying active regions are positioned on opposite sides of the radiation input-output region (longitudinal section).

Embodiments of the Invention

The proposed SOA schematically depicted in Fig. 1 comprises a master source 1 and an optical system 2 for forming the input radiation, which are positioned on the same optical axis, and an AC 3, the longitudinal axis of whose active region is not an extension of the optical axis of the first two elements. AC 3 is implemented as a semiconductor laser heterostructure 4 positioned on a substrate 5 and consisting of an active layer 6, cladding layers 7 and 8, which are on both sides of active layer 6, and a contact layer 9 on cladding layer 7. Cladding layer 8 is positioned on substrate 5. The highly doped contact layer 9 (a *p*-type design in the example in question) is intended to make an ohmic contact 10 with it. A second ohmic contact 11 is made with substrate 5 on its outer surface (see Fig. 10).

The active gain region (see Fig. 2) is implemented by forming a mesa strip 12 by means of barrier regions 13. In this modification the configuration of the active gain region has been selected to be expandable, as schematically illustrated in Fig. 2. The width W_{in} at the input has been selected to be 10 μm , and at the output W_{out} is 160 μm . The optical facet 14 of the input face of the active gain region and the optical facet 15 of the output face of the active gain region, which we conditionally call first optical facets 14 and 15, with antireflective coatings 16 applied to them. In the case in question, the latter have reflection coefficients of 0.001, and substrate 5 is the radiation input-output region 17.

On the radiation input and output side, radiation input-output region 17 is bounded by second optical facets 18 and 19, to which antireflective coatings 16 with a reflection coefficient of 0.001 for input and output radiation were also applied. In the

design corresponding to that schematically depicted in Fig. 1, the first optical facets 14 and 15 and second optical facets 18 and 19 subtend an acute angle with the plane of active layer 6, and are directed at corresponding angles of inclination to the normal plane: ψ_1 and ψ_2 , which are equal to ξ , and ψ_3 and ψ_4 , which are equal to φ ; here, the angle ξ is equal to the angle φ and has a value of $9^\circ 30'$. The permissible deviation of the angle ξ from the angle φ does not exceed the calculated value of the dispersion divergence angle, $\Delta\varphi$, for outflow radiation, equal to 1° . The adjustment of the angle ξ is achieved through the alignment of the angle of incidence, δ , of the input radiation to the second optical branch 18 RIOR 17. The inner surface 20 of radiation input-output region 17 borders on cladding layer 8 and has a length $L_{\text{IOR-I}}$ along the radiation gain axis of at least length L_{AGR} . For the given design, the indicated lengths are practically equal, and the outer surface 21 of radiation input-output region 17 has a length $L_{\text{IOR-O}}$ shorter than the length $L_{\text{IOR-I}}$. The length $L_{\text{IOR-O}}$ of the proposed SOA is practically equal to the length L_{AGR} , which is $1500 \mu\text{m}$. The thickness d_{IOR} of radiation input-output region 17 was selected to be $260 \mu\text{m}$.

The longitudinal section of AC 3 (see Fig. 1) depicts the sequence of optically homogeneous layers and sublayers of a laser heterostructure with one optically homogeneous subregion of radiation input-output region 17 and a contact layer 9. Cladding layer 7 consists of two sublayers, 22 and 23, active layer 6 consists of one sublayer, and cladding layer 8 consists of two sublayers 24 and 25; layer 25 adjoins radiation input-output region 17 (see Table 1). To create the design in question, the semiconductor layers were grown by the known MOCVD method on substrate 5 from electrically conductive gallium arsenide, which acts as radiation input-output region 17. The composition, thicknesses, refractive indices, type and concentrations of doping, and the corresponding absorption coefficients of the layers of heterostructure 4 of radiation input-output region 17 are presented in Table 1 and also in Figs. 4 and 5. The wavelength λ (μm) of the amplified radiation was chosen to lie within the gain band, which is determined by the composition of active layer 6 and has a size of $0.980 \mu\text{m}$.

When the proposed SOA is connected to a power source, nonequilibrium carriers, which effect in [the AC 3], as in the AC of the known SOA (see the device of L. Goldberg *et al.*, *IEEE J. Of Quantum Electronics* (1993), Vol. 29, No. 6, pp. 2028–2042), amplification of the input radiation of wavelength λ (μm), or of wavelengths within the gain band of the device, that is input into the active region are injected into active layer 6 of AC 3.

Twenty-five milliwatts of input radiation collimated in the vertical plane was incident on the second optical facet 18, with an input area S_{in} of $2,475 \mu\text{m}^2$ ($247.5 \mu\text{m}$, the vertical extent of input, multiplied by $10 \mu\text{m}$, the horizontal extent of input).

The standard lines with arrows show the directions of the collimated input radiation from master source 1 with an input angle δ to second optical facet 18 and of diffraction-limited amplified output radiation with a refractive index ϵ to second optical facet 19. For the design in question (see Fig. 1), when the device is in operation radiation input and output occur along normals to the corresponding second optical facets. The same method is used to indicate the direction of ingoing radiation into laser heterostructure 4 at an inflow angle ξ , and of outgoing radiation from laser heterostructure 4 at an outflow angle φ within radiation input-output region 17.

The basic parameters for both the heterostructure and the SOA in the example in question were obtained by a numerical simulation performed according to a program especially developed by us, underlying which is the matrix method (J. Chilwall and I. Hodgkinson, *Journ. Opt. Soc. Amer., A* (1984), Vol. 1, No. 7, pp. 742–753) of solving Maxwell's equations with the corresponding boundary conditions in multilayer laser heterostructures.

These calculations used the following initial data:

- $g_0 = 200 \text{ cm}^{-1}$ — the material gain in active layer 6 that is needed to achieve inversion;
- $\mu = 5 \times 10^{-16} \text{ cm}^2$ — a proportionality factor between $(g + g_0) (\text{cm}^{-1})$ and the injected-electron concentration $N_e (\text{cm}^{-3})$, where $g (\text{cm}^{-1})$ is the material gain in the active layer;
- $\tau = 1 \text{ nsec}$ is the lifetime of nonequilibrium electrons in the active layer;
- $\alpha_{\text{AGR}} = 5 \text{ cm}^{-1}$ is the optical loss factor for absorption and scattering of the amplified radiation in the active gain region;
- $\alpha_{\text{IOR}} = 0.001 \text{ cm}^{-1}$ — the optical loss factor in radiation input-output region 17; this value was taken for radiation input-output region 17 of gallium arsenide from (H. C. Huang *et al.*, *Journ. Appl. Phys.* (1990), Vol. 67, No. 3, pp. 1497–1503) for a wavelength $\lambda = 0.98 \text{ }\mu\text{m}$ and a carrier (electron) concentration of $1 \times 10^{18} \text{ cm}^{-3}$; and
- $\alpha_{15} = 15 \text{ cm}^{-1}$ — the loss factor for radiation emerging at the end of the active gain region through first optical facet 15.

Possible losses and distortions of the radiation fronts in radiation input-output region 17 due to radiation scattering were not taken into account in the calculations — radiation input-output region 17 was assumed to be optically homogeneous.

The assumed values of the parameters are typical of the InGaAs/GaAs/AlGaAs-based laser heterostructure 4 in question. If a laser heterostructure 4 using different connections is employed instead, these parameters may change.

The following results were obtained by numerical calculation for the SOA in question:

- the net loss factor $\alpha_{\text{OR}} (\text{cm}^{-1})$ for the net outgoing radiation from the active gain region into radiation input-output region 17 is: $\alpha_{\text{OR}} = 177.2 \text{ cm}^{-1}$;
- the loss factor for outgoing radiation from the active gain region into contact layer 9 is $\alpha'_{\text{OR}} = 1 \times 10^{-5} \text{ cm}^{-1}$;
- the effective refractive index of the aggregate of laser heterostructure 4 with radiation input-output region 17 is $n_{\text{eff}} = 3.4775$;

- the near-field distribution of amplified radiation in the plane perpendicular to the layers of laser heterostructure 4 and the layer of radiation input–output region 17 (see Fig. 5); and
- the corresponding far-field distribution of the amplified radiation intensity (see Fig. 6).

We also determined the following on the basis of the assumed parameters and the dimensions of the SOA as in Example 1:

- the angle φ of outflow of radiation from the active gain region into radiation input–output region 17: $\varphi = 9^\circ 30'$;
- the efficiency of output of outgoing radiation from the active gain region into radiation input–output region 17: $\eta_1 = 0.8986$;
- the input efficiency η_{2in} of the input radiation and the output efficiency η_2 of the output radiation, which are related to the optical losses (absorption) of the corresponding radiations upon passage through radiation input–output region 17 and to the losses to reflection from the corresponding second optical facets 18 and 19, are: $\eta_2 = \eta_{2in} \approx 0.99$;
- the differential efficiency is: $\eta_g = \eta_1 \times \eta_2 = 0.9$;
- the output power P_{out} of the amplified radiation for an operating current of 3.825, A is 4.32 W;
- the output radiation is directed at an angle to the plane of the active layer that is equal to the outflow angle $\varphi = 9^\circ 30'$, and its angle of divergence $\theta_{\perp}$ in the vertical plane is 3.96 mrad;
- the effective angle of divergence $\theta_{||}$ of the output radiation in the horizontal plane is 6.12 mrad;
- the areas of the input and output apertures are $S_{in} = 2,475 \mu\text{m}^2$ and $S_{out} = 39,600 \mu\text{m}^2$, respectively; and
- the density ρ_{19} of the output amplified radiation on the output optical surface of the second optical facet is: $\rho'_{19} = 1.09 \times 10^4 \text{ W/cm}^2$.

In the SOA design considered above, laser heterostructures 4 and radiation input–output region 17, which are schematically depicted in Figs. 7–9, may be modified. If this were done, the characteristics of the SOA would change as follows.

In Fig. 7 the cladding sublayer 25 adjacent to the radiation input–output region is made of two subregions 26 and 27. Selecting a thickness of $0.2 \mu\text{m}$ bordering on the first optical facet of subregion 27, and a length thereof equal to 0.03 times L_{AGR} , we will obtain a significant decrease in the radiation power density in the face of the active gain region on the first optical facet 15.

In Fig. 8 radiation input–output region 17 is made of sublayers: the first sublayer 28 is $30 \mu\text{m}$ thick and is electrically conductive (for a carrier concentration of $3 \times 10^{18} \text{ cm}^{-3}$), and the second sublayer 29 is lightly doped to a concentration of 1×10^{16} to $1 \times 10^{17} \text{ cm}^{-1}$. In this case, absorption losses can be reduced, and the efficiency of the SOA can be increased, as a result of the additional decrease in the optical loss factor α_{IOR} in the second sublayer 29 of radiation input–output region 17. Here, an ohmic contact 11 can be made directly with sublayer 28 as shown in Fig. 12. Note that in the case of small values of W_{in} and W_{out} , ohmic contact 11 can be formed with one of the cladding sublayers of

cladding layer 8, which is adjacent to radiation input–output region 17, as shown in Fig. 11.

In Fig. 9 a highly doped additional semiconductor layer 30 whose bandgap is smaller than E_a for active layer 6, such as one made of $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$, is placed on radiation input–output region 17 on the side opposite laser heterostructure 4. The presence of this layer 30 leads to additional stabilization of the operation of the SOA as a result of the absorption of possible spurious optical reflections, and at the same time will make it possible to decrease the resistance of ohmic contact 11. Furthermore, if necessary, the stabilization of the operation of the SOA can be intensified by varying the inclination of the second optical facet 19 to a value such that the amplified radiation reflected from it is not incident on the active gain region.

In other embodiments of the SOA in question, as depicted in Figs. 1, 2, and 10, the active region was formed by a strip with a width $W_{\text{in}} = W_{\text{out}} = 200 \mu\text{m}$; the length L_{AGR} on the order of $L_{\text{IOR-I}}$ and the thickness d_{IOR} of radiation input–output region 17 were chosen to be $10,000 \mu\text{m}$ and $1,700 \mu\text{m}$. Note that when this was done condition (10) was fulfilled. The previously considered first embodiment of the proposed SOA was selected as the master source 1 of output radiation with 4.32 W of power (for an operating current of 3.825 A). Optical system 2 for shaping the input radiation was not present, and the output radiation of master source 1 was sent directly on the normal to the plane of the second optical facet (not shown in Fig. 1). The main difference in this embodiment lay in the significant increase in the power of the amplified radiation at the output of the SOA (P_{out} is 72 W) and in the decrease in the angle of divergence $\theta_{\perp}$ in the vertical plane ($\theta_{\perp}$ is equal to 0.6 mrad).

The other embodiments of the SOA shown in Figs. 13–16 differed from the ones considered above in the size of the angles of inclination of the second optical facets. For the SOA (see Fig. 13) both optical facets 18 and 19 were parallel to the normal plane. This led to a situation in which the input angle δ of the collimated input radiation and angle of refraction ε for the amplified output diffraction-limited radiation were the same:

$$\delta = \varepsilon = \arcsin(n_{\text{IOR}} \sin \varphi) = 35^{\circ}30'.$$

In the next embodiment of the SOA (see Fig. 14), the second optical facet 18 was made parallel to the normal plane, and the second optical facet 19 was at an angle of inclination ψ_4 equal to the outflow angle φ , specifically $9^{\circ}30'$. This embodiment differed from the previous one in that the amplified radiation emerged through optical facet 19 on the normal to it (the angle of refraction ε was zero).

For the SOA (see Fig. 15) both second optical facets 18 and 19 of radiation input–output region 17 were made at angles of inclination ψ_3 and ψ_4 equal to $(\pi/2 - \varphi/2)$, in this case $40^{\circ}15'$, which were obtuse relative to the inner surface 20 of radiation input–output region 17. Here the collimated input radiation and amplified output radiation were directed on the normal to outer surface 21 of radiation input–output region 17.

Figure 16 depicts one embodiment of the proposed two-pass SOAs in which amplification of the input radiation takes place not only during forward traversal but also during return traversal of the active gain region as a result of the formed reflective coatings 31 to the first optical facet 15 and the second optical facet 19. The latter were made, as in the SOA in Fig. 13, parallel to the normal plane. In the proposed embodiment

of the two-pass SOA, there is more efficient use of the length L_{AGR} ; here, the input and output of amplified radiation on second optical facet 18 are spatially separated, and the values of the angles δ and ϵ are the same as for the SOA in Fig. 13.

The designs of multibeam SOAs depicted in Figs. 17–18 were proposed for a number of applications in fiber-optic communications lines for fabrication of optical power amplifiers in branched communications networks. In these SOAs radiation input–output region 17 consists of a series of subregions 32, which are successively positioned along the gain axis at equal distances from each other and are separated by the second optical facets 19 and 18. In the SOA embodiment according to Fig. 17, the second optical facets 18 and 19, except the second optical facet 18 to which the input radiation is supplied from master source 1, are formed for each subregion 32 at angles of inclination ψ_3 and ψ_4 that are equal to each other and have a value of $40^\circ 15'$. The input radiation from master source 1 is input into AC 3 as depicted for the SOA embodiment in Fig. 1. After traversing the first subregion 32 of radiation input–output region 17, the radiation will be output, as described previously, after reflection from the second optical facet 19 of the aforementioned subregion 32 through the output surface, which is on the projection of the aforementioned second optical facet 19 onto the outer surface 21 of radiation input–output region 17. The remainder of the amplified radiation propagated in the active gain region will enter the next analogous second subregion 32 of radiation input–output region 17, and the aforementioned process will be successively repeated in all subsequent subregions 32 of radiation input–output region 17.

In another embodiment of the multibeam AC 3 of the proposed SOA (see Fig. 17), the second optical facets 19 and 18 of each of the subregions 32 are formed at acute angles to active layer 6 and intersect on the inner surface 20 of radiation input–output region 17. Input of the input radiation into the first subregion 32 is performed by analogy with the SOA design in Fig. 13. Output of the outgoing amplified radiation is performed upon total internal reflection from the second optical facets 19 in the direction of laser heterostructure 4. The angle of inclination ψ_4 of the aforementioned facets was chosen from the range from $(\pi/4 + \varphi/2 - \sigma/2)$ to $(\pi/4 + \varphi/2 + \sigma/2)$ and is 51° (for an outflow angle φ of $9^\circ 30'$). At the point where the rays emerge, the contact layer 9 and ohmic contact 10 are removed, and antireflective coating 16 is applied.

Figures 19–24 depict other modifications of the proposed SOAs, including integrated ones (see Figs. 21–24). In the latter, output–input–output of radiation are accomplished within the unified radiation input–output region 17.

SOAs (see Figs. 19 and 21) in which a second amplifying component (MS-AC 1) (see Fig. 19) analogous to AC 3, or a second active gain region (see Fig. 21), which in the absence of feedback will be sources of directional superluminescent radiation in the discrete (see Fig. 19) and integrated design (see Fig. 21), are used as master source 1. To accomplish efficient input of input radiation into AC 3 from MS-AC 1, all inflow angles ξ and outflow angles φ were chosen to be identical, and the outer surfaces 21 in MS-AC 1 (see Fig. 19) and in the integrated SOA (see Fig. 21) were made reflective (total internal reflection from the surface).

To implement MS-AC 1 as a coherent emitter (see Fig. 20), we selected for it the design of AC 3 depicted in Fig. 14, with additionally formed reflective coatings 31 on the first optical facets 14 and 15, on second optical facet 18, and in part on second optical

facet 19. In this case, by virtue of the generation of feedback MS-AC 1 acquires the properties of a laser diode, and the outgoing radiation generated by it, after being reflected from reflective coating 31 on second optical facet 18 without any optical system, is effectively coupled to AC 3. Here, second optical facet 18 of AC 3 must be built in parallel to second optical facet 19 of MS-AC 1.

The SOAs depicted in Figs. 21–24 (in contrast to Figs. 19–20) include several interconnected ACs 3, which operate in a multistage amplifier circuit: the output of the amplified radiation of one amplifier is the input of the next. The active gain regions of master source 1 and all ACs 3 for the SOAs according to Figs. 21–23 are positioned along the gain axis on one inner surface of radiation input–output region 17. Here, coupling between the active gain regions is achieved as a result of total internal reflection from the outer surface of the radiation input–output region 17 common to them; the longitudinal distance between the initial points of the active gain regions was selected to be $2d_{\text{IOR}}/\tan \varphi$.

For the SOA depicted in Fig. 24, beginning with master source 1 the active gain regions are positioned alternately on opposite surfaces of radiation input–output region 17, with selection of the shortest distance between the initial faces of the active gain regions on opposite surfaces to be $d_{\text{IOR}}/\sin \varphi$.

A feature of the proposed SOA using discrete components (see Fig. 19) is that the thickness of radiation input–output region 17 for AC 3 is greater than the thickness of radiation input–output region 17 in MS-AC 1. This makes it possible to reduce, without degradation of other parameters, the diffraction angle of divergence for the amplified output radiation and also, if necessary, to increase the distance between the active gain regions in the case of a multistage amplifier.

A feature of the integrated SOA (see Fig. 24) is that, to effect lasing at one wavelength, optical feedback in the active gain region of master source 1 is formed by distributed retrodirective microreflectors 33, whose spacing is related in a known way to the wavelength of the radiation being generated (Handbook of Semiconductor Lasers and Photonic Integrated Circuits, edited by Y. Suematsu and A. R. Adams, Chapman–Hill, London, 1994, pp. 402–407). The active gain regions in AC 3 are made expandable so that the width W_{in} of each successively active gain region of AC 3 exceeds the width W_{out} of the previous one to the extent that the losses of the radiation being amplified are insignificant. The amplified output radiation of such a SOA should distinguish not only the monofrequency nature of its radiation but also the ability to obtain high output powers with small angles of divergence in both the vertical and horizontal planes with low astigmatism.

Thus, in comparison with the prior art (L. Goldberg et al., IEEE J. Of Quantum Electronics (1993), vol. 29, No. 6, pp. 2028–2042), in the proposed SOAs the input and output apertures of AC 3 are increased by a factor of more than 200, the divergences for the input radiation and amplified output radiation are reduced by the same factor (here, diffraction-divergent radiation was obtained in two mutually perpendicular directions), the effective length of the gain region in the SOA is increased by a factor of 6.6, and the output radiation power is increased by a factor of almost 30.

Commercial Applicability

In addition to injection lasers, semiconductor optical amplifiers are used to pump solid-state and fiber lasers, in building laser radiation sources in the visible region of the spectrum (red, green, and blue light) using second-harmonic generation in nonlinear optical crystals, medical equipment, laser process equipment, and systems for energy and data transmission over large distances, in modern fiber-optic communications systems.

Table

Name, No. of layers of regions	Composition of layer	Thickness d of layer (μm)	Refractive index n	Type of conduction	Carrier concentration N_c (cm^{-3})	Optical loss factor α (cm^{-1})
1	2	3	4	5	6	7
Contact layer	9 GaAs	0.3	3.52	P	2×10^{19}	20.0
Cladding	7 23 $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$	1.2	3.25	P	1×10^{18}	7.0
Layer	7 22 GaAs	0.3	3.525	—	—	2.0
Active layer	6 $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$	0.008	3.63	—	—	2.0
Cladding	8 24 GaAs	0.2	3.525	—	—	2.0
Layer	8 25 $\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}$	0.512	3.45	N	1×10^{18}	2.0
Radiation input- output region 1	5-17 GaAs	260.0	3.525	N	1×10^{18}	0.001

AMENDED CLAIMS

(Received by the International Bureau June 18, 1999 (6/18/99))
 Originally Filed Claims 1–51 Are Replaced
 by New Claims 1–56 (11 Pages))

1. A semiconductor optical amplifier which includes a master source of input radiation and an amplifying component optically coupled to it, said amplifying component being implemented on the basis of a semiconductor heterostructure that contains an active layer positioned between two cladding layers, in each of which there are ohmic contacts for at least one sublayer, said semiconductor optical amplifier being *distinctive* in that at least one additional layer is introduced on at least one side of the heterostructure, and the additional layer adjacent to the heterostructure is designated the input–output region for radiation to which it is transparent and is made of at least one sublayer and whose sublayers have refractive indices $n_{\text{IOR}q}$ and optical loss factors $\alpha_{\text{IOR}q}$ (cm^{-1}), where $q = 1, 2, \dots, p$ are defined as integers signifying the sequential numbers of the sublayers of the radiation input–output region, counted from its boundary with the heterostructure, and in the operating amplifier the angle of input δ of the input radiation and the net loss factor α_{OR} (cm^{-1}) for the amplified radiation flowing from the active layer are selected accordingly, and the effective refractive index n_{eff} of the heterostructure, in aggregate with the radiation input–output region, and the refractive index $n_{\text{IOR}1}$ of the radiation input–output region satisfy the relations

$$0 < \arccos \frac{n_{\text{eff}}}{n_{\text{IOR}1}} \leq \arccos \frac{n_{\text{eff-min}}}{n_{\text{IOR}1}},$$

such that $n_{\text{eff-min}}$ is greater than n_{min} , where $n_{\text{eff-min}}$ is the minimum value of n_{eff} out of all possible n_{eff} for the multiplicity of heterostructures that are of practical interest, in aggregate with radiation input–output regions, and n_{min} is the smallest of the refractive indices of the layers of the heterostructure.

2. A semiconductor optical amplifier as in Claim 1, which is distinctive in that the input radiation of the operating amplifier is formed to be collimated.

3. A semiconductor optical amplifier as in Claim 2, which is distinctive in that the input angle δ , which is equal to the angle of incidence of the input radiation on the input surface, is determined by ensuring that the inflow angle ξ and the outflow angle φ , which are respectively formed by the normal of the input ingoing radiation front and the normal of the outgoing amplified radiation, to the plane of the active layer of the heterostructure, be equal, and $\xi = \arccos (n_{\text{eff}}/n_{\text{IOR}1})$.

4. A semiconductor optical amplifier as in any of claims 1–3, which is distinctive in that in the operating amplifier the net loss factor α_{OR} (cm^{-1}) for amplified radiation emerging from the active layer at the boundary between the sublayer of the cladding layer and the radiation input–output region is selected from a range of values bounded at the bottom of the range, α_{ORmin} (cm^{-1}), by the permissible minimum value of the efficiency of conversion of the electric power supplied to the active gain region while the amplifier is in operation, into amplified radiation power, and on the top, α_{ORmax} (cm^{-1}), by the maximum permissible value of the operating-current density.

5. A semiconductor optical amplifier as in any of claims 1–4, which is distinctive in that barrier regions are introduced, the amplifying component is made with at least one active gain region of width W_{in} (μm) at its start, of width W_{out} (μm) at its end, and of length L_{AGR} (μm), with first optical facets that bound, on the face sides, the start and end of the active gain region and that subtend angles of inclination ψ_1 and ψ_2 with the plane perpendicular to the longitudinal axis of the active layer, which is called the normal plane.

6. A semiconductor optical amplifier as in any of claims 1–5, which is distinctive in that the radiation input–output region is made to have a width no smaller than the width of the active gain region, and the radiation input–output region surface bordering the heterostructure, which is called the inner surface, is made of a length L_{IOR-I} (μm) no shorter than the length L_{AGR} (μm).

7. A semiconductor optical amplifier as in any of claims 1–6, which is distinctive in that W_{in} (μm) is selected to be equal to W_{out} (μm).

8. A semiconductor optical amplifier as in any of claims 1–6, which is distinctive in that W_{out} is selected to be larger than W_{in} .

9. A semiconductor optical amplifier as in any of claims 1–8, which is distinctive in that the radiation input–output region is made of an optically homogeneous material.

10. A semiconductor optical amplifier as in Claim 9, which is distinctive in that the radiation input–output region is made of a semiconductor having a bandgap E_{IOR} (eV) exceeding the bandgap for the active layer E_a (eV) by more than 0.09 eV.

11. A semiconductor optical amplifier as in any of claims 1–10, which is distinctive in that the thickness d_{IOR} of the radiation input–output region is selected to be in the range 5–50,000 μm .

12. A semiconductor optical amplifier as in any of claims 1–11, which is distinctive in that the median plane of the active layer is located at a distance from the inner surface of the additional layer such that the amplified radiation intensity in the aforementioned median plane of the active layer that arises when the amplifier is in operation differs from the maximum intensity by no more than 20%.

13. A semiconductor optical amplifier as in any of claims 1–12, which is distinctive in that at least one of the sublayers of the cladding layers of the heterostructure is made with a refractive index of at least n_{IOR1} .

14. A semiconductor optical amplifier as in any of claims 1–13, which is distinctive in that the heterostructure layer adjacent to the radiation input–output region is made of at least two introduced regions whose bordering surfaces are perpendicular to the plane of the active layer.

15. A semiconductor optical amplifier as in Claim 14, which is distinctive in that the refractive indices of the adjacent regions are different.

16. A semiconductor optical amplifier as in Claim 14, which is distinctive in that the thicknesses of the adjacent regions are different.

17. A semiconductor optical amplifier as in any of claims 1–16, which is distinctive in that the outer additional layer is made of a material that absorbs the radiation being amplified.

18. A semiconductor optical amplifier as in any of claims 1–16, which is distinctive in that the additional layers are made electrically conductive.

19. A semiconductor optical amplifier as in Claim 18, which is distinctive in that an ohmic contact is formed with the free surface of the additional layers.

20. A semiconductor optical amplifier as in any of claims 1–17, which is distinctive in that the radiation input–output region is made electrically conductive.

21. A semiconductor optical amplifier as in Claim 20, which is distinctive in that an ohmic contact is formed with the surface of the radiation input–output region.

22. A semiconductor optical amplifier as in any of claims 1–21, which is distinctive in that the radiation input–output region is made to have an optical loss factor α_{IORq} of no more than 0.1 cm^{-1} .

23. A semiconductor optical amplifier as in any of claims 1–21, which is distinctive in that the radiation input–output region is formed of two sublayers, such that the first sublayer, which borders on the laser heterostructure, is electrically conductive, and the second layer is made of a material with an optical loss factor α_{IOR2} of no more than 0.1 cm^{-1} .

24. A semiconductor optical amplifier as in Claim 23, which is distinctive in that an ohmic contact is made with the first sublayer of the radiation input–output region.

25. A semiconductor optical amplifier as in any of claims 1–22, which is distinctive in that an ohmic contact from the direction of the radiation input–output region is made with one of the electrically conductive sublayers of the cladding layer positioned between the active layer and the radiation input–output region.

26. A semiconductor optical amplifier as in Claim 25, which is distinctive in that an ohmic contact is made with the electrically conductive layer with the smallest bandgap value.

27. A semiconductor optical amplifier as in any of claims 1–26, which is distinctive in that a second optical facet with an introduced antireflective coating, which is introduced in the radiation input–output region from the direction of radiation input, is made parallel to the normal plane, and the input angle δ is selected to satisfy the condition $\arcsin(n_{\text{IORq}} \sin \xi)$.

28. A semiconductor optical amplifier as in any of claims 1–26, which is distinctive in that the antireflective coating is formed on a part, determined by the size of the input aperture, of the radiation input–output region surface that is opposite the region's inner surface and adjacent to the second optical facet from the direction of radiation input, which subtends an obtuse angle with the plane of the active layer and is formed at an angle of inclination ψ_3 to the normal plane, selected from the range

$$[(\pi/4) - (\xi/2) - (\sigma/2)] \text{ to } [(\pi/4) - (\xi/2) + (\sigma/2)],$$

where π is equal to 3.1416 radians, and σ is the angle of total internal reflection for the outgoing radiation in the radiation input–output region.

29. A semiconductor optical amplifier as in Claim 28, which is distinctive in that the angle of inclination ψ_3 is selected to be $[(\pi/4) - (\xi/2)]$, and the output radiation is directed along the normal to the input surface.

30. A semiconductor optical amplifier as in any of claims 1–26, which is distinctive in that the second optical facet with an antireflective coating from the direction of radiation input, which subtends an acute angle with the plane of the active layer, is made with an angle of inclination ψ_3 selected from the range from $(\xi - \sigma)$ to $(\xi + \sigma)$.

31. A semiconductor optical amplifier as in Claim 30, which is distinctive in that the angle of inclination ψ_3 is selected to be equal to the inflow angle ξ , and the output radiation is directed along the normal to the input surface.

32. A semiconductor optical amplifier as in any of claims 1–26, which is distinctive in that the second optical facet with an antireflective coating, which is introduced in the radiation input–output region from the direction of radiation output and subtends an acute angle with the plane of the active layer, is made with an angle of inclination ψ_4 to the normal plane, which is selected from the range from $(\varphi - \sigma)$ to $(\varphi + \sigma)$

33. A semiconductor optical amplifier as in Claim 32, which is distinctive in that the angle of inclination ψ_4 is selected to be equal to the outflow angle φ .

34. A semiconductor optical amplifier as in any of claims 1–26, which is distinctive in that the second optical facet with an antireflective coating on the side of radiation output is made parallel to the normal plane, and the outflow angle φ is selected to be smaller than the angle of total internal reflection σ from the aforementioned facet.

35. A semiconductor optical amplifier as in Claim 29, which is distinctive in that an introduced reflective coating is made on one of the second optical facets, and one is formed parallel to the normal plane; an antireflective coating is made on another, opposite second optical facet, and radiation input is provided for through one part of it, which is determined by the size of the input aperture and which is located, beginning with the boundary of the second optical facet with the inner surface of the radiation input–output region, at a distance of no more than $L_{AGR} \tan \varphi$, and radiation output is provided for through the same facet in another part thereof.

36. A semiconductor optical amplifier as in Claim 35, which is distinctive in that a reflective coating is made on the first optical facet adjacent to the second optical facet with the reflective coating.

37. A semiconductor optical amplifier as in any of claims 1–26, which is distinctive in that the antireflective coating is made on a part, determined by the size of the output aperture, of the radiation input–output region surface opposite this region's inner surface and adjacent to the second optical facet from the direction of radiation output, which subtends an obtuse angle with the plane of the active layer and is formed at an angle of inclination ψ_4 selected to be in the range from $[(\pi/4) - (\varphi/2) - (\sigma/2)]$ to $[(\pi/4) - (\varphi/2) + (\sigma/2)]$.

38. A semiconductor optical amplifier as in Claim 37, which is distinctive in that the angle of inclination ψ_4 is selected to be $[(\pi/4) - (\varphi/2)]$, and the output radiation is directed along the normal to the output surface.

39. A semiconductor optical amplifier as in Claim 32, or 33, or 37, or 38, which is distinctive in that the radiation input–output region is made of at least two introduced subregions, the first of which is optically coupled to the master source, and the subregions are separated by second optical facets for output of radiation from each subregion.

40. A semiconductor optical amplifier as in Claim 39, which is distinctive in that the second optical facets in the direction of radiation output, which subtend an acute angle with the plane of the active layer, are formed at an angle of inclination ψ_4 selected to be in the range from $[(\pi/4) + (\varphi/2) - (\sigma/2)]$ to $[(\pi/4) + (\varphi/2) + (\sigma/2)]$, and antireflective coatings are made in the regions of their projections on the surface of the heterostructure opposite the location of the radiation input–output region.

41. A semiconductor optical amplifier as in any of claims 1–26, or in any of claims 32–34, or Claim 37, or Claim 38, which is distinctive in that at least two active gain regions that have an identical inflow angle ξ and outflow angle φ for each gain region, are formed on the same surface of the radiation input–output region.

42. A semiconductor optical amplifier as in Claim 41, which is distinctive in that at least two active gain regions are formed along the same line parallel to the surface of the radiation input–output region and to the plane of the active layer, with a spacing $2d_{\text{IOR}}/\tan \varphi$ between the starts of the active regions.

43. A semiconductor optical amplifier as in any of claims 1–26, or as in any of claims 32–34, or Claim 37, or Claim 38, which is distinctive in that at least one active gain region having an identical inflow angle ξ and outflow angle φ for each gain region is formed on opposite surfaces of the radiation input–output region.

44. A semiconductor optical amplifier as in Claim 43, which is distinctive in that at least one active gain region is formed along each of two lines that are parallel to each other and that are located on opposite surfaces, the shortest distance between the starts of active gain regions on opposite sides being $d_{\text{IOR}}/\sin \varphi$.

45. A semiconductor optical amplifier as in any of claims 1–26, or as in any of claims 32–38, which is distinctive in that the master source of input radiation is formed as a second amplifying component.

46. A semiconductor optical amplifier as in Claim 45, which is distinctive in that reflectors are introduced into the active gain region of the second amplifying component.

47. A semiconductor optical amplifier as in any of claims 1–26, or as in any of claims 32–34, or Claim 37, or Claim 38, which is distinctive in that the active gain region of the master source is located on the radiation input–output region of the amplifying component, and the outflow angle φ of the active gain region of the master source is identical to the inflow angle ξ of the active gain region of the amplifying component.

48. A semiconductor optical amplifier as in Claim 47, which is distinctive in that reflectors are introduced into the active gain region of the master source.

49. A semiconductor optical amplifier as in Claim 47 or 48, which is distinctive in that the active gain regions of the master source and amplifying component are located on the same inner surface of the radiation input–output region.

50. A semiconductor optical amplifier as in Claim 49, which is distinctive in that the active gain regions of the master source and amplifying component are located on the same line parallel to the surface of the radiation input–output region and to the plane of the active layer, with a spacing $2d_{\text{IOR}}/\tan \varphi$ between the starts of the active regions.

51. A semiconductor optical amplifier as in Claim 47 or 48, which is distinctive in that the active gain regions of the master source and amplifying component are located on opposite surfaces of the radiation input–output region.

52. A semiconductor optical amplifier as in Claim 51, which is distinctive in that the active gain regions of the gain region of the master source and amplifying component are formed along each of two lines that are parallel to each other and that are located on opposite surfaces, the shortest distance between the starts of active gain regions on opposite surfaces being $d_{\text{IOR}}/\sin \varphi$.

53. A semiconductor optical amplifier as in any of claims 41–52, which is distinctive in that at least part of at least one surface of the radiation input–output region is made reflective.

54. A semiconductor optical amplifier as in any of claims 46–53, which is distinctive in that the reflectors are implemented as reflective coatings.

55. A semiconductor optical amplifier as in any of claims 46–53, which is distinctive in that the reflectors are implemented as distributed Bragg reflectors.

56. A semiconductor optical amplifier as in any of claims 46–53, which is distinctive in that the reflectors are implemented in the form of distributed feedback reflectors along the entire length of the active gain region of the master source.