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New diode lasers with leaking emission in an optical cavity

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***Abstract*.** **A new type of a wide-aperture, high-power and efficient semiconductor laser with emission leaking from an active region and involved in lasing is proposed. The principle of its operation is described. Single-mode semiconductor lasers with output apertures at the optical facet of 5 × 6 μm, 7 × 7.5 μm, and 10 × 10 μm and diffraction-limited divergence angles of emission from 6.9 to 12° in the vertical plane and from 3.3 to 7.7° in the horizontal plane are created for the first time. A single-mode cw output power of 0.5 W is obtained at 980 nm in a single-frequency regime with diffraction-limited divergence angles in the horizontal and vertical planes equal to 5.7° and 12.3°, respectively. In the multimode regime, the output powers of 1.3 and 3.0 W were obtained with small divergence angles for ridge widths of 10 and 50 μm, respectively.**

Keywords: *diode laser, leaking emission, optical cavity, aperture and divergence of emission.*

1. Introduction

Semiconductor injection lasers being compact and efficient diode converters of the electric current energy to laser emission have become key and irreplaceable elements in modern achievements of civilisation such as optical telecommunication, optical memory devices, fibre and solid-state lasers, laser printers, laser medicine, material machining, and many other fields.

Edge diode lasers, which are most popular at present, have a substantial disadvantage, namely, a small vertical size of the emitting region in the output facet, which is usually of about 1 μm and smaller. This circumstance, which is fundamental for diode lasers, provides a high density of laser emission at the output facet and causes a high divergence of laser emission in the vertical plane. A high emission density restricts the level of the output power because of the catastrophic damage of the facet and substantially reduces the reliability and the operating life of diode lasers in regimes with emission densities at the output mirror close to ultimate values.

Thus, the maximum output power of a single-mode diode laser with the typical width of a stripe contact $w = 3$ μm and the ultimate power density of the facet damage (without strengthening covers) $p_{\text{cr}} \approx 10^6$ W cm^{-2} is estimated as 30 mW and 1 W for a multimode diode laser with $w = 100$ μm. The divergence angles θ_{ver} in the vertical plane (at the 0.5 level) are usually 25° – 45°, which often complicates the design of lasers and results in significant losses upon coupling emission into single-mode optical fibres. For this reason, the enlargement of the size of an emitting area in the output facet of a diode laser in the vertical plane is of great practical importance.

Diode lasers with an enlarged emitting area, in which leaking emission is used, were proposed and realised only in a few papers [1 – 6]. A common feature of these papers is that lasing is developed within a thin waveguide active region (as in usual edge diode lasers), while output emission is emission leaking to a semiconductor substrate. Although these diode lasers emit highly directional emission ($\theta_{\text{ver}} = 1.2°$ [4] and even 0.45° [5], they have the following disadvantages:

(i) the use of a substrate as a region in which emission propagates restricts the choice of both emission wavelengths (because a substrate should be transparent) and of required leakage angles, especially in the region of their small values;

(ii) the presence of adjacent emission channels on one facet (leaking and traditional facet) reduces the efficiency of the diode laser because of the technological problems involved in the separation of these emissions.

The designs of diode lasers in which new principles of the involvement in lasing of the emission leaking from an active region (optical waveguide) under certain conditions were proposed in Refs [7, 8]. These designs of diode lasers with leaking emission in an optical cavity (hereafter, LEOC DL) have many advantages, including a manifold enlarged emitting area on the output facets of the laser. In this paper, we consider the basic properties of one of such designs and present the first results of measurements of its main parameters.

2. Principle of operation of a LEOC DL

A scheme of one of the possible simplest designs of a heterostructure for a LEOC DL emitting in the spectral range from 900 to 1100 nm is shown in Fig. 1. The active region of the heterostructure consists of two active quantum-well InGaAs layers (*1*) and (*2*) and three barrier

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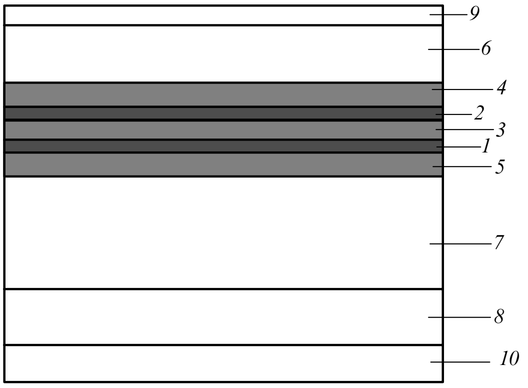

Figure 1. Scheme of a simplest heterostructure for a LEOC DL: (*1*, *2*) active InGaAs layers; (*3*–*5*) barrier GaAs layers; (*6*) limiting *p*-layer; (*7*) leakage layer; (*8*) reflecting *n*-layer for leaking emission; (*9*) contact p^+-layer; (*10*) *n*-GaAs substrate.

GaAs layers (*3*), (*4*), and (*5*). A limiting $Al_xGa_{1-x}As$ layer (*6*) is located on a barrier layer (*4*) on the side of the *p* contact. A highly doped contact p^+-GaAs layer (*9*) is contiguous to layer (*6*). A barrier layer (*5*) is contiguous on the side of the *n* contact with the $Al_yGa_{1-y}As$ leak-in layer (*7*), which has, as a rule, the greatest thickness (approximately 3 – 10 µm and above). A reflecting $Al_xGa_{1-x}As$ layer (*8*) (with $x > y$) is located on the *n* type GaAs substrate.

Although usual laser heterostructures appear similar to the LEOC DL heterostructures, they differ fundamentally from each other because in the first case the leaking emission should be reduced virtually to zero (because these are losses of laser emission), whereas in a LEOC DL a sufficiently high level of emission transfer from the active layer to the leak-in layer is provided in the region of operating currents. The emission leakage is controlled by a proper choice of the composition and thickness of the heterostructure layers, including the leak-in layer introduced technologically, which provides the excess of the refractive index n_{in} of the leak-in layer over the effective refractive index n_{eff} of the heterostructure at least within the specified interval of currents [7, 8].

The emission leaking from the active layer and distributed over the entire surface (and, hence, having a small divergence angle) will enter a leak-in layer along the longitudinal axis of the optical cavity at angles $\varphi = \pm\cos(n_{\text{eff}}/n_{\text{in}})$ in two opposite directions. In the case under study, when $\tan\varphi$ is several (two-three) times greater than the ratio of the thickness d_{in} of the leak-in layer to the length L_{cav} of the optical cavity, the leaking emission is multiply reflected in the vertical plane from the limiting and reflecting layers, and from mirrors of the optical cavity (with reflection coefficients R_1 and R_2). As a result, a waveguide emission mode is formed in the LEOC DL. The output emission will be directed at a right angle to the plane of the output optical facet, and the emission pattern will depend mainly on the number of an excited mode and the thickness of the leak-in layer.

A fundamental feature of the LEOC DL is the possibility of the single-mode operation even at a large thickness of the leak-in layer, at least up to 10 µm, as we established experimentally. This allowed us to increase the output aperture in the vertical plane up to 10 µm and to obtain the divergence angle $\theta_{\text{ver}} = 6.9°$, whereas known diode lasers with an expanded waveguide [9] exhibit high-order transverse modes already when the width of the waveguide layer exceeds 1 µm. Such a great difference is explained by a fundamentally different mechanism of mode formation in the LEOC DL, where the number of the excited mode is strictly determined by the leakage angle φ, which in turn depends on the thickness d_{in} of the leak-in layer.

To create an efficient LEOC DL emitting high-quality emission, it is necessary to control the current dependence of the confinement coefficient Γ of optical emission in the active layer. To provide low lasing thresholds at low current densities, the coefficient Γ should be relatively large and compared to that for usual diode lasers. In this case, the leaking emission can be weak or even absent at all. After the achievement of the lasing threshold, it is only sufficient to maintain the threshold emission level in the active layer over the entire range. The leaking emission will now increase with increasing the above-threshold current, and when the lasing threshold is sufficiently exceeded, the confinement coefficient Γ in the active layer of the LEOC DL can be one-two orders of magnitude (and more) smaller than that for usual diode lasers.

3. Experiment

We focused our attention in the development of a LEOC DL laser on producing emission at 980 nm, which is extensively used for pumping fibre amplifiers and lasers. Before growing a heterostructure, we performed numerical calculations, which provided the fulfilment of the above conditions for emission leakage in the LEOC DL.

The heterostructures for the LEOC DL on n-GaAs substrates were fabricated by the MOCVD method at a reduced pressure. Both strained quantum-well $In_{0.20}Ga_{0.80}As$ active layers had a thickness of 8 nm. The thickness of a barrier layer between them was 12 nm. The limiting and reflecting *p*- and *n*-layers had the same composition $Al_{0.3}Ga_{0.79}As$ and the same thickness of 1 µm. The leak-in layer of the *n* type was grown from pure $Al_{0.21}Ga_{0.79}As$ of the *n* type of thickness 5 µm. The thickness of highly doped contact GaAs layer of the p^+ type was 0.1 µm.

The active element of a ridge LEOC DL was fabricated by ion etching followed by a closure of etched side regions with a semi-insulating zinc selenide [10]. The widths of ridges pumped by the current were chosen equal to 6, 10, 15, 20, and 50 µm. The ohmic contacts to the *p*-side were formed by laser deposition of thin Ni layers doped with Zn. Then, barrier Mo – Ti – Ni layers were deposited, which followed by thermal deposition of Au. The ohmic contacts to the *n*-GaAs substrate were obtained by usual thermal deposition of Ge – Au.

The LEOC DL was assembled in a standard way. The active elements for the LEOC DL were soldered on a copper plate of size 2 × 3 × 4 mm using an indium solder. The plate was placed inside a cylindrical housing of diameter 11 mm. The housing was mechanically attached to a heat removing mass. All the measurements with the LEOC DL were performed in a continuous regime without using forced cooling.

First we fabricated and studied five groups of samples for the LEOC DL with the ridge width $w = 50$ µm. One of the cleaved facets of samples of four groups had a highly reflecting coating ($R_1 \approx 95\,\%$) deposited on it, and another facet had coatings with $R_2 = 3\,\%$, $10\,\%$, $30\,\%$ (neutral coating), and $80\,\%$, respectively. Samples in the fifth group had no covers on their mirror facets, so that for them $R_1 = R_2 \approx 30\,\%$. The lengths L_{cav} of optical cavities of lasers of all the groups were 600, 1000, and 1600 μm.

We measured the watt–ampere and volt–ampere characteristics of all the samples and the far-field emission distribution in the vertical and horizontal planes. The threshold current densities j_{th} for most samples were 200–330 A cm^{-2}. The differential efficiency η_{d} for three groups of samples was 52 %–79 % and for the fourth group (with $R_2 = 80\,\%$) of about 33 %.

The watt–ampere characteristics for two LEOC DLs with $w = 50$ μm, $L_{\text{cav}} = 1600$ μm, and $R_2 = 10\,\%$ are shown in Fig. 2. The output emission power of the first of them was 3 W. The bend of the watt–ampere characteristic at currents above 2 A is caused by heating. The output power of the second laser, which was placed, unlike the first laser, with the heterostructure upside on a copper plate, was measured only up to 2 W. One can see that the watt–ampere characteristics of both lasers are virtually identical despite substantial different mountings of the laser crystals.

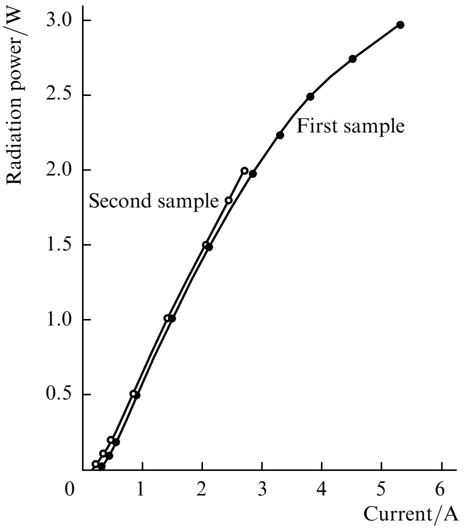

Figure 2. Watt–ampere characteristics of the LEOC DL with the ridge width of 50 μm for the first LEOC DL sample soldered on a copper plate with the heterostructure below and the second sample soldered with the heterostructure above.

The far-field emission pattern in the vertical plane for LEOC DLs without coatings (the fifth group of samples) has an unusual shape (Fig. 3a). The deposition of a highly reflecting coating with $R_1 \approx 95\,\%$ on one facet of all the samples resulted in a smooth emission distribution (Fig. 3b). In this case, the divergence angle θ_{ver} was within 11.07°–12.3°, depending on the values of L_{cav} or R_2. We also observed for these LEOC DLs with $w = 50$ μm a very weak dependence of the angle θ_{ver} (at the 0.5 level) on the output power (Fig. 4), whereas the divergence angle θ_{hor} (at the 0.5 level) in the horizontal plane increased from 3.28° at the 100-mW output power to 7.8° at 800 mW (Fig. 5). The far-filed emission patterns presented in Figs 4 and 5 show that these lasers with $w = 50$ μm emit no less than 100 mW in a single spatial mode.

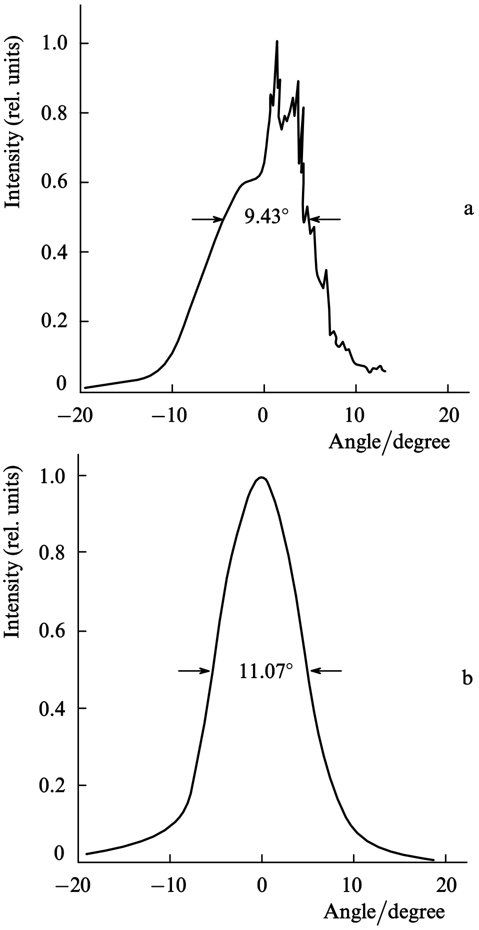

Figure 3. Far-field emission distributions in the vertical plane for the LEOC DL with the ridge width $w = 50$ μm and optical facets without covers (a) and with a reflection cover with $R_2 = 95\,\%$ deposited on one of the optical facets (b).

By analysing the dependences η_{d} on α_{out} and j_{th} on α_{out}^{-1} (where $\alpha_{\text{out}} = L_{\text{cav}}^{-1} \ln (R_1 R_2)^{-0.5}$), we estimated the internal parameters of LEOC DLs, namely, the internal quantum efficiency η_{int}, optical non-resonance losses α_{int}, and the value of $2j_0 + j_{\text{leak}}$, where j_0 is the inversion current density

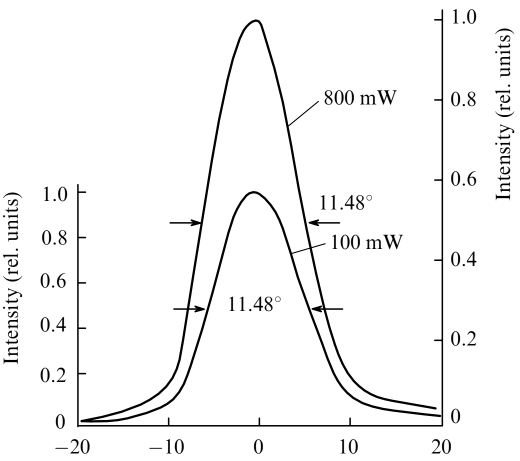

Figure 4. Far-field emission distributions in the vertical plane for the LEOC DL with $w = 50$ μm, $L_{\text{cav}} = 1600$ μm, and $R_2 = 10\,\%$ for output powers 100 and 800 mW.

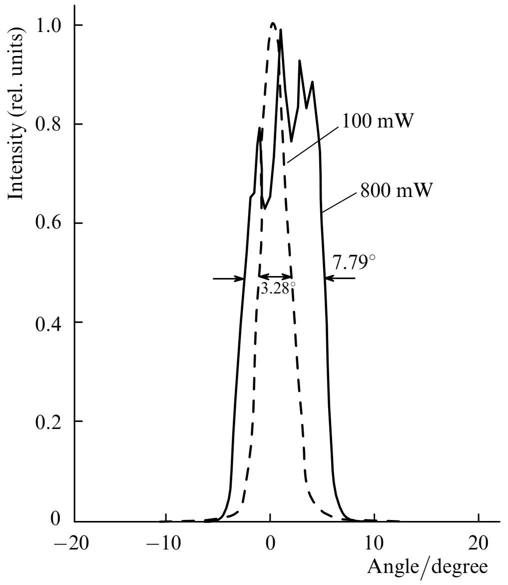

Figure 5. Far-field emission distributions in the horizontal plane for the LEOC DL with $w = 50$ μm, $L_{cav} = 1600$ μm, and $R_2 = 10\,\%$ for output powers 100 and 800 mW.

for carriers in one quantum well, and j_{leak} is the possible density of the over-barrier leakage current. We found that $\eta_{int} = 87$ %, $\alpha_{int} = 4.0 \pm 1.0$ cm^{-1} and $2j_0 + j_{leak} = 101$ A cm^{-2}. The value $\alpha_{int} = 4.0$ cm^{-1} shows that the grown heterostructure has a low quality and explains not sufficiently high values of η_d for LEOC DLs studied. Note that the differential resistances of the diode lasers calculated from volt–ampere characteristics in the current interval from 0.4 to 1.4 A were 1.24×10^{-4} Ω cm^2.

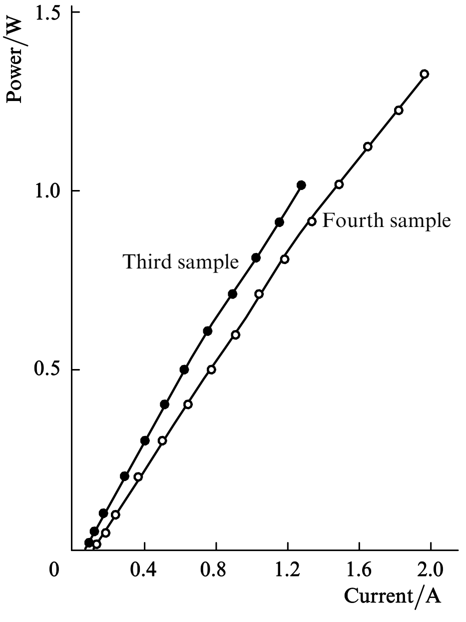

Figure 6. Watt–ampere characteristics of the LEOC DL with $w = 10$ μm, $L_{cav} = 1600$ μm, $R_1 = 95\,\%$, and $R_2 = 7\,\%$.

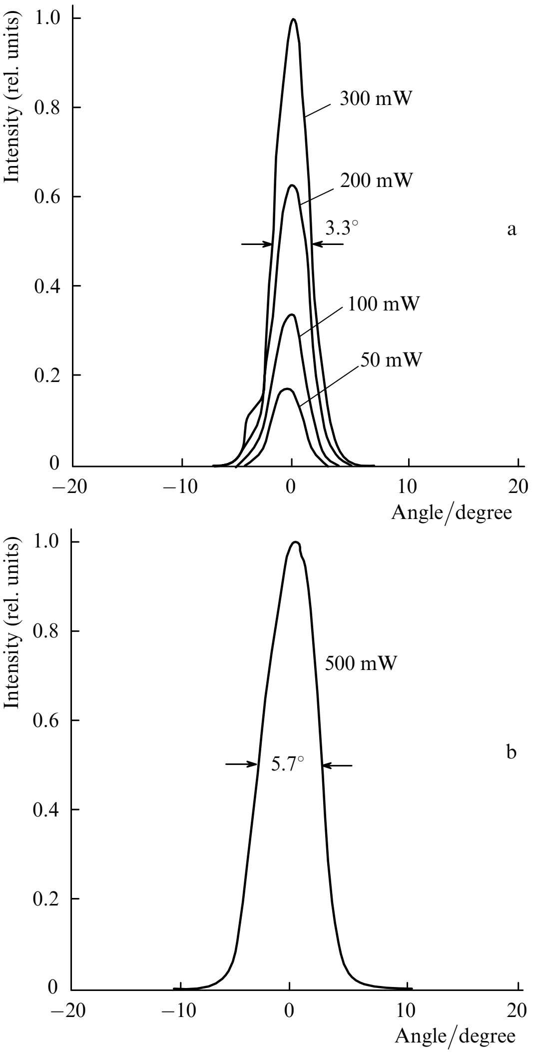

Figure 7. Far-field emission distributions in the horizontal plane for the LEOC DL with $w = 50$ μm, $L_{cav} = 1600$ μm, and $R_1 = 95\,\%$ and $R_2 = 7\,\%$ for output powers from 50 to 300 mW (a) and 500 mW (b).

Fig. 6 shows watt–ampere characteristics for two LEOC DLs with the ridge width $w = 10$ μm. The reflection coefficients R_1 and R_2 of facets were 95 % and 7 %, and the cavity length was $L_{cav} = 1600$ μm. The output powers were measured up to 1 W (third sample) and 1.3 W (fourth sample). The threshold current of the third sample was $j_{th} = 70$ mA and the maximum differential efficiency was $\eta_d = 58\,\%$. Unlike LEOC DLs with $w = 50$ μm, the divergence angle θ_{ver} increased from 11.5° to 12.3° with increasing output power from 100 to 1000 mW. The lasers produced a stable single-mode emission up to the output power of 0.5 W. In the output power range from 50 to 500 mW, the emission divergence is diffraction limited, and the angle θ_{hor} increases from 3.3° at 300 mW to 5.7° at 500 mW (Fig. 7). As the power was further increased up to 1 W, a single transverse mode retained in the vertical plane with increasing θ_{ver} up to 12.3°, whereas in the horizontal plane (Fig. 8) a 'weak mode playing' was observed at which the angle θ_{hor} increased up to 7.0° (i.e., approximately by 13 %).

We also fabricated LEOC DLs emitting at 915 nm. The main features of heterostructures used in these lasers were that their leak-in layer was grown from $Al_{0.30}Ga_{0.70}As$ and its width was increased up to 7 μm, while the limiting and reflecting layers were grown from $Al_{0.60}Ga_{0.40}As$. The width of ridges of the active element (7.5 μm) was chosen approximately equal to the width of the leak-in layer, the cavity length L_{cav} was 1000 μm, and the reflection

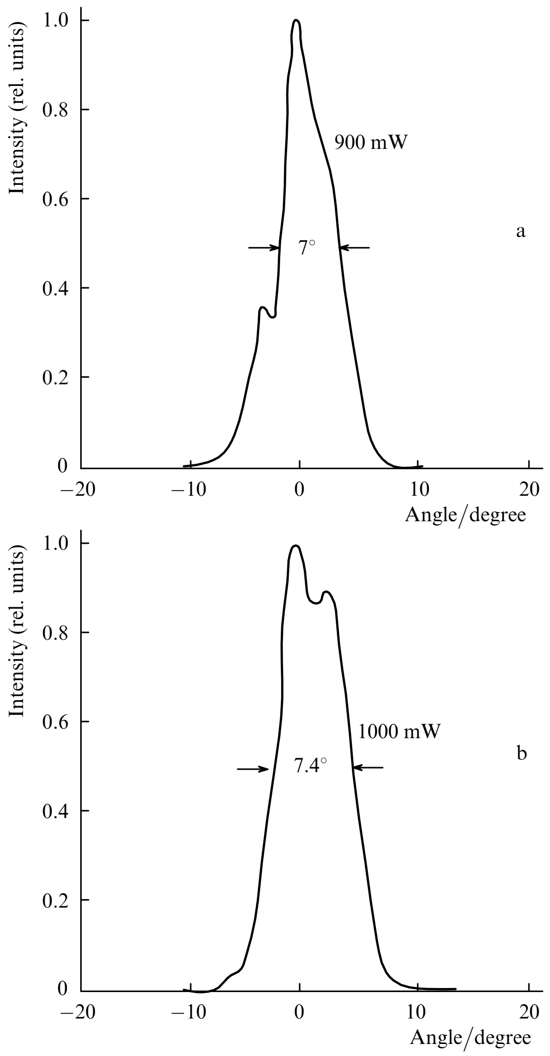

Figure 8. Far-field emission distributions in the horizontal plane for the LEOC DL with $w = 50$ μm, $L_{\text{cav}} = 1600$ μm, and $R_1 = 95\,\%$ and $R_2 = 7\,\%$ for output powers from 900 (a) and 1000 mW (b).

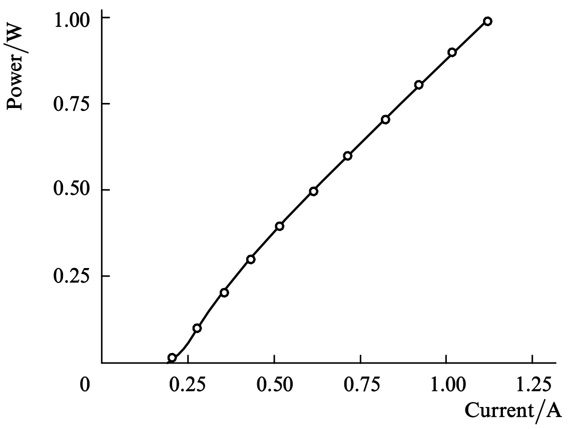

Figure 9. Watt – ampere characteristics for the LEOC DL emitting at 915 nm with $d_{\text{in}} = 7$ μm, $w = 7.5$ μm, $L_{\text{cav}} = 1600$ μm, $R_1 = 95\,\%$, and $R_2 = 5\,\%$.

coefficients R_1 and R_2 were 95 % and 5 %, respectively. The maximum output power of these LEOC DLs was 1 W (Fig. 9). The threshold current (204 mA) was relatively high ($j_{\text{th}} = 2.7$ kA cm^{-2}).

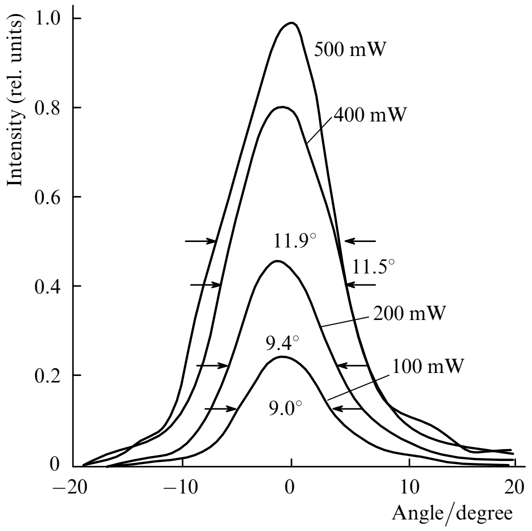

Figure 10. Far-field emission distributions in the vertical plane for the LEOC DL emitting at 915 nm for output powers from100 to 500 mW.

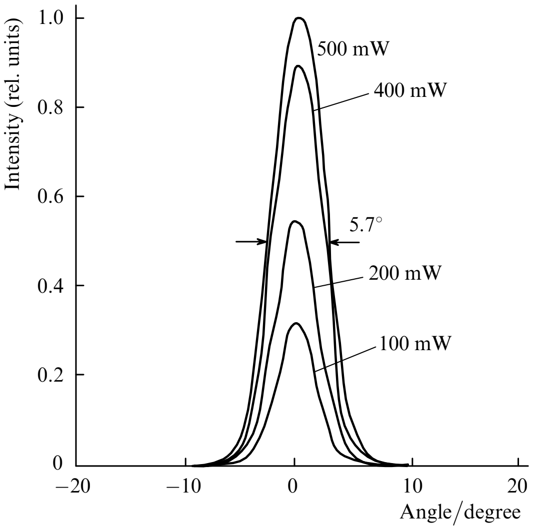

Figure 11. Far-field emission distributions in the horizontal plane for the LEOC DL emitting at 915 nm for output powers from 100 to 500 mW.

At the same time, the high values of the differential efficiency η_{d} were close to the ultimate values up to the output power of 500 mW, which was followed by a some decrease in η_{d} (approximately down to 85 % at $P = 1$ W). In this case, stable lasing was observed at a single fundamental transverse mode in the vertical plane over the entire power range, whereas stable single-mode lasing in the horizontal plane was observed up to the output power of 500 mW. The angle θ_{ver} changed in this case from 9.0° at 100 mW to 11.9° at 500 mW (Fig. 10), while the angle θ_{hor} changed from 4.1° at 50 mW to 5.7° at 500 mW (Fig. 11). The measurements of the emission spectrum of this LEOC DL showed that the laser operated in a single-mode regime in the power range from 100 to 500 mW. The emission wavelength increased from 916.4 nm at 100 mW to 925.0 nm at 500 mW.

The minimum divergence angle θ_{ver} in the vertical plane equal to 6.9° at the output power of 400 mW and current 1.47 A (Fig. 12) was achieved for the LEOC DLs with $d_{\text{in}} = w = 10$ μm emitting at 980 nm. Despite a high thre-

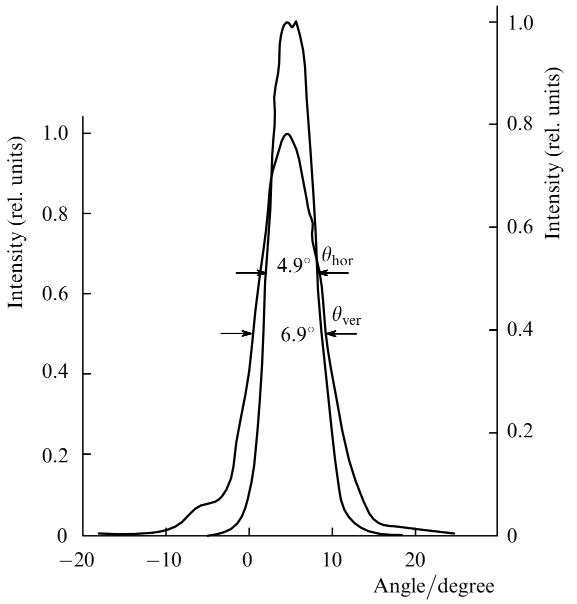

Figure 12. Far-field emission distribution for a 980-nm LEOC DL with dimensions $d_{\rm in} = w = 10$ μm, $L_{\rm cav} = 1600$ μm, $R_1 = 95\,\%$, and $R_2 = 12\,\%$ for $P = 400$ mW in the vertical and horisontal planes.

shold current $J_{\rm th} = 1.07$ A ($j_{\rm th} = 6.75$ kA cm^{-2}), these lasers also produced stable single-mode emission up to $P = 500$ mW and had a rather high value of $\eta_{\rm d}$ (80 %). The high threshold current densities for these LEOC DLs can be caused both by the non-optimal heterostructure and the non-optimal ridge structure.

4. Conclusions

We have proposed in this paper a new type of wide-aperture, efficient and high-power semiconductor lasers with emission leaking from the active region and involved in lasing. We have fabricated the experimental samples of these lasers and measured their basic parameters during cw lasing. We have fabricated for the first time semiconductor lasers emitting a single transverse mode with the near-field size from 5 to 10 μm and the emission divergence angles in the vertical plane from 11.1° to 6.9°, respectively. We have fabricated semiconductor lasers with the output aperture close to the square one of size 5×6 μm, 7×7.5 μm, and 10×10 μm. We have fabricated for the first time a 0.5-W single-mode laser and a 1.3-W laser with a high brightness emitting at 980 nm and having the ridge width $w = 10$ μm, the divergence angles in the vertical and horizontal planes equal to 12.3° and 5.7°, respectively, and low threshold current densities. A cw output of 3.0 W was achieved in a wide-aperture laser with the ridge width of 50 μm and the divergence angles equal to 11.5° and 7.2°. A 500-mW single-mode output was obtained at 915 nm with the divergence angles equal to 12° and 5.7°.

Note in conclusion that, by optimising the conditions of the epitaxial growth of laser heterostructures, we can obtain the loss factor for a diode laser $\alpha_{\rm int} = 0.75 - 1$ cm^{-1} (see, for example, [11]). Because a greater part of the LEOC DL emission propagates in a transparent homogeneous pure leak-in layer (the confinement coefficient Γ for the LEOC DL can be, for example, 10^{-4} instead of its usual value of 10^{-2} for diode lasers), we can expect the loss factor $\alpha_{\rm int}$ of the LEOC DL based on high-quality heterostructures can be noticeably lower than 1 cm^{-1}. In this case, we can hope to fabricate LEOC DLs that will have substantially greater efficiency and power than lasers considered here.

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References

1. Scrifers D.R., Burnham R.D., Streifer W. USA Patent 'Leaky wave diode laser' No. 4063189 (1977), H01S 3/19.
2. Scrifers D.R., Streifer W., Burnham R.D. *Appl. Phys. Lett.*, **29**, 23 (1976).
3. Shveikin V.I., Bogatov A.P., Drakin A.E., Kurnyavko Yu.V. Russian Federation Patent 'Injection Laser', No. 2133534 (08.08.1997).
4. Zvonkov N.B., Zvonkov B.N., Ershov A.V., Uskova E.A., Maksimov G.A. *Kvantovaya Elektron.*, **25**, 622 (1998) [*Quantum Electron.*, **28**, 605 (1998)].
5. Shveikin V.I., Bogatov A.P., Drakin A.E., Kurnyavko Yu.V. *Kvantovaya Elektron.*, **26**, 33 (1999) [*Quantum Electron.*, **29**, 33 (1999)].
6. Bogatov A.P., Drakin A.E., Shveikin V.I. *Kvantovaya Elektron.*, **26**, 28 (1999) [*Quantum Electron.*, **29**, 28 (1999)].
7. Shveikin V.I. Russian Federation Patent 'Injection Laser', No. 2142665 (10.08.1998).
8. Shveikin V.I. International Pending Patent 'Injection Laser', PCT/RU99/00275 (publication No. WO00/10235, 24.02.2002) and an addition (05.06.2000).
9. Garbuzov D.Z., et al. *J. IEEE Quantum Electron.*, **33**, 2266 (1997).
10. Davydova E.I., Popovichev V.V., Usinskii M.B., Khlopotin S.E., Shveikin V.I., Shishkin V.A. Russian Federation Patent 'Injection Laser', No. 2035103 (26.01.1993).
11. Jun Wang, Smith B., Xiaotin Xie, Xingiao Wang, Burnham G.T. *Appl. Phys. Lett.*, **74** (11), 1525 (1999).