Quantum Electronics **41** (2) 95 – 98 (2011)

LASERS

PACS numbers: 42.55.Px; 42.60.Lh; 78.45.+h
DOI: 10.1070/QE2011v041n02ABEH014462

Amplified luminescence and output characteristics of high-power InGaAs/AlGaAs laser diode arrays

V.V. Kabanov, Y.V. Lebiadok, A.A. Ramanenka, A.G. Ryabtsev,
G.I. Ryabtsev, M.A. Shchemelev, S.K. Mehta

***Abstract*. The influence of the amplified luminescence (AL) and spreading of nonequilibrium charge carriers on the threshold, dynamic, and power characteristics of high-power InGaAs/AlGaAs laser diode arrays (LDAs) is studied. It is found that, depending on the near-field fill factor, the contribution of AL-induced recombination to the lasing threshold of LDAs may reach 11 %. It is shown that the losses of the LDA pump energy, associated with the AL, increase with the injection current growth above its threshold value because of the increase in the intensity of radiation, propagating normally to the LDA cavity axis.**

Keywords: *laser diode arrays, lasing threshold, spreading of the charge carriers, amplified luminescence, near-field radiation fill factor.*

1. Introduction

Laser diode arrays (LDAs) based on InGaAs/AlGaAs heterostructures are widely used in diode pumping [1, 2]. High-power LDAs have sufficiently large geometric dimensions (the cavity length up to 1.5 mm, the total width of the laser array up to 10 mm); therefore, in their active layers intense flows of amplified luminescence (AL) radiation can develop [3 – 6] that can considerably affect the LDA output characteristics. The geometry of the LDA crystal determines not only the AL properties, but also the factor γ of near-filed radiation fill factor, on which, as shown in [7], the power characteristics of erbium diode-pumped laser are largely dependent. It is important to estimate and properly take into account the AL flow and the factor γ in the course of LDA optimisation.

The present paper is devoted to the determination of the degree of influence of the recombination, induced by AL, on the transient, threshold, and power characteristics of high-power LDAs based on the InGaAs/AlGaAs heterostructure, emitting in the spectral band 940 – 980 nm. The main interest in the consideration of the AL is paid to the flow, propagating perpendicular to the LDA cavity axis. With regard to the problem of optimising the conditions of the erbium laser pumping, the relation between the near-field radiation fill factor and the output optical characteristics of the LDA is studied.

2. Modelling the optical processes in LDAs based on InGaAs/AlGaAs heterostructures

The role of the AL in the laser radiation was studied in high-power LDAs having the parameters close to those of the LDAs based on InGaAs/AlGaAs heterostructures, manufactured by the Polyus Research and Development Institute (Moscow, Russia). The LDA studied was based on a heterostructure, comprising two quantum-well active layers of InGaAs with the thickness $d = 5.3$ nm and three barrier layers of GaAs (one 10 nm and two 7 nm thick). The cavity length was $L = 800$ μm, the total width of the array $W_{\rm LDA}$, comprising $p = 75$ stripe contacts, each $w = 100$ μm wide, was equal to 10 mm. The stripe contacts of the LDA are allocated in separate groups, the number of which is equal to $q = 5$. Each group contains $m = 15$ stripe contacts, the separation between the adjacent stripes within the group is $a = 30$ μm. The separation between the groups of stripe contacts is $b = 80$ μm. The first group is located at the distance a from the LDA edge, the last one is at the distance $l = 50$ μm. For these values of the geometrical parameters of the laser crystal the near-field radiation fill factor γ of the LDA, calculated using the formula

$$\gamma = \frac{pw}{pw + [1 + (m-1)q]a + (q-1)b + l} = \frac{pw}{W_{\rm LDA}}, \qquad (1)$$

equals 0.75.

The modelling of the dynamic and power characteristics of the LDA was carried out using the set of rate equations [8]

$$\begin{aligned} \frac{{\rm d}S_\nu^{\rm las}}{{\rm d}t} &= V_{\rm g}\big[(\Gamma G_\nu - \alpha_{\rm las})S_\nu^{\rm las} + \alpha_{\rm las} W_{{\rm sp}\,\nu}\big], \\ \frac{{\rm d}S_{x\nu}^{\rm lum}}{{\rm d}t} &= V_{\rm g}\big[\big(\Gamma G_\nu - \alpha_{x\nu}^{\rm lum}\big)S_{x\nu}^{\rm lum} + \alpha_L W_{{\rm sp}\,\nu}\big], \qquad (2) \\ \frac{{\rm d}S_{y\nu}^{\rm lum}}{{\rm d}t} &= V_{\rm g}\big[\big(\Gamma G_\nu - \alpha_{y\nu}^{\rm lum}\big)S_{y\nu}^{\rm lum} + \alpha_L W_{{\rm sp}\,\nu}\big], \end{aligned}$$

V.V. Kabanov, Y.V. Lebiadok, A.A. Ramanenka, G.I. Ryabtsev
B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, prosp. Nezavisimosti 68, 220072 Minsk, Belarus;
e-mail: ryabtsev@dragon.bas-net.by;
A.G. Ryabtsev, M.A. Shchemelev Belarus State University, prosp. Nezavisimosti 4, 220030 Minsk, Belarus;
S.K. Mehta Solid State Physics Laboratory, Lucknow Road, Nimarpur, 110054 Delhi, India

Received 11 October 2010; revision received 6 December 2010
Kvantovaya Elektronika **41** (2) 95 – 98 (2011)
Translated by V.L. Derbov

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{j}{2de} - BN^2 - CN^3 - R_{\mathrm{lum}} - R_{\mathrm{las}},$$

$$R_{\mathrm{lum}} = \int_{\nu_1}^{\nu_N} \frac{1}{h\nu}\Gamma G_\nu \big(S_{x\nu}^{\mathrm{lum}} + S_{y\nu}^{\mathrm{lum}}\big)\mathrm{d}(h\nu),$$

$$R_{\mathrm{las}} = \int_{\nu_1}^{\nu_N} \frac{1}{h\nu}\Gamma G_\nu S_\nu^{\mathrm{las}}\mathrm{d}(h\nu),$$

where S_ν^{las} is the density of the laser radiation flow; $S_{y\nu}^{\mathrm{lum}}$ and $S_{x\nu}^{\mathrm{lum}}$ are the spectral densities of the AL flows, propagating along (y axis) and perpendicularly (x axis) to the LDA cavity axis, respectively; V_{g} is the group velocity of the radiation propagation through the active layer of the LDA; $\alpha_{\mathrm{las}} = \rho + (1/L)\ln(1/\sqrt{R_1 R_2})$ is the coefficient of total loss for the laser radiation; $\rho = 1000\ \mathrm{m}^{-1}$ is the coefficient of the internal optical losses of the radiation, propagating in the active layer of the LDA; $R_1 = 0.95$ and $R_2 = 0.12$ are the reflection coefficients of the highly reflecting and output mirrors, respectively; G_ν is the gain; $\Gamma = 0.011$ is the optical confinement factor; $W_{\mathrm{sp}\,\nu}(x, y)$ is the volume spectral density of the spontaneous emission; $B = 1.4 \times 10^{-16}\ \mathrm{m}^3\ \mathrm{s}^{-1}$, and $C = 5.0 \times 10^{-42}\ \mathrm{m}^6\ \mathrm{s}^{-1}$ are the coefficients of spontaneous recombination and nonradiative Auger recombination for InGaAs, respectively [9]; $\alpha_{\mathrm{las}} = 8.0 \times 10^{-4}$ is the contribution of the spontaneous emission to the flow of the generated radiation; $\alpha_L = 0.1$ is the contribution of the spontaneous emission to the AL, calculated following the approach, developed in Ref. [10]; ν_1 and ν_N are the limiting frequencies of the spectral interval, in which $G_\nu > 0$ for the given injection level; N is the concentration of the injected nonequilibrium charge carriers; e is the charge of electron. The loss coefficients, depending on the frequency ν, for the AL flows, propagating along the axes x ($\alpha_{x\nu}^{\mathrm{lum}}$) and y ($\alpha_{y\nu}^{\mathrm{lum}}$), were calculated using the method, described in Ref. [11] and based on a spectroscopic model with no selection rules for the wave vector taken into account. The current density in the region under the stripe contact was used for the injection current density j. In the model described by Eqns (2) two flows of the AL, propagating along the axes x and y, are taken into account. Due to the waveguide properties and the symmetry of the active layer, one can suppose that these flows affect the optical characteristics of high-power LDAs most significantly. Taking into account the AL flows, propagating in other directions with respect to the cavity axis, makes the computation procedure significantly more complicated without qualitative changes of the results.

Modelling of the optical properties of LDAs was performed both with and without taking into account the effect of charge carrier spreading in the domains under the contact and waveguide layers of the heterostructure [12]. In the calculations of the current density distribution function in the LDA active layer the parameters summarised in Table 1 were used.

3. Results and discussion

As follows from Fig. 1, the spreading effect leads to the increase in the concentration of nonequilibrium charge carriers in the domains of the active layer, located in the spaces between the adjacent stripe contacts. In calculations with no account taken of the effect of spreading [Fig. 1, curve (*1*), point B], the charge carriers in these spaces arise because of diffusion in the active layer, which was taken into account in the calculation of the loss coefficients for the AL flows [11]. In this case, the concentration N_{stripe} of the nonequilibrium charge carriers in the domains of active layer, located directly under the stripe contacts, is reduced. At the injection current $I = 27$ A, close to the threshold value, and the factor $\gamma = 0.75$, the concentration N_{A} of the nonequilibrium charge carriers (point A in Fig. 1) between the adjacent contact stripes, calculated with spreading taken into account, is almost an order of magnitude higher than that, calculated with no account taken of the spreading effect (point B in Fig. 1). Near the lasing threshold in the LDAs under study the value of N_{A} practically approaches the transparency value $N_{\mathrm{e}} = 2.74 \times 10^{18}\ \mathrm{cm}^{-3}$, which results in substantial improvement of conditions for the propagation of the frequency-integrated AL flow S_x along the x axis. The flows S_x at the injection current 27 A ($\gamma = 0.75$), calculated without ($7.4 \times 10^9\ \mathrm{W\ m}^{-2}$) and with ($2.3 \times 10^{10}\ \mathrm{W\ m}^{-2}$) the spreading of the injected charge carriers taken into account, differ almost by three times. The frequency-integrated flow of the AL S_y, propagating along the y axis, is less sensitive to the spreading effect and equals $3.8 \times 10^{10}\ \mathrm{W\ m}^{-2}$ without and $1.9 \times 10^{10}\ \mathrm{W\ m}^{-2}$ with the spreading taken into account. Such a variation of the flow S_y is explained by the reduction of the nonequilibrium charge carriers in the domains of the active layer under the stripe contacts because of the effect of spreading and recombination, induced by the flow S_x.

Table 1. Parameters of the InGaAs/AlGaAs heterostructure layers.

Layer	Layer thickness/μm	Specific resistance/Ω m
Contact (GaAs : Zn)	0.35	2.0×10^{-4}
Emitter ($\mathrm{Al_{0.29}Ga_{0.71}As:Zn}$)	1.73	1.0×10^{-3}
Waveguide ($\mathrm{Al_{0.26}Ga_{0.74}As_{0.2}}$)	0.2	0.7×10^{-2}
Barrier (GaAs)	0.007	0.3×10^{7}

The distributions of charge carrier concentrations, presented above, with their spreading taken into account, are obtained under the assumption that the LDA chip is manufactured without etching the small-scale mesastructure in the space between the adjacent stripe contacts. Taking

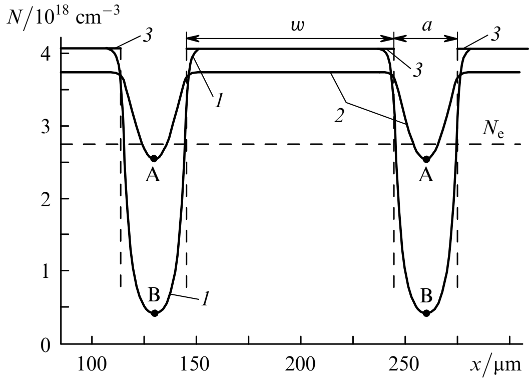

Figure 1. Distribution of the concentration of nonequilibrium charge carriers along the x axis in the active LDA layer, calculated at an injection current $I = 27$ A near the threshold value without (*1*) and with (*2*) the charge carrier spreading taken into account; (*3*) are the stripe LDA contacts.

into account the mesastructure, having the form of an etched contact layer and an $Al_{0.29}Ga_{0.71}As:Zn$ emitter half-thick layer, yields the increase in the concentration of nonequilibrium charge carriers in the domain of the active layer under the stripe contact by 4 % (in comparison with the concentration, obtained without etching taken into account), and the reduction of the concentration between the adjacent contacts by the factor 2.2 (at $I = 30$ A). As a consequence, the AL flow along the x axis decreases nearly by two times, and the AL flow along the y axis increases by 20 % – 30 %. However, these changes of the AL flows do not reduce significantly the AL effect on the oscillatory properties of the LDA.

The influence of the charge carrier spreading on the optical characteristics of LDAs essentially depends on the separation between the adjacent stripe contacts and, therefore, on the near-field radiation fill factor of LDAs. For example, when γ increases from 0.5 to 0.9, the concentration N_A changes from 1.0×10^{18} to 2.6×10^{18} cm^{-3} ($I = 27$ A). This means that, at other conditions being equal, the growth of γ leads to the increase in the AL flow, propagating along the x axis (perpendicular to the cavity axis), i.e., to degradation of oscillatory properties of the LDA.

The spreading of the injected charge carriers also affects the transient characteristics of the LDA. As follows from Fig. 2, a threshold oscillation spike M is clearly distinguished against the transient characteristic, obtained at the injection current $I_0 = 30.5$ A, nonregistering the spreading effect [curve (*1*)]. At the same initial parameters, taking the spreading into account results in the growth of the threshold current and, consequently, there is no oscillation spike on the corresponding transient characteristic [curve (*2*)]. The threshold current I_1, calculated at $\gamma = 0.75$ with the spreading taken into account, is 2 % higher than the threshold injection current I_0.

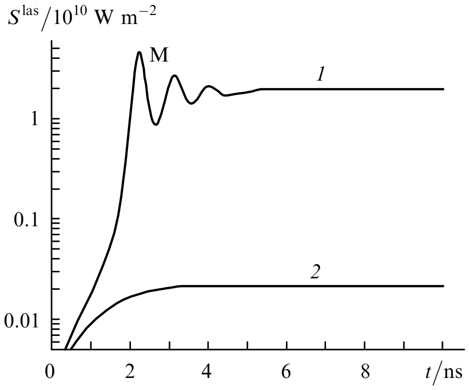

Figure 2. Transient characteristics calculated at $\gamma = 0.75$ and the injection current $I_0 = 30.5$ A without (*1*) and with (*2*) the charge carrier spreading taken into account.

The influence of the AL on the threshold characteristics of the InGaAs/AlGaAs LDA was studied with the effect of charge carrier spreading taken into account. The account taken of the AL flow, propagating along the y axis, leads to a 4.2 % increase in the lasing threshold current (compare the current values I_0 and I_2, where I_2 is the threshold current, calculated with the account taken of the flow S_y) (Fig. 3). With the flow S_x taken into account (in addition to the flow S_y), the threshold current I_3 of the LDA increases by 6.2 % with respect to I_0. The influence of the AL on the lasing threshold depends on the near-field radiation fill factor γ. For example, the increase of γ from 0.5 to 0.9 leads to the growth of the threshold current, calculated with the AL flows and the spreading effect taken into account, by 5 %.

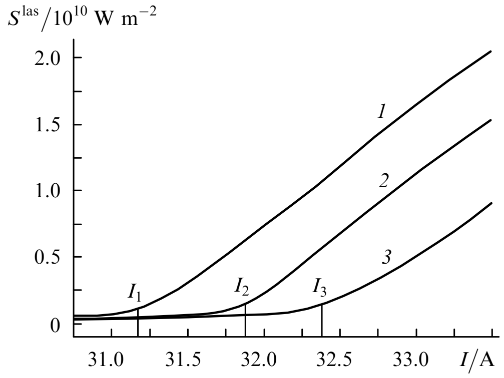

Figure 3. Light – current characteristics of the LDA, calculated in the presence of spreading with no AL flows (*1*), with the flow S_y (*2*), and with the flows S_x and S_y (*3*) taken into account.

It is important to note, that the losses of the generated radiation due to the AL-induced recombination, should increase above the lasing threshold as well, mainly because of the growth of the flow S_x. This agrees with the results of other papers [13 – 15]. According to our preliminary calculations, at the injection current 1.5 times the threshold value, the flow S_x increases nearly by 2.5 times. The dependence of the flow S_y on the pump level demonstrates a tendency to saturation. However, the quantitative estimation of the AL effect on the LDA oscillation processes at the pump level highly exceeding the threshold requires further investigations.

The transient characteristic of InGaAs/AlGaAs LDAs under study, calculated for different near-field radiation fill factors at the same injection current density are presented in Fig. 4. At a fixed injection current density under the stripe contact and all other parameters, the increase of γ from 0.5 to 0.9 leads to the growth of the lasing threshold. That is why at $j = 470$ A cm^{-2} the transient curve for LDA with $\gamma = 0.5$ exhibits an intense oscillation spike [curve (*1*)],

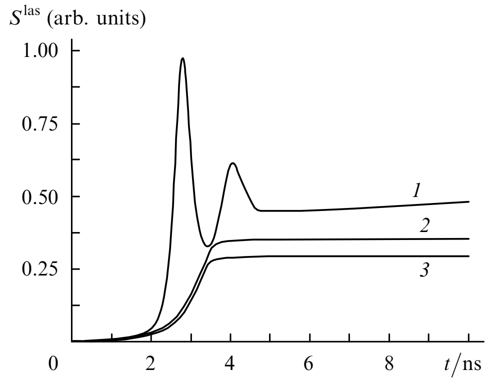

Figure 4. Transient characteristics of the LDA, calculated at $j =$ 470 A cm^{-2} and the values of the near-field radiation fill factor $\gamma = 0.5$ (*1*), 0.75 (*2*), and 0.9 (*3*).

while the transient characteristics for the LDA with $\gamma = 0.75$ and 0.9 have the form of curves with saturation.

4. Conclusions

The obtained results make it possible to conclude that it is important to take into account the spreading of the injected charge carriers in the analysis of the influence of AL on the optical processes in high-power InGaAs/AlGaAs LDAs. This effect manifests itself in the increase in the non-equilibrium charge carriers concentration in the domains of the active layer, located in the spaces between the adjacent stripe contacts. The spreading of the charge carriers affects the development of the AL flow in the active layer of LDA. Thus, the flows S_x, calculated without and with the spreading taken into account, equal 7.4×10^9 and 2.3×10^{10} W m^{-2}, respectively. At the same time, the flow S_y, calculated with the spreading taken into account (1.9×10^{10} W m^{-2}), is two times smaller than S_y, calculated without the spreading (3.8×10^{10} W m^{-2}).

The formation of the AL flows at the values of the near-field radiation fill factor $\gamma \sim 0.75$ and greater may lead to the growth of the threshold current by more than 11 %. This fact should be taken into account in optimisation of the parameters of LDAs, used to pump the solid-state erbium lasers.

The pump energy losses in LDAs, associated with the development of AL flows, continue to grow with the injection current above its threshold value. In this case the dominant contribution to the losses is caused by the flow S_x. At the injection current equal to 1.5 times the threshold value, the flow S_x is 2.5 times higher than that at the lasing threshold. For the dependence of the flow S_y upon the injection current a tendency to saturation is typical. The increase in the flow S_x with increasing LDA pump level is one of the causes decreasing the power of laser radiation.

The necessity to account for the flow S_x in the studies and optimisation of the transient, threshold, and power characteristics of high-power LDAs is confirmed by the results of our preliminary experiments, in the course of which, both below and above the lasing threshold, an intense radiation was registered, coming out from the side face of the LDA structure and possessing all basic features of AL.

The conclusions about the role of AL in the process of oscillation in InGaAs/AlGaAs LDAs are to a certain degree applicable also to LDAs, radiating in the spectral range 810–815 nm.

Acknowledgements. This work is partially carried out within the framework of Contract 178 with the Solid State Physics Laboratory (Delhi, India).

References

1. Katsavets N.I., Buchenkov V.A., Demidov D.M., et al. *Pis'ma Zh. Tekh. Fiz.*, **30**, 43 (2004) [*Tech. Phys. Lett.*, **30** (12), 1039 (2004)].
2. Ryabtsev G.I., Bogdanovich M.V., Enzhievskii A.I., et al. *J. Opt. Technol.*, **75**, 704 (2008).
3. Gribkovskii V.P., Kononenko V.K., Ryabtsev G.I., Samoilyukovich V.A. *IEEE J. Quantum Electron.*, **12**, 322 (1976).
4. Chuang S.L., O'Gorman J., Levi A.F. *IEEE J. Quantum Electron.*, **29**, 1631 (1993).
5. Burov L.I., Ryabtsev G.I., Smal A.S., Waraxe I.N. *Appl. Phys. B*, **75**, 63 (2002).
6. Ryabtsev G.I., Bezyazychnaya T.V., Bogdanovich M.V., et al. *Appl. Phys. B*, **90**, 471 (2008).
7. Bogdanovich M.A., Kabanov V.V., Lebiadok Y.V., et al. *Techn. Program 14th Int. Conf. on Laser Optics* (St-Petersburg, 2010) p. 71.
8. Burov L.I., Savva V.A., Rusov S.G., et al. *Nonlin. Phenom. Compl. Syst.*, **7**, 273 (2004).
9. Hadley G.R., Hohimer J.P., Owyoung A. *IEEE J. Quantum Electron.*, **24**, 2138 (1988).
10. Samson A.M. *Zh. Prikl. Spektrosk.*, **2**, 232 (1964) [*J. Appl. Spectrosc.*, **2** (3), 152 (1965)].
11. Kabanov V.V., Lebiadok Y.V., Ramanenka A.A., et al. *Zh. Prikl. Spektrosk.*, **77**, 875 (2010) [*J. Appl. Spectrosc.*, **77** (6), 810 (2010)].
12. Casey H.C., Panish M.B. *Heterostructure Lasers, part B* (New York: Academic Press, 1978).
13. Sommers H.S. *Appl. Phys. Lett.*, **19**, 424 (1971).
14. Paoli T.L. *IEEE J. Quantum Electron.*, **9**, 267 (1973).
15. Sommers H.S., North D.O. *J. Appl. Phys.*, **45**, 1787 (1974).