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Leaky-wave semiconductor laser with improved energetic characteristics and very narrow dirrectional pattern

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***Abstract*. A leaky-wave semiconductor laser diode has been developed based on the InGaAs/GaAs/InGaP heterostructure. This design made it possible to obtain a high radiation output in a narrow angular range (about 1° – 2°) with an energy of 170 μJ in a laser with a cavity length of 0.8 mm and a stripe contact width of 360 μm, pumped by a single current pulse with an amplitude of 88 A and width of 5 μs.**

Keywords: *diode laser, narrow directional pattern, leaky-wave semiconductor laser.*

The technical (primarily, energetic) parameters of the currently used semiconductor lasers are close to the theoretical limit [1, 2]. Further development, expansion, and mastering of new areas of application of diode lasers is hindered by the high density of laser radiation at the output mirror, which is determined by the narrowness of the waveguide layer and significantly limits the output power. In addition, conventional lasers have a very wide output directional pattern in the plane perpendicular to the p – n junction, as a result of which the radiation deteriorates. One of the main reasons limiting the output power is the presence of ultimate light wave field in the cavity, which is in fact determined by the probability of optical phonon emission [2]. The second circumstance is the degradation of laser mirrors in strong fields. Both these factors suggest that there should be some limiting power density for the laser cavity. High-power lasers are designed based on either very wide cavities [1, 2] or two [3, 4] (three [5]) successively located lasers, connected by a tunnel p – n junction.

However, the ultimate laser power can be increased in a different way. If most of the laser radiation leaks not through the mirror but through the substrate, which is several orders of magnitude thicker than the waveguide layer, the total power can be significantly increased. The radiation leakage through the substrate (leaky-wave regime) can be performed by reducing the thickness of the barrier between the waveguide layer and the substrate. Obviously, these lasers should have a high threshold current because of the high leak-induced loss. Therefore, many quantum wells (QWs) must be incorporated into the laser active region to increase the gain. An important advantage of these lasers is the significant narrowing of the directional pattern in the plane perpendicular to the p – n junction.

Our design of a leaky-wave laser eliminates the above-mentioned technical limitations on the parameters and makes it possible to develop a new generation of semiconductor lasers with significantly improved energetic, spatial, and spectral characteristics.

The purpose of this work was to develop and investigate a semiconductor laser with a wide waveguide and an active medium of enlarged volume, containing six QWs. Optimisation of this structure, aimed at providing conditions for radiation leaking mainly into the substrate, made it possible to obtain a very narrow directional pattern in the plane perpendicular to the p – n junction. The yield of the laser diodes of new design, with radiation leaking into the substrate, was about 84 % in a narrow angular range (about 1° –2 °), which greatly exceeds the yield of conventional laser diodes with radiation leaking into a substrate [6] (50 % in a narrow beam). An experimental study of the energetic parameters of semiconductor lasers with an exit aperture of 360 μm showed that a 170-μJ pulse can be obtained under pumping by a single current pulse with an amplitude of 88 A and width of 5 μs.

A GaAs/InGaP/InGaAs heterostructure was grown by hydride – metalorganic vapor phase epitaxy under atmospheric pressure at the Physicotechnical Research Institute, Nizhnii Novgorod State University. The layer parameters are listed in Table 1. Based on this heterostructure, we designed semiconductor lasers with an active region width of 360 μm and cavity lengths of 0.5, 0.8, 1, 1.3, and 2 mm.

The temperature dependences of the threshold current density for the laser diodes are shown in Fig. 1. All samples exhibited a decrease in the threshold current upon cooling. The temperature dependences of the external differential efficiency η for laser diodes are presented in Fig. 2. One can see that the quantum efficiency increases with decreasing temperature.

Figure 3 presents the emission spectra of a laser diode with a cavity length of 1 mm, measured at 300 K under different pump currents. These spectral measurements revealed that at liquid-nitrogen temperatures lasing begins under pumping by a dc current of 0 9 A (current density

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Table 1. Parameters of laser layers.

Layer number	Layer type	Doping and layer composition	Thickness/nm
1	substrate	n-GaAs	–
2	buffer	n-GaAs	540
3	limiting	n-InGaP	80
4	waveguide	n-GaAs	504
5	waveguide	i-GaAs	108
6	QW 1	InGaAs	9
7	waveguide	i-GaAs	108
8	QW 2	InGaAs	9
9	waveguide	i-GaAs	108
10	QW 3	InGaAs	9
11	waveguide	i-GaAs	108
12	QW 4	InGaAs	9
13	waveguide	i-GaAs	108
14	QW 5	InGaAs	9
15	waveguide	i-GaAs	108
16	QW 6	InGaAs	9
17	waveguide	i-GaAs	108
18	waveguide	p-GaAs	504
19	limiting	p-InGaP	432
20	contact	p^+-GaAs	216

250 A cm^{-2}); this is in agreement with the fact that the threshold current density tends to decrease upon cooling [Fig. 1, curve (*3*)].

We measured the directional patterns in the p–n junction plane and in the plane perpendicular to it. Figures 4 and 5 demonstrate the directional radiation patterns for laser diodes with cavity lengths of 1 and 2 mm. The patterns of the laser diodes with cavity lengths of 0.5, 0.8, and 1.3 mm in the plane perpendicular to the p–n junction had a single-lobe shape (as well as for the 1-mm cavity laser), with deviation by 10° from the normal toward the substrate. The width of the directional pattern at half maximum was 1°–2°. A comparison of the power of highly divergent radiation from the waveguide layer with the radiation through the substrate (characterised by a narrow directional pattern) showed that 84 % radiation power is concentrated in a narrow angle. With an increase in the laser

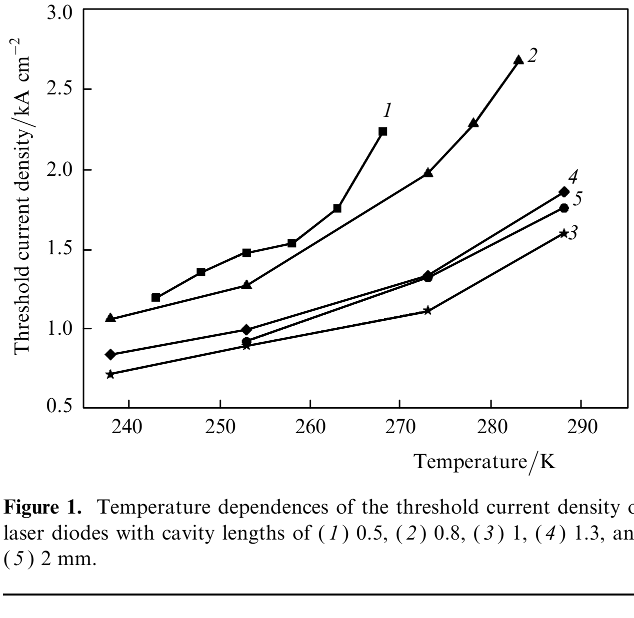

Figure 1. Temperature dependences of the threshold current density of laser diodes with cavity lengths of (*1*) 0.5, (*2*) 0.8, (*3*) 1, (*4*) 1.3, and (*5*) 2 mm.

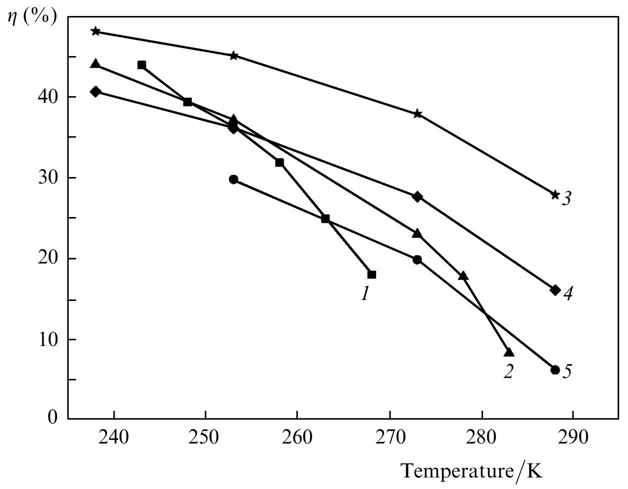

Figure 2. Temperature dependences of the external differential efficiency η for laser diodes with cavity lengths of (*1*) 0.5, (*2*) 0.8, (*3*) 1, (*4*) 1.3, and (*5*) 2 mm.

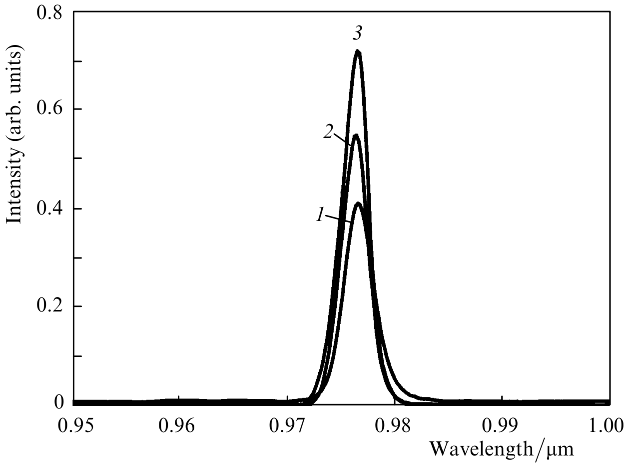

Figure 3. Emission spectra of a laser diode with a cavity length of 1 mm at pump currents of (*1*) 10, (*2*) 20, and (*3*) 30 A; the heat sink temperature is 300 K.

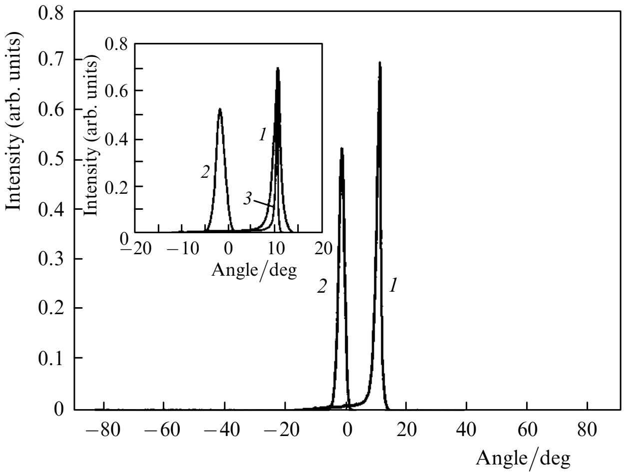

Figure 4. Directional patterns of a laser diode (*1*) in the plane perpendicular to the p–n junction plane and (*2*) in the p–n junction plane (cavity length 1 mm, heat sink temperature 25 °C, pump current 7 A). The inset shows the same curves on the larger angular scale [curve (*3*) is the calculated directional radiation pattern in the plane perpendicular to the p–n junction].

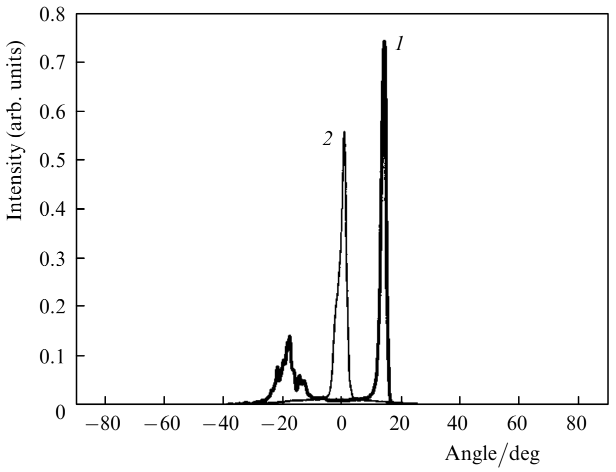

Figure 5. Directional patterns of a laser diode (*1*) in the plane perpendicular to the p−n junction plane and (*2*) in the p−n junction plane (cavity length 2 mm, heat sink temperature 25 °C, pump current 26 A).

diode length to 2 mm an additional peak arises in the angular diagram, which is caused by the radiation reflection from the upper rough boundary of the substrate (Fig. 5); as a result, the output radiation deteriorates. Note that the occurrence of additional peak is also determined by the substrate thickness (160 μm in our experiments).

The dependence of the pulse energy for a leaky-wave laser diode with a cavity length of 0.8 mm on the pump current for a 5-μs pump pulse is shown in Fig. 6 [curve (*1*)]. For comparison curve (*2*) shows a similar dependence for a conventional laser diode with a 1-mm cavity (the laser active region contained six QWs, its structure was similar to that of the lasers under study and differed only by the presence of a wide InGaP barrier between the waveguide and substrate). Deposition of reflection and antireflection coatings on the end faces of the leaky-wave laser made it possible to obtain a radiation energy of 170 μJ [Fig. 6, curve (*3*)] under pumping by a single 5-μs current pulse with an amplitude of 88 A. As can be seen in Figs 4 and 6, the radiation leakage through the substrate significantly reduces the electromagnetic field density at the mirrors, as a result of which a much higher output energy can be obtained at a higher pump current in comparison with conventional diode lasers. In addition, the radiation quality is significantly improved due to the very narrow directional pattern.

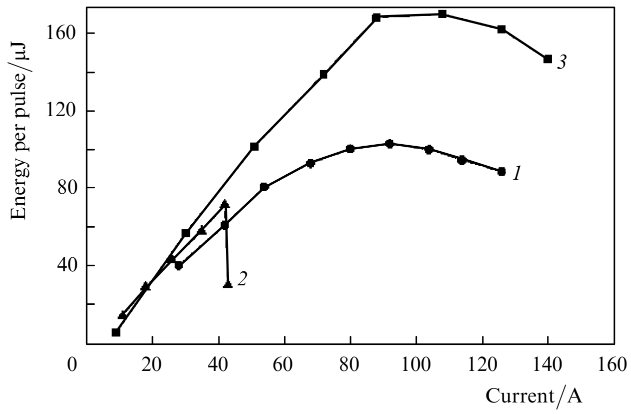

Figure 6. Dependences of the laser pulse energy on the pump current at a current pulse width of 5 μs for (*1*, *3*) a leaky-wave laser diode, without (*1*) and with (*3*) deposited reflection and antireflection coatings, and (*2*) a conventional laser diode (cavities lengths 0.8 and 1 mm, respectively).

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References

1. Gelovani V.A., Skorokhodov A.P., Shveikin V.I. *Vysokomoshchnye diodnye lazery novogo tipa* (Novel High-Power Lasers) (Moscow: Editorial URSS, 2005).
2. Slipchenko CO., Sokolova Z. N., Pikhtin N.A., Borshchev K.S, Vinokurov D.A., Tarasov I.S. *Fiz. Tekh. Poluprovodn.*, **40** (8), 1017 (2006).
3. Zverkov M.V., Konyaev V.P., Krichevskii V.V., Ladugin M.A., Marmalyuk A.A., Padalitsa A.A., Simakov V.A., Sukharev A.V. *Kvantovaya Elektron.*, **38** (11), 989 (2008) [*Quantum Electron.*, **38** (11), 989 (2008)].
4. Vinokurov D.A., Konyaev V.P., Ladugin M.A., Lyutetskii A.V., Marmalyuk A.A., Padalitsa A.A., Petrunov A.N., Pikhtin N.A., Simakov V.A., Slipchenko S.O., Sukharev A.V., Fetisova N.V., Shamakhov V.V., Tarasov I.S. *Fiz. Tekh. Poluprovodn.*, **44** (2), 251 (2010).
5. Davydova E.I., Zverkov M.V., Konyaev V.P., Krichevskii V.V., Ladugin M.A., Marmalyuk A.A., Padalitsa A.A., Simakov V.A., Sukharev A.V., Uspenskii M.B. *Kvantovaya Elektron.*, **39** (8), 723 (2009) [*Quantum Electron.*, **39** (8), 723 (2009)].
6. Zvonkov N.B., Zvonkov B.N., Ershov A.V., Uskova E.A., Maksimov G.A. *Kvantovaya Elektron.*, **25** (7), 622 (1998) [*Quantum Electron.*, **28** (7), 602 (1998)].