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Degradation and Spectral–Spatial Characteristics of the Radiation of High-Power Laser Diodes

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Abstract—Characteristics of the radiation of high-power injection lasers with quantum wells (QW) at 965 nm are measured before and after 30 and 100 h of operation. The relation between slow laser degradation and their spectra, radiation patterns, and radiation polarization is demonstrated. A dynamic self-consistent laser model is developed.

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INTRODUCTION

Studies focused on constructing high-power (at least 0.5 W) injection laser diodes (LDs) are now underway [1–4]. The record radiation power of LDs is 20–22 W from a single crystal. However, these record values were determined in very brief measurements. High power values are obtained using QW laser diodes with an expanded asymmetric waveguide and a strip contact. While strip contacts with widths of 3–10 μm are used in low-power lasers, high-power lasers with high pump currents require that we extend the contact width to 100–200 μm.

Using a strip contact with a width of 100–200 μm (which is needed to increase the LD's radiation power) results in independent generation channels and possibly several lateral modes in each channel [5]. This is due primarily to the spatial burning of carriers and nonlinear refraction in the active LD layer. The inhomogeneities of optical density and the amplification of the active laser medium caused by the spatial burning of nonequilibrium carriers produce self-focusing radiation filaments. Nonphased radiation channels emerge in LDs with wide contacts due to the lateral inhomogeneity of the structure and because the length of induced radiation coherence in semiconductor lasers is short (1–3 cm). The number of generation channels depends directly on the length of nonequilibrium carrier diffusion in the active LD layer. The LD degradation caused by an increase in the number of defects along dislocations in a strained semiconductor structure changes the length of diffusion and thus alters the profile and number of generation channels [5]. The frequency spectrum of LD radiation is filled with a greater number of overlapping lines. If an LD has a complex wide frequency spectrum at the initial stage of operation, the service life of this LD will surely be shorter than that of an LD with clearly defined spectral lines.

Experimental data and a technique for calculating the near field are presented below. The influence of degradation on the spectra, polarization, and near-field distribution of high-power LDs is also discussed.

EXPERIMENTAL RESULTS

In this work, we used a high-power (0.5–1 W) LD based on an $Al_{0.27}Ga_{0.73}As/In_{0.26}Ga_{0.74}As_{0.47}P_{0.53}/In_{0.14}Ga_{0.86}As$ heterostructure with an $In_{0.14}Ga_{0.86}As$ quantum well (12 nm), a fine mesostructure with an active region width of 100 μm, and an expanded 1000-μm-long waveguide (2-μm-thick) [1]. The threshold LD current was $I_{th} = 400$ mA.

Laser degradation increased the number of generation channels and the inhomogeneity of radiation along the lateral *YZ* plane. This is seen clearly in Fig. 1, which shows the radiation pattern (RP) of an LD detected on a plane screen with a fluorescent material. The LD had accumulated (a) 30 or (b) 100 service hours.

The radiation spectra were measured in isolated RP spots of an LD at different pump currents for two radiation polarizations: one in the central and one in the side spot. Analysis of the spectra in the central RP spot at different pump currents (Fig. 2a) showed that (i) a dominant generation channel at the zero transverse mode (965.1 nm) with self-modulation at a frequency of about 110 GHz (central group of equidistant lines), (ii) a channel with lower brightness at

963.8 nm with self-modulation at 10 GHz (left group of lines), and (iii) a dim channel close to the lasing threshold (965.9 nm) were present in the LD radiation. At higher currents (650 and 900 mA), a beats regime and then chaos are observed in the spectra. The last two diagrams in Fig. 2a (1150 and 1350 mA) show that generation reverts to the beats regime, and the fourth and the fifth channels of CW generation at the zero mode (967.1 and 963.8 nm) are visible.

Spectral dependences of radiation with orthogonal polarization (with respect to the plane of LD layers) are shown in Figs. 2a and 2b (heavy curves). They roughly follow the transformation of spectra of TE modes, but are less intense than the lines with lateral polarization.

The first side RP spot is represented by the spectra of odd modes in generation channels. These spectra are shown in Fig. 2b. It can be seen that the radiation of lateral modes on an order different (odd) from the one in the central lobe was concentrated in the lateral RP lobe. This is apparent from the considerable difference between the frequencies of the primary radiation lines. However, the nature of the dynamics and switching of modes remained roughly the same as in the central lobe. In general, analysis of spectra and polarization in RP lobes provides valuable data on the laser's quality, its degree of degradation, and the dynamic processes within the laser.

The effect of self-modulation is generally attributed to defects in the waveguide layer and the LD with QWs behaving as saturable absorbers that promote periodic (or irregular, in the chaotic regime) changes in the Q factor of the laser cavity under the influence of radiation. The difference between the frequencies of self-modulation peaks is determined by the absorber relaxation time (10^{-11}–10^{-10} s) [6].

Analysis of the first lateral mode contributing to the first lateral RP lobe suggests that this mode also emerges in the generation channels and is involved in the dynamics of LD radiation. This mode exhibits the same patterns that are typical of the zero mode, but the spectrum is shifted toward longer wavelengths.

Characteristic dependences of the degree of linear polarization of radiation in RP spots were obtained experimentally (Fig. 3).

The degree of polarization was reduced when the pump current was raised. The same effect was observed as the laser accumulated service hours. It is arguable that the deterioration of the degree of polarization is a phenomenon that accompanies LD degradation. Long-term changes in LDs that are reflected in the spectra and in the degree of polarization of radiation under one and the same pump current turn out to be similar to those observed in short-term measurements, but with different currents.

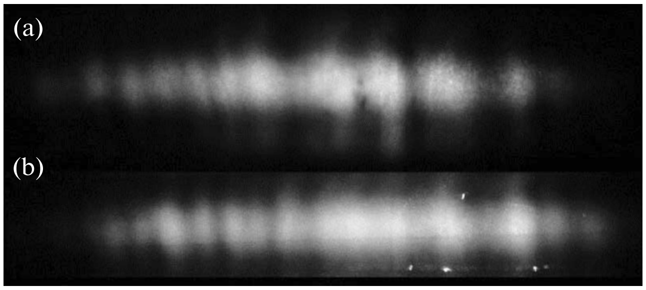
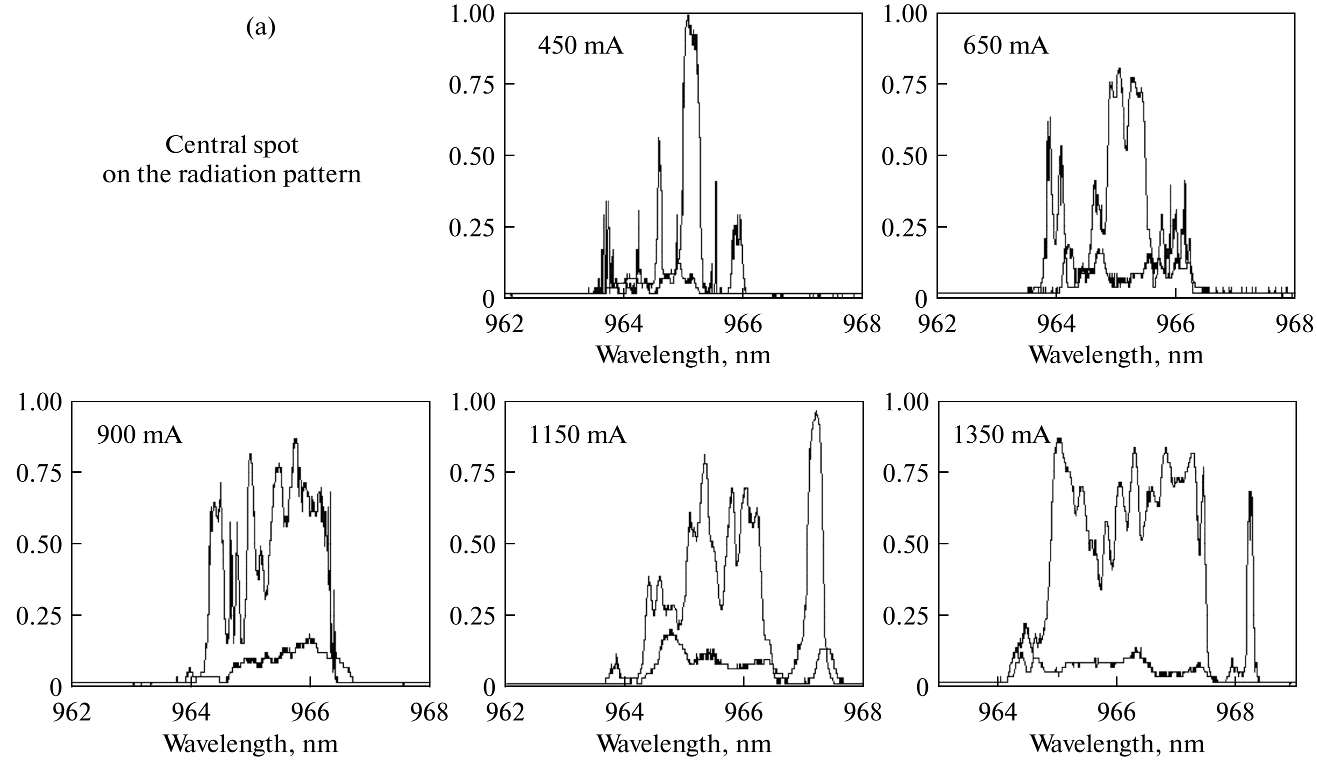


Fig. 1. LD directivity diagram detected on a screen plane with a fluorescent material. The LD had accumulated (a) 30 and (b) 100 service hours.

REASONS FOR CHANGES IN POLARIZATION

The deterioration of polarization could be due to an increased contribution from light holes to the allowed laser transition. It is known that the subband of light holes in a strained structure (QW) is detached from the subband of heavy holes [7] and is not involved in the generation of induced radiation. The hole degeneracy in the center of the Brillouin zone is lifted, and the band of light holes moves down. The bandgap width in a strained structure is increased. These features of a strained structure stem from the lattice parameter in an $In_{0.14}Ga_{0.86}As$ QW being reduced during epitaxial growth on gallium arsenide. This effect is similar to that of external pressure being applied to a semiconductor in one direction, and it considerably alters the valence band structure. It is improbable that light holes participate in radiative transitions.

Since optical transitions in a QW with the participation of heavy holes are allowed only for a single light polarization in which vector $\vec{E}$ of the electric field of radiation lies within the QW plane, the polarization should theoretically be around 100%. However, the presence of heteroboundaries and a reduction of symmetry of atomic bonding at the boundaries due to morphological features of the process of epitaxial growth result in the mixing of the states of heavy and light holes. In addition, the deviation of the QW potential profile from a rectangular form reduces the polarization by 2–5%. This effect gets stronger with time, since dislocations and defects that relieve the strain in the QW and affect its structure emerge during operation. A reduction in the degree of anisotropy enhances the contribution from light holes (TM polarization), and their levels approach those of heavy holes. The degree of linear polarization is reduced to 0.7–0.8, and the radiation bands are shifted toward longer wavelengths [5]. An increase in the number of defects in the structure leads to a reduction in the length of diffusion and to multichannel generation, establishing the conditions for rapid deterioration.



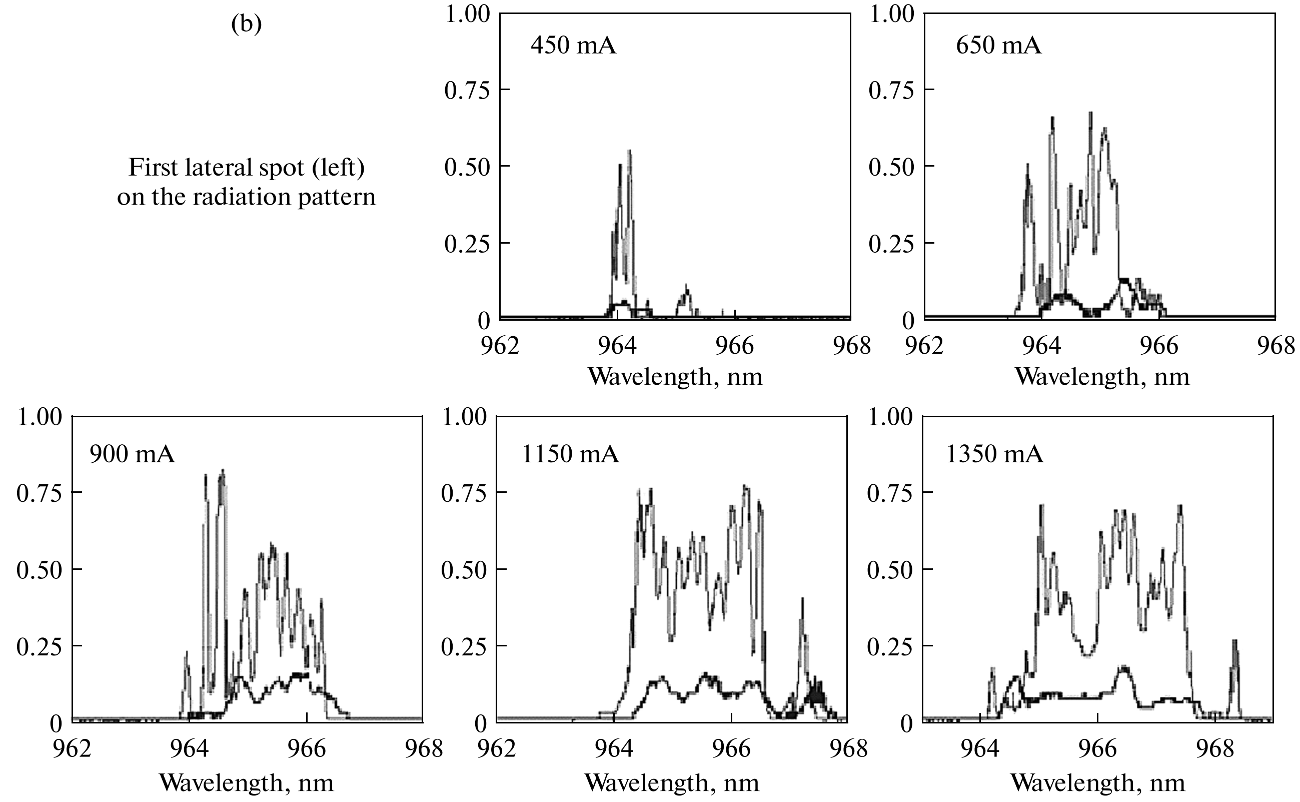


Fig. 2. Laser emission spectra in the (a) central and (b) first lateral lobes (spots) of the radiation pattern at different pump currents for two types of linear polarization. The LD had accumulated 100 service hours.

QUANTUM EXPLANATION OF THE REASONS FOR POLARIZATION CHANGES

The interaction between optical radiation and charge carriers in semiconductors in the dipole approximation is characterized by the matrix element [7]

$$\left|\langle c|\vec{A}\cdot\hat{p}|v\rangle\right|^2 = \frac{\left|\vec{E}\right|^2}{4q^2}\left|\int\varphi^{*}_{c,\vec{k}_c}(r)\exp\left[i(\vec{q}-\vec{k}_c)\cdot\vec{r}\right]\right. \tag{1}$$

$$\left.\times\,(\vec{e}\cdot\vec{p})\varphi_{V,k_v}(\vec{r})\exp\left[i(\vec{k}_v\cdot\vec{r})\right]dr\right|^2,$$

where $\vec{A} = A\vec{e}$ is the vector potential of the electromagnetic wave, $\vec{e}$ is a unit vector parallel to $\vec{A}$, $\hat{p}$ is the electron quasi-momentum operator, $\vec{k}_c$ and $\vec{k}_v$ are the electron wave vectors in the conduction band and in the valence band, and $|\vec{q}| = \frac{2\pi}{\lambda}$ is the photon wave vector.

If vectors $\vec{A}$ and $\vec{p}$ are orthogonal, the matrix element of interaction equals zero. The matrix element is often calculated for the degenerate extremum in the upper valence bands of semiconductors with a sphalerite structure (InAs and GaAs). The wave functions of these valence bands are *p*-functions. The spin–orbit interaction that leads to splitting of the lower subband must also be taken into account. The linear $\vec{k}\cdot\vec{p}$ term equals zero in sphalerite crystals. All directions of vector $\vec{k}$ are equally probable in this case, and radiation emitted during interband transitions is nonpolarized. Indeed, spontaneous emissions of laser diodes do not contain polarized components. However, the induced emission that emerges in the active region has a high degree of polarization, due to the selective properties of the waveguide for TE polarization.

Different conditions are established in QW structures with strong anisotropy. Terms linear in $\vec{k}$ can be present in crystals that do not observe inversion symmetry [8]. This effect is also visible in QWs. The directions of wave vectors of carriers are not equally probable, and the subband structure is altered. The active layer in QW structures is highly strained: it is grown on a GaAs substrate, which induces strain in the material. This strain is relieved gradually during laser operation through the emergence of defects and dislocations.

SELF-CONSISTENT DYNAMIC MODEL OF A HIGH-POWER LASER DIODE

A mathematical model that characterizes the formation of generation channels in high-power LDs is presented below. The modeling of such lasers is reduced to solving a self-consistent problem that implies solving two kinetic equations simultaneously for the densities of nonequilibrium carriers and photons in the active laser region together with the wave equation for several transverse modes and channels in the laser cavity. This model is specific in that it necessarily takes into account the presence of several noncoherent generation channels that radiate at different frequencies not related to each other in phase.

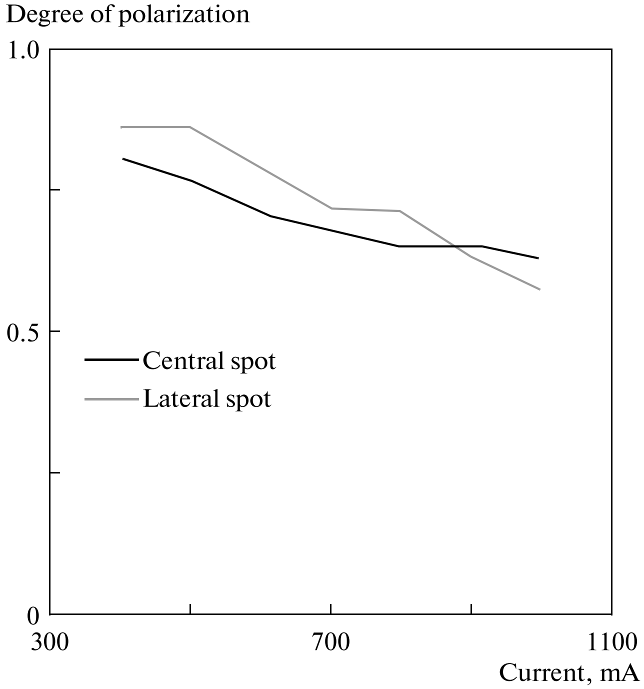


Fig. 3. Dependence of the degree of radiation polarization on the pump current in a high-power LD in the central and the lateral RP lobes. The LD had accumulated 100 service hours.

The equation for lateral modes for a known function of the profile of effective dielecteic permittivity $\varepsilon(y)$ of the waveguide takes the form [9]

$$\frac{d^2\psi_j(y)}{dy^2} + \left(\frac{\omega_j^2}{c^2}\varepsilon(y) - \beta^2\right)\psi_j(y) = 0, \tag{2}$$

where y is the lateral coordinate, $\omega_j = c\beta n_{j\,\mathrm{eff}}$ are the complex frequencies of radiation modes, c is the speed of light in vacuum, $n_{j\,\mathrm{eff}}$ are the effective refraction indices (eigen values, EVs), and $\psi_j(y)$ are the profiles of intensity (eigen functions, or EFs) of the transverse modes. Longitudinal propagation constant β is set in the single-mode approximation with respect to the longitudinal mode relying on the central wavelength of the laser spectrum (λ = 965 nm) and the effective refraction index for the zero transverse mode of the laser waveguide ($n_{\mathrm{eff}} = 3.538$).

The interaction between laser radiation and nonequilibrium carriers, the density of which affects the value of effective dielecteic permittivity $\varepsilon(y)$ [10], was taken into account in the self-consistent LD model. In addition to Eq. (2), the self-consistent LD model

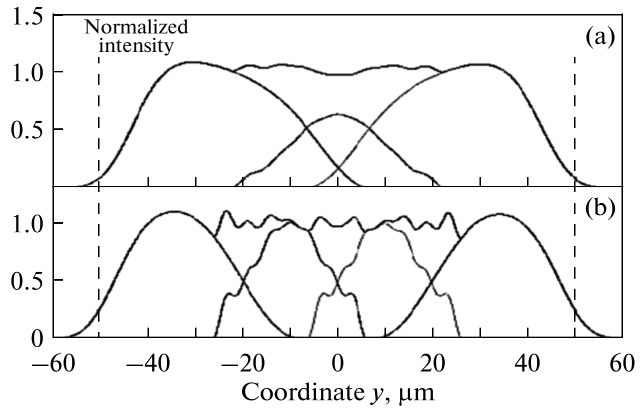


Fig. 4. Calculated intensity profiles of the near field of a high-power LD with (a) three-channel and (b) four-channel generation. Pump current $I = 2I_{th}$, diffusion length L_{diff} = (a) 15 μm or (b) 3 μm. The overlap between the regions of channel calculations is 30%.

incorporates the following system of differential kinetic equations:

$$\frac{\partial N(y,t)}{\partial t} = \frac{J(y,t)}{ed} - \frac{N(y,t)}{\tau_{sp}} + D\frac{\partial^2 N(y,t)}{\partial y^2} - \Gamma\frac{c}{n^*}g(N)\sum_j S_j(t)\left|\psi_j(y,t)\right|^2; \quad (3)$$

$$\frac{dS_j(t)}{dt} = G_j(t)S_j(t) + \frac{\eta}{\tau_{sp}}\langle N(t)\rangle, \quad (4)$$

where $N(y,t)$ is the density of nonequilibrium carriers in the active layer, $J(y,t)$ is the density of pump current, $S_j(t)$ is the average density of photons in mode no. j, D is the coefficient of ambipolar diffusion of injected carriers, $G_j(t) = -\mathrm{Im}(\omega_j)$ is the mode amplification, η is the spontaneous emission factor, τ_{sp} is the spontaneous carrier recombination time, τ_{ph} is the lifetime of photons in a cold cavity, e is the electron charge, d is the active layer (QW) thickness, $g(N) = a^*(N(y,t) - N_{tr})$ is the material amplification, a^* is the differential amplification factor, N_{tr} is the transparency density, $\Gamma = 0.012$ is the QW optical confinement factor, n^* is the average effective refraction index, and $\langle N(t)\rangle$ is the average carrier density.

The length of ambipolar diffusion $L_{diff} = \sqrt{D\tau_{sp}}$ was used as the key parameter that is altered in the process of LD degradation.

Equations (3) were written for all lateral modes and all generation channels. We limited ourselves to lower-order modes ($j \leq 6$) and 3–4 channels. The total number of considered modes was either 18 or 24.

The calculation model was constructed with a forced subdivision of radiation into channels, since it was not possible to achieve ideal LD layer quality. Owing to the local instability of the system, this leads to the inevitable decay of radiation into channels with frequencies covering the amplification line. Since the channels were not phased with each other due to the short length of radiation coherence, Eq. (1) does not yield adequate calculation results over the entire region of generation (axis y).

If the effective refraction index method [9] is applied to multilayer waveguides, the relation between effective dielecteic permittivity $\varepsilon(y)$ of the waveguide and density $N(y,t)$ of injected carriers can be presented in the form

$$\varepsilon(y) = \varepsilon^0 - A\cdot N(y) + j(B\cdot N(y) - F), \quad (5)$$

where ε^0, A, B, and F are constants associated with the geometry and materials of layers.

The self-consistent problem was solved using differential methods with the help of the MatLab program. To speed up the calculations, the approximate threshold values of pump current density J_{th}, average density of nonequilibrium carriers N_{th} in the QW, and photon density S_{th} were determined in advance. These values were used as the initial conditions in Eqs. (3) and (4).

CALCULATION RESULTS

Our experiment showed that three peaks (at wavelengths of 962.3, 964.1, and 965.3 nm) were present in the frequency spectrum at the initial stage of operation of the investigated device. After 100 h of operation, the spectrum grew wider, and two peaks at 961.8 and 962.7 nm emerged at the position of the peak at 962.3 nm. This suggests that two processes developed as the device degraded: the emergence of a new generation channel and the dynamics of modes in channels.

The results from calculations performed using the above technique demonstrate the possibility of all three regimes of LD generation emerging: stationary, self-modulation periodic, and chaotic. Figures 4a and 4b show the calculated distribution of intensity of stationary laser radiation in the near field of an LD mirror in lateral direction Y for a 30% overlap between the regions of generation channel calculations and a two-fold excess over the lasing threshold ($I = 2I_{th}$). Three generation channels are visible in Fig. 4a. They provide an almost uniform cover for the entire mirror. Calculations were performed for L_{diff} = 15 μm. Figure 4b presents the results from calculating the near field of four-channel laser generation with a shorter carrier diffusion length (L_{diff} = 3 μm).

CONCLUSIONS

We have demonstrated the relation between the slow degradation of high-power semiconductor injection lasers with quantum wells and their spectra, radiation pattern, and radiation polarization.

Measuring the spectra and the degree of linear polarization as a function of pump currents at the initial stage of operation of high-power LDs allows us to estimate and predict the service life of lasers. It would be worthwhile to develop methods for rapid diagnostics of quality of high-power LDs based on the comparison of spectra and the degree of linear polarization of radiation of these devices.

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