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MEASUREMENT OF LASER RADIATION PARAMETERS

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Mode structure in the far field radiation of a leaky-wave multiple quantum well laser

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Abstract. **The radiation patterns of a leaky-wave InGaAs/GaAs/InGaP laser are studied. In the subthreshold regime, several peaks are found, corresponding to the emission of fundamental and excited modes. The dependences of the amplitude, position and width of the peaks on the pump current are investigated and explained.**

Keywords: *leaky-wave laser, radiation pattern, mode composition.*

Leaky-mode semiconductor lasers [1] have a number of interesting features that can be used for practical applications. First, the radiation pattern of the lasers, in which the main power is concentrated in the leaky mode [2], in a plane perpendicular to the p – n junction is more than ten times narrower than that of conventional semiconductor lasers. Second, the power density on the mirrors of these lasers is much less than that of traditional laser designs. These two factors create the conditions for the creation of high-power pulsed diode lasers with a narrow radiation pattern [2], when using multiple quantum wells (QWs) as the active regions.

Unlike conventional lasers, in leaky-wave lasers the mode structure of the far-field pattern in the subthreshold regime, shown by narrow lobes on the radiation pattern, is observed [3, 4]. Bogatov et al. [4] found that in such lasers, the experimental measurement of the radiation patterns (including those in the subthreshold regime) and the corresponding calculations make it possible to quantify the effective refractive index of the mode, the optical confinement factor and the coefficient describing the change in the refractive index of the active layer with increasing concentration of injected carriers. However, as was calculated in [4], the width of the radiation pattern for the peaks corresponding to the waveguide modes was significantly less than that observed. The authors of paper [4] explained this difference by the ‘small-angle scattering’, which was not accounted for in the construction of the calculated far-field pattern. In addition, the shift of the peaks in the radiation pattern with an increase in the pump current was explained by changes in the effective refractive index due to the QW filling with nonequilibrium carriers and heating of the semiconductor, which, as we will show, is not always true.

This paper studies the radiation pattern of electroluminescence of a leaky-mode semiconductor laser containing six QWs. It is shown that the width of the electroluminescence peaks corresponding to waveguide modes is determined mainly by the width of the electroluminescence spectrum. A sharp narrowing of the pattern with the onset of stimulated emission is found. It is shown that the change of the position of the waveguide peaks on the radiation pattern results from a change not only in the effective refractive index of the mode due to heating of the core layer and an increase in the carrier concentration in it, but also from a change in the emission spectrum by varying the pump current.

The laser GaAs/InGaP/InGaAs heterostructure was grown by MOCVD at atmospheric pressure. The parameters of the layers are listed in Table 1. Using the heterostructures grown, laser diodes were fabricated with the active region width of 360 μm and cavity length of 1 mm. The faces of the laser chips were not coated with antireflection and high-reflection coatings. The active area of the structure consisted of six QWs.

The spectral dependences and radiation patterns were measured under cw and pulsed pumping (pulse width 220 ns, repetition rate 1.43 kHz). All measurements were performed at room temperature. Lasing occurred at a current of 7 A, and the radiation wavelength was ~1 μm.

Figure 1 shows the radiation patterns in a plane perpendicular to the p – n laser junction at a constant injection current of 0.15 and 1.8 A. At a current of 0.15 A, a pronounced

Table 1. Parameters of the laser heterostructure layers.

Layer number	Layer type	Doping and layer composition	Layer 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	36
8	Compensating	i-GaAsP	36
9	Waveguide	i-GaAs	36
10 – 25	Layers 6 – 9 are repeated four times		
26	QW 6	InGaAs	9
27	Waveguide	i-GaAs	36
28	Compensating	i-GaAsP	36
29	Waveguide	i-GaAs	108
30	Waveguide	p-GaAs	504
31	Limiting	p-InGaP	432
32	Contact	p^+-GaAs	216

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four-lobe radiation pattern [curve (*1*)] is observed, the maxima of this pattern being at angles 2°, 23°, 43° and 69°. With increasing pump current, the central peak (*2*) shifts to higher angles and at a current of 1.8 A corresponds to the angle 5° [curve (*2*)]. The angular position of the other peaks remains almost unchanged. Note also the presence of a peak near the angle −55°, which is due to the reflection of the radiation mode, corresponding to the angle 69°, from the boundary of the substrate, which is opposite to the epitaxial side.

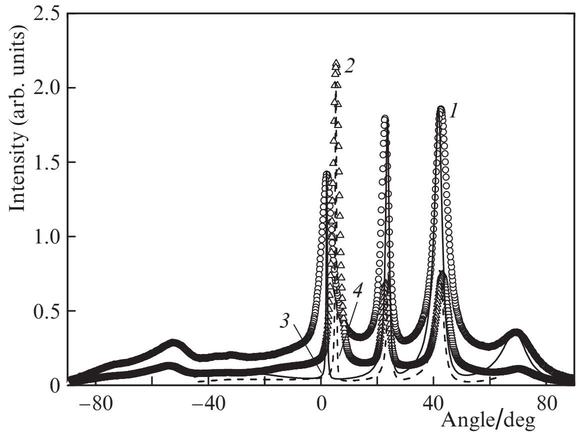

Figure 1. Radiation pattern of the laser at constant pump currents 0.15 (*1*) and 1.8 A (*2*) and calculated patterns for fixed wavelengths 0.964 and 0.983 μm and refractive indices of the waveguide layer 3.518 and 3.517 [curves (*3*) and (*4*), respectively].

The calculations of the laser structure in question (Fig. 2) confirm that four-mode lasing is possible. The calculated optical confinement factor Γ of these modes is 0.023 for the zeroth, 0.007 for the first, 0.013 for the second and 0.014 for the third modes. However, if we take into account the nonuniformity of filling of quantum wells with carriers, previously observed in lasers with many QWs [5], we can assume that at low currents, when there is spontaneous luminescence, current carriers generally fill extreme QWs. In this case, the factor Γ is 0.007 for the zeroth, 0.003 for the first, 0.003 for the second and 0.006 for the third modes, which is in satisfactory agreement with the experiment (Fig. 1). Figure 1 also shows the radiation pattern calculated for the model described in [6] for two values of the refractive index in the central GaAs waveguide layer: 3.518 [curve (*3*)] and 3.517 [curve (*4*)] at two fixed wavelengths (0.964 and 0.983 μm, respectively), corresponding to the maxima of the luminescence spectra (Fig. 3). Note that in contrast to [7], where the authors observed the features in the emission spectrum of a leaky-wave laser, in our case, no special features in the emission spectrum were observed, which can be explained by differences in the design of the lasers. Figure 1 shows good agreement between the positions of the maxima of the calculated [curves (*3*) and (*4*)] and measured [curves (*1*) and (*2*)] patterns. With the increase in the injection current the central waveguide layer is filled with the current carriers, leading to a decrease in the refractive index of the layer, as noted in earlier studies (see, for example. [4]). In addition, the refractive index decreases with increasing wavelength.

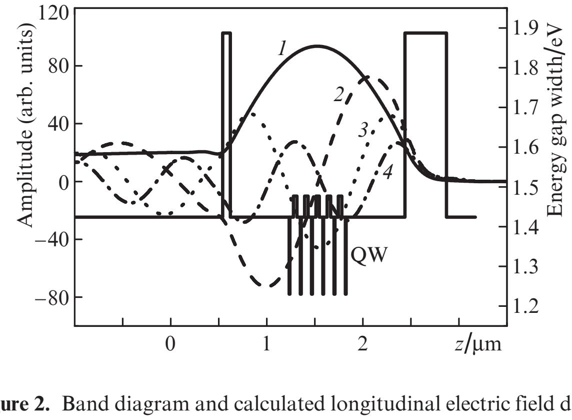

Figure 2. Band diagram and calculated longitudinal electric field distribution of the zeroth (*1*), first (*2*), second (*3*) and third (*4*) modes.

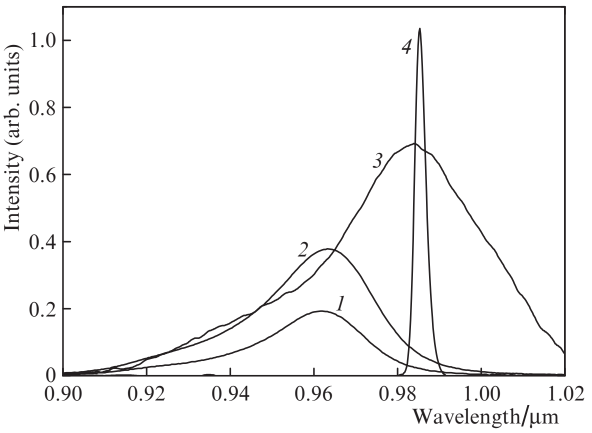

Figure 3. Luminescence spectra of the laser for current 0.15 (*1*), 0.4 (*2*), 1.8 (*3*) and 10 A (*4*).

Figure 4 shows the radiation patterns in a plane perpendicular to the p−n laser junction at a pulsed pump current of 5 and 10 A. With the current growth from 5 to 10 A [curves (*1*) and (*2*), respectively], the structure starts lasing, and the radiation pattern changes to the single lobe pattern with an angle of 6° and a peak width of 2°. Comparison of the patterns in Figs 4 and 1 shows that in the lasing regime the structure emits only on the zeroth mode that is characterised by the

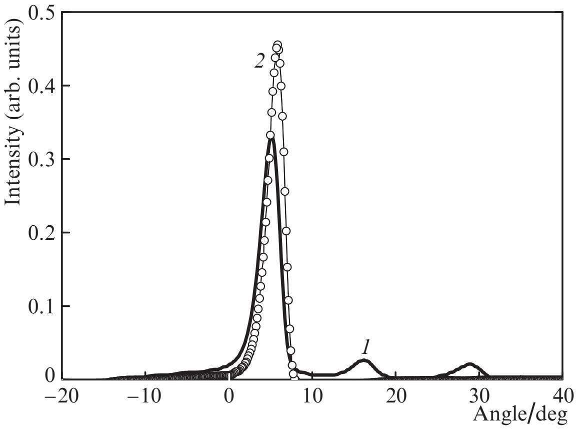

Figure 4. Radiation pattern of the laser at pulsed pump currents 5 (below the threshold) (*1*) and 10 A (above the threshold) (*2*).

highest Q factor. Note that for these pump currents, the heating of the central layer, as compared to an increase in the concentration of carriers in this layer, does not exert any significant influence on the pattern; otherwise, it would lead to an increase in the refractive index of the waveguide layer and, consequently, to a reduction of the angle of the zeroth mode, which was observed and explained in [4].

Figure 1 also shows that the widths of the experimental and theoretical peaks are very different (this was noted in [4]). This difference can be explained by two mechanisms of broadening of the experimental curves. According to equation (2) in paper [4], the angle of radiation output from the substrate is determined by the effective wave propagation vector of the corresponding mode. In the first case (the broadening mechanism is independent of the pump current), the uncertainty of the effective wave propagation vector can be caused by a wide laser cavity (in our case, 360 μm) and by the parameters of the experimental setup used to measure the radiation pattern. According to the estimates, the spread of the output angle for the first broadening mechanism in this case is about 2°. The second mechanism is related to the spectral width of the luminescence line, since the effective wave propagation vector depends both on the radiation frequency and the pump current. Figure 5 compares the experimental pattern [curve (*1*)] and the patterns calculated without [curve (*2*)] and with [curve (*3*)] the spectral luminescence width taken into account for the current 0.15 A (~30 nm, Fig. 3). In the latter case, there is good agreement with experiment. At a current of 10 A, the line width at half maximum is about 2 nm, and therefore the characteristic width of the radiation pattern should be about 0.1°, but in the experiment, it is about 2° and does not decrease with increasing current. It can therefore be concluded that under subthreshold pumping, the main broadening mechanism is associated with a broad line of spontaneous luminescence, and at currents above the lasing threshold, the main broadening mechanism is the uncertainty of the effective wave propagation vector.

Thus, in studying the radiation pattern in the subthreshold regime (spontaneous emission), there are several peaks corresponding to the fundamental and the excited modes. The increase in the pump current causes an offset of the peak of the fundamental mode, which is due to a decrease in the refractive index of the active region resulting from its filling with the carriers and shift of luminescence maximum to longer wavelengths. The dependence of the peak amplitudes on the pump current is studied. Inhomogeneous filling of QWs with the carriers is shown experimentally in the subthreshold regime, which appears to change the intensity of the narrow lobes of the radiation pattern.

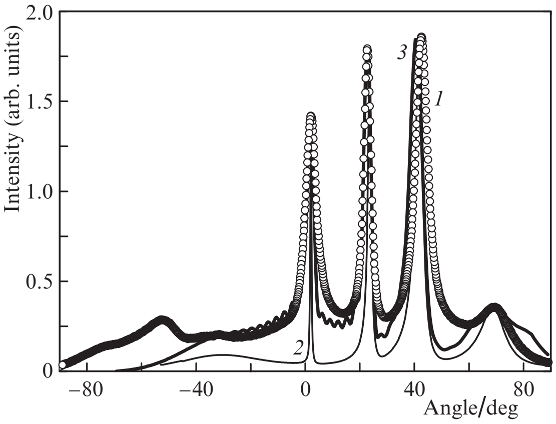

Figure 5. Experimental radiation pattern (*1*) and calculated patterns without (*2*) and with (*3*) the spectral luminescence width taken into account for the current 0.15 A.

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