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Effect of laser cavity parameters on saturation of light–current characteristics of high-power pulsed lasers

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Abstract. **We report an experimental study of power characteristics of semiconductor lasers based on MOVPE-grown asymmetric separate-confinement heterostructures with a broadened waveguide as functions of cavity length, stripe contact width and mirror reflectivities. It is shown that at high current pump levels, the variation of the cavity parameters of a semiconductor laser (width, length and mirror reflectivities) influences the light–current (L–I) characteristic saturation and maximum optical power by affecting such laser characteristics, as the current density and the optical output loss. A model is elaborated and an optical power of semiconductor lasers is calculated by taking into account the dependence of the internal optical loss on pump current density and concentration distribution of charge carriers and photons along the cavity axis of the cavity. It is found that only introduction of the dependence of the internal optical loss on pump current density to the calculation model provides a good agreement between experimental and calculated L–I characteristics for all scenarios of variations in the laser cavity parameters.**

Keywords: *semiconductor laser, internal optical loss, pulse pumping.*

1. Introduction

This work continues the series of papers devoted to the study of high-power pulsed semiconductor lasers [1–3]. The research is aimed at finding possible reasons for the saturation of light–current (L–I) characteristics of lasers based on quantum asymmetric separate-confinement double heterostructures with a broadened waveguide, grown in AlGaAs/GaAs/InGaAs solid solutions. It should be noted that this issue has been addressed in numerous works carried out at various scientific centres [4–7].

In our previous work [3], we have demonstrated the dependence of the L–I characteristic saturation of a pulsed laser on the internal optical loss with increasing pump current density. However, the physical mechanisms underlying this process remain unclear.

The aim of this work is to study experimentally the effect of the laser cavity parameters (length, width, mirror reflectivities) on L–I characteristics of high-power pulsed semiconductor lasers and to elaborate a computational model, which describes power characteristics of these lasers with allowance for an increase in the internal optical loss at high pulsed current pump levels.

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2. Test samples and results of experimental studies

We fabricated and studied plane-cavity semiconductor lasers based on a broadened-waveguide quantum asymmetric separate-confinement double heterostructure whose parameters are listed in Table 1 of paper [3]. The heterostructure in question was designed for high-power cw semiconductor lasers and was not optimised for pulsed regime. The lasers were manufactured with the stripe contact width of W = 100 or 200 μm and cavity lengths of 2–5 mm. To prevent the spreading of charge carriers, use was made of 'deep mesas', when layers of the laser structure are etched down to the substrate on the boundary of the stripe contact. For studies we prepared standard lasers with one highly reflecting mirror (reflectance R = 95%) and one AR-coated mirror (R = 5%), as well as lasers with both AR-coated mirrors. The latter were mounted on specially designed heat sinks to ensure an unobstructed observation of lasing in both directions.

Using experimental samples we studied the L–I characteristics at high-current pump pulses with an amplitude up to 100 A, a duration of 100 ± 10 ns and a repetition rate of 1 kHz. The peak optical power and pump current amplitude were measured using the method described in [3]. In the lasers with both AR-coated mirrors the optical power was summed after successive measurements from the two end faces of the cavity to avoid errors due to nonuniform deposition of the mirrors. In the lasers in question the output optical power at both end faces coincided within the measurement accuracy.

Figure 1a shows the dependence of the peak optical power of two lasers with a stripe contact width of 100 and 200 μm on the pump current. Both lasers had a cavity of length L = 3 mm and mirror reflectivities R_1 = 5% and R_2 = 95%. For the same values of the pump currents, the lasers with W = 200 μm exhibited a larger optical radiation power and a smaller deviation from the L–I characteristic linearity than the lasers with W = 100 μm. It should be noted that the density of the pump current flowing through the lasers differed twice. The dependences of the output power on the pump current density for the same lasers are shown in Fig. 1b. Characteristic is a two-fold increase in the optical power in

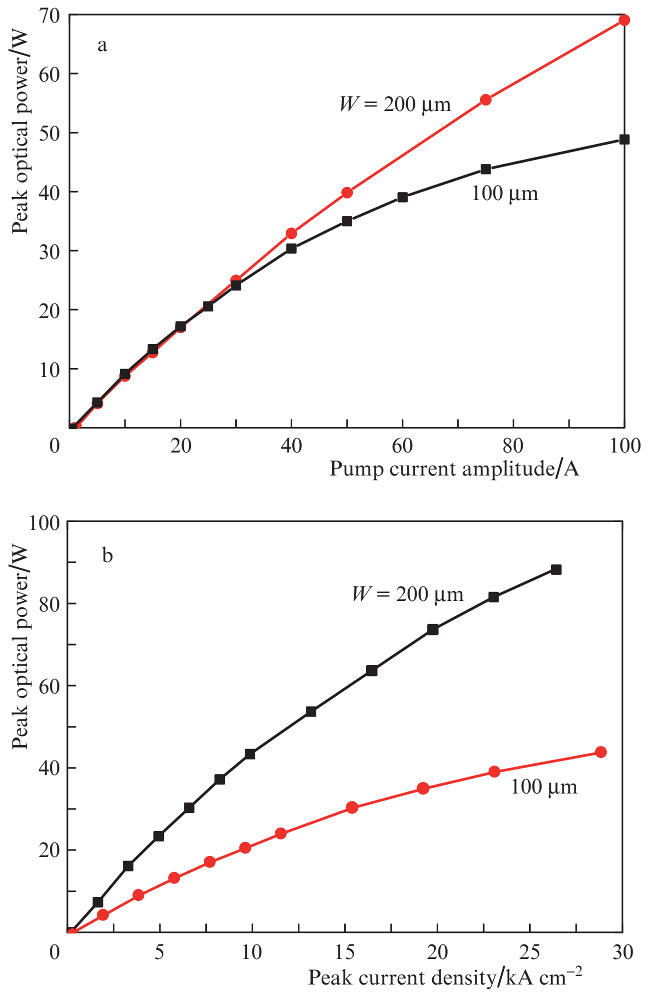

Figure 1. $L-I$ characteristics of pulsed lasers with stripe contact widths $W = 200$ and 100 µm; $L = 3$ mm, $R_1 = 5\%$, $R_2 = 95\%$.

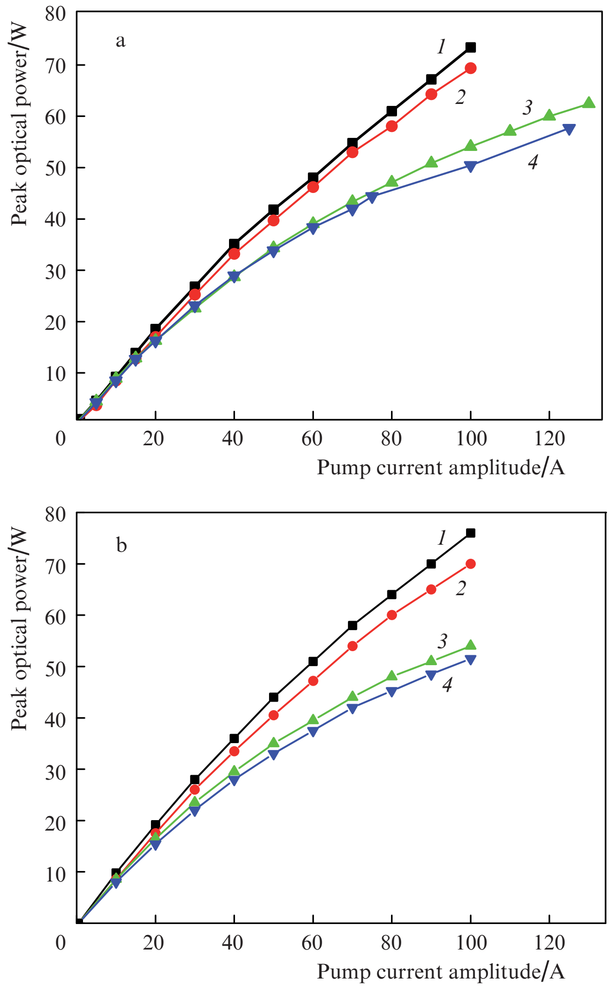

Figure 2. (a) Experimentally measured and (b) theoretically obtained $L-I$ characteristics of pulsed lasers with a stripe contact width $W = 100$ µm and different parameters of the cavity: (*1*) $L = 2220$ µm, $R_1 = R_2 = 5\%$; (*2*) $L = 5170$ µm, $R_1 = R_2 = 5\%$; (*3*) $L = 2688$ µm, $R_1 = 5\%$, $R_2 = 95\%$; (*4*) $L = 3990$ µm, $R_1 = 5\%$, $R_2 = 95\%$.

the laser with $W = 200$ µm, compared with the laser with $W = 100$ µm at the same pump current density.

A decrease in the pump current density of the laser with a wider stripe contact slows the growth of the internal optical loss and reduces the degree of the $L-I$ characteristic saturation of the laser when the absolute value of the pump current increases. Thus, increasing the width of the stripe contact is a structurally reliable technical solution for improving the $L-I$ characteristic linearity of a pulsed semiconductor laser.

It could be assumed that an increase in the cavity length, which also leads to a decrease in the pump current density, will increase the optical power and reduce the degree of the $L-I$ characteristic saturation of a semiconductor laser. However, in lasers with a greater cavity length we failed to observe an increase in the maximum achievable power and a reduction in the degree of the $L-I$ characteristic saturation [Fig. 2a, curves (*3*) and (*4*)]. Unfortunately, despite the fact that an increase in the cavity length leads to a proportional decrease in pump current density and internal optical loss [3], there simultaneously occurs a reduction of the useful optical output loss $\alpha_{\rm out}$. As a consequence, at lower pump currents I the differential quantum efficiency falls

$$\eta_{\rm d} = \eta_{\rm i} \frac{\alpha_{\rm out}}{\alpha_{\rm out} + \alpha_{\rm i}}, \qquad (1)$$

the $L-I$ characteristic is saturated and the maximum achievable optical power decreases

$$P_{\rm out} = \eta_{\rm d} \frac{h\nu}{q_{\rm e}} I. \qquad (2)$$

Here, $\eta_{\rm i}$ is the stimulated quantum efficiency; $\alpha_{\rm i}$ is the internal optical loss; $h\nu$ is the photon energy; and $q_{\rm e}$ is the electron charge.

Thus, in the structures under study an increase in the cavity length does not lead to an increase in the maximum emitted optical power, despite the reduction in the pump current density and internal optical loss. By increasing the cavity length, the value of $\alpha_{\rm out}$ is reduced stronger than $\alpha_{\rm i}$.

Application of an AR coating on both cavity mirrors of the laser provides a more linear $L-I$ characteristic and a higher maximum optical power (in both directions) [Fig. 2a, curves (*1*, *2*)]. In other words, a strong increase in optical output loss $\alpha_{\rm out}$ compensates for their decrease due to an increase in the cavity length and slows down a decrease in the differential quantum efficiency $\eta_{\rm d}$ to larger values of the internal optical loss $\alpha_{\rm i}$. Unfortunately, this way of enhancing of the optical power and $L-I$ characteristic linearity finds no practical application.

3. Theoretical studies

In [3] we obtained an expression approximating the experimental dependence of the internal optical loss on the pump current [3, Fig. 5]:

$$\alpha_{\mathrm{i}} = \alpha_{\mathrm{i}}^0 + kJ, \tag{3}$$

where $\alpha_{\mathrm{i}}^0 = 0.4$ cm^{-1} is the internal optical loss at the lasing threshold; $k = 1.2\times10^{-4}$ is the approximation coefficient (cm A^{-1}); and J is the current density (A cm^{-2}). It should be noted that this approximation is not universal, and the coefficient k can be applied for the lasers under study. The dependence obtained was used in the calculations of $L-I$ characteristics of high-power pulsed semiconductor lasers with different parameters of the cavity, experimentally investigated previously (Fig. 2a). The calculations simultaneously took into account the nonuniform distribution of the concentration of charge carriers and photons in the cavity, as well as an approximation of the experimental dependence of the internal optical loss on the pump current density (3).

To determine the concentration of electrons in the quantum well (QW) of the active region and the concentration of photons along the cavity axis we solved the systems of stationary rate equations:

$$\frac{\mathrm{d}n_{\mathrm{QW}}(z)}{\mathrm{d}t} = \frac{\eta_{\mathrm{i}}J}{q_{\mathrm{e}}d_{\mathrm{QW}}} - Bn_{\mathrm{QW}}^2 - \frac{c}{\sqrt{\varepsilon}}\frac{g(z)}{\Gamma}[S^+(z) + S^-(z)], \tag{4}$$

$$\frac{\mathrm{d}S^{\pm}(z)}{\mathrm{d}z} = \pm[g(z) - \alpha_i]S^{\pm}(z), \tag{5}$$

where n_{QW} is the concentration of charge carriers in the quantum well; z is the coordinate along the longitudinal axis of the cavity; t is the time; d_{QW} is the thickness of the active region; B is the coefficient of radiative recombination; c is the velocity of light; $\sqrt{\varepsilon}$ is the refractive index in the waveguide of the laser; $g(z)$ is the coordinate-dependent modal gain; Γ is the optical confinement factor of radiation in the active region; and $S^+(z)$ and $S^-(z)$ are the concentrations of photons in the fluxes propagating in opposite directions (the total concentration of photons at any point of the cavity is equal to the sum of these concentrations).

Equation (4) determines the rate of change in the concentration of charge carriers in the QW. The first term takes into account the income of charge carriers into the QW due to the current injection and the second and third terms – outcome of the carriers from the QW due to spontaneous and stimulated recombinations. The Auger recombination in the QW is not considered, because both experimentally investigated lasers emit at wavelengths of 1.0–1.1 μm in which the nonradiative process is quite negligible. Equation (4) does not take into account the diffusion of charge carriers along the cavity axis in the QW of the active region of the laser structure. In the heterostructure in question the calculated diffusion length does not exceed a few microns, which is several orders of magnitude less than the cavity length, and so the diffusion should not strongly smooth the profile of the carrier concentration distribution.

Equations (5) determine the distribution of the photons along the cavity axis and take into account the internal optical loss.

To solve equations (4) and (5) requires the use of the relationship of the modal gain with the concentration of charge carriers. Therefore, using the experimental results of measurements of threshold currents for lasers with cavities having different lengths we obtained (as in [8]) a logarithmic dependence of the gain on the concentration of charge carriers.

It should be noted that although in this paper we investigate semiconductor lasers operating in pulsed regime, the pulse duration (100 ns) is by orders of magnitude greater than the characteristic times for both photon and electronic subsystems. Therefore, we assume that this regime is equivalent to cw mode, and the laser does not accumulate and redistributes energy between subsystems, which means that there is no need to solve the nonstationary problem.

As boundary conditions we used expressions specifying the reflection on the cavity mirrors [9]:

$$S^+(0) = R_1 S^-(0), \qquad S^+(L) = R_2^{-1} S^{-1}(L). \tag{6}$$

The unknowns, with respect to which the calculation is performed in system (4) and (5), are coordinate-dependent concentrations of charge carriers and photons in two opposite directions, respectively.

The optical output power P_{out} in both directions is found from the expressions

$$P_{\mathrm{out}}^+ = [S^+(L) - S^-(L)]h\nu\frac{c}{\sqrt{\varepsilon}}WD_{\mathrm{eff}}, \tag{7}$$

$$P_{\mathrm{out}}^- = [S^-(0) - S^+(0)]h\nu\frac{c}{\sqrt{\varepsilon}}WD_{\mathrm{eff}}, \tag{8}$$

where D_{eff} is the effective width of the fundamental transverse mode in the laser waveguide at half maximum. For lasers with both AR-coated mirrors the optical power was calculated in both directions. For lasers with an AR-coated mirror and a highly reflecting mirror we took into account only the power coupling out of the AR-coated mirror.

Equations (4)–(8) were calculated numerically. To verify the correctness of the calculations we used the expression

$$\frac{1}{L}\int_0^L g(z)\,\mathrm{d}z = \alpha_{\mathrm{i}} + \alpha_{\mathrm{out}}, \tag{9}$$

the meaning of which is that the integral gain in the laser cavity must always correspond to the total optical loss [10]. For all the calculations performed, condition (9) was met with high accuracy.

The solution of stationary equations (4) and (5) under conditions of negligible current leakage ($\eta_{\mathrm{i}} = 1$) and constant internal optical loss ($\alpha_{\mathrm{i}} = 0.4$ cm^{-1}, [3]) made it possible to obtain the concentration distribution of photons and charge carriers along the cavity length as a function of the pump current. In the concentration distribution of charge carriers, one can observe the effect of their longitudinal 'burning' at the output mirror of the cavity and an increase in the concentration of charge carriers at the mirror with a high degree of reflectivity [7–11]. However, the calculated $L-I$ characteristics obtained by solving equations (4) and (5) do not experience saturation. In other words, the phenomenon of longitudinal 'burning' of charge carriers by stimulated emission does not lead to saturation of the $L-I$ characteristic and the emitted optical power continues to increase in proportion to the pump current. Only the use of the dependence of the internal optical loss on pump current density (3) in calculations provides a virtually absolute coincidence of experimental and calculated $L-I$ characteristics (Figs 2a and 2b) with accuracy up to a measurement error or inaccuracy of the parameters included in the calculation.

4. Discussion of the results and conclusions

Thus, variations in the parameters of a semiconductor laser (width, length and reflectivities of both mirrors) change the dependence of the internal optical loss on pump current by affecting other parameters (pump current density, external optical loss). This is reflected in an increase or a decrease in the degree of the $L-I$ characteristic saturation as well as in a decrease or an increase in the maximum achievable optical output power. The general behaviour of the dependence of the $L-I$ characteristic is preserved for all variations of the cavity parameters, which confirms the results [3] of the dependence of the internal optical loss on pump current.

Calculations of the emitted optical power as a function of the pump current, that we carried out by using the developed program, show that only taking into account the dependence of the internal optical loss on the current pump provides a complete agreement between the calculated and experimental $L-I$ characteristics. Excluding this dependence from the calculations leads to linearity of the $L-I$ characteristic. An increase in internal optical loss in a laser based on a separate-confinement double heterostructure may be due to an increase in the concentration of charge carriers in the waveguide layers or QWs of the active region at high pump currents. In many experimental and theoretical papers [6, 7, 12–14], the growth of the internal optical loss due to an increase in the concentration of charge carriers in the waveguide layers has been identified as one of the main reasons for the $L-I$ characteristic saturation at high pump currents. Therefore, at present it is unclear how the contributions to the growth of the internal optical loss in the QW of the active region and in the waveguide layers of a laser separate-confinement heterostructure are interrelated. We hope to address this issue in our future research.

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