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Output power of a ridge semiconductor laser in the single-frequency regime

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***Abstract*.** **It is shown that the single-frequency output power of a semiconductor laser with a built-in horizontal waveguide and typical parameters is restricted from above. This restriction is caused by a change in the effective gain for longitudinal modes adjacent to the laser mode due to a nonlinear process producing oscillations of the carrier concentration at the intermode frequencies. If the laser resonator contains random or deliberately introduced inhomogeneities, the maximum achievable single-frequency output power can considerably (more than by an order of magnitude) exceed the output power in the absence of inhomogeneities.**

Keywords: *semiconductor laser, single-frequency lasing, nonlinear interaction of modes, longitudinal instability.*

1. Introduction

The manufacturing technology of modern heterolasers, in particular, based on AlGaAs/InGaAs/GaAs heterostructures with quantum-well active regions has achieved so high level that now it is possible to simulate reliably many emission parameters of these lasers. This is related to a high reproducibility of their manufacturing process and the exclusion of uncontrollable factors which are not taken into account in a physical model of lasers. For example, in papers [1 – 3] the transverse distribution of the laser beam intensity, its divergence, and the light – current characteristic of near-IR ridge lasers were simulated. Moreover, in [3] the simulation was performed taking into account the spatial 'burning out' of the inversion in the resonator, i.e. taking into account the optical nonlinearity of saturation of the active region. This nonlinearity is significant for high pump levels and, correspondingly, for high output energies of lasers. The latter circumstance is especially typical of modern heterolasers.

Despite the advances achieved, the simulation of some emission characteristics of heterolasers is still complicated. First of all, it is the emission spectrum and, in particular, the radiation power achievable upon single-frequency lasing. Note at once that we will consider below the most popular lasers with the Fabry – Perot resonator without selective elements such as phase and amplitude gratings or reflectors. The emission spectrum, i.e. the structure of excited longitudinal modes cannot be predicted even for ridge lasers [1 – 3], for which the spectrum of transverse modes can be simulated. The difficulties encountered in simulating the emission spectrum of a typical heterolaser are related to a broad width of the gain band compared to the spectral interval between adjacent longitudinal modes. As a result, the gain difference for adjacent longitudinal modes is extremely small, being $10^{-3} - 10^{-5}$ of the gain.

Thus, the lasing spectrum is formed by a rather 'flat' top of the gain band. This leads to a high sensitivity of the heterolaser spectrum to various perturbations resulting in the redistribution of the mode gain at the $10^{-3} - 10^{-5}$ level of the threshold. Such perturbations can be caused by many reasons. In this paper, we will consider only two reasons, which cannot be eliminated in principle. The first one is the residual optical inhomogeneity of the resonator along its axis, which is always present in real lasers and is determined by the quality of the manufacturing technology of heterostructures. The residual inhomogeneity produces random spectral selectivity, and its influence on the lasing spectrum was investigated in a number of papers (see, for example, [4 – 10]). The second fundamental physical reason for changing the mode gain is the nonlinear interaction of modes through oscillations of the inversion (carrier concentration) at the intermode frequencies caused by the beats of the total laser radiation intensity. In our opinion, this mechanism dominates at high output powers. For a laser with the resonator formed by the diode faces, this mechanism was studied in connection with the problem of stability of single-frequency lasing [11].

Among many quite intricate problems of simulating the spectral parameters of heterolasers, we will consider only the simplest problem of simulating the output power in the single-frequency regime for a ridge laser or its physical analogue. Lasers of this type (index-guided lasers) have a technologically built-in waveguide. The main specific feature of these lasers is that they are transversely single-mode and, moreover, the transverse distribution of the laser-mode amplitude is specified in them only by the built-in waveguide, i.e. is independent of the lasing regime, and is close to the distribution characterising the 'cold' (in the absence of pumping) resonator. In this case, on the one hand, the interaction of the field and inversion can be considered taking into account their spatial inhomogeneity, by using in this way the adequate and comparatively simple laser model. On the other hand, the index-guided lasers have many

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applications at present, and therefore the problem of simulating their limiting single-frequency output power is of current interest.

Thus, the aim of this paper is to determine the maximum output power that can be achieved in the single-frequency regime in ridge heterolasers and to study the influence of the optical inhomogeneity along the laser resonator axis on this power.

2. Analysis of the stability of single-frequency lasing

We will represent the field in the resonator of a semiconductor laser in the single-frequency regime in the form of the superposition of the strong laser-mode field and weak fields of the subthreshold longitudinal modes, which are spectrally close to the laser mode (we assume that all the transverse modes, except the fundamental mode, are suppressed):

$$E(\boldsymbol{r},t) = \upsilon(x,y)\Big[C_0\exp(-\mathrm{i}\omega_0 t)U_0(z) + \sum_{m\neq 0} C_m(t)\exp(-\mathrm{i}\omega_m t)U_m(z)\Big] + \text{c.c.}, \quad (1)$$

where C_0 is the laser-mode amplitude; $C_m(t)$ are the amplitudes of subthreshold modes with the mode index m measured from the laser-mode index (which is positive for higher-frequency modes compared to the laser mode and negative for lower-frequency modes.) We assume that the z axis is directed along the resonator axis. The transverse distribution of the field $\upsilon(x,y)$ corresponds to the fundamental mode of a waveguide formed by the heterostructure layers and the ridge.

As shown in [11], the system of equations for the slowly varying complex amplitudes $C_m(t)$ of subthreshold modes in the presence of the strong laser mode splits into pairs of equations for the modes located in the spectrum symmetrically with respect to the laser mode. These equations have the form

$$\frac{2n_{\mathrm{g}}}{c}\dot{C}_m + \varDelta_m C_m + (\alpha+\mathrm{i})\chi_m\big(C_m + C^*_{-m}\big) = 0,$$
$$\frac{2n_{\mathrm{g}}}{c}\dot{C}^*_{-m} + (\varDelta_{-m} + \mathrm{i}\kappa_m)C^*_{-m} + (-\alpha+\mathrm{i})\chi_m(C_m + C^*_{-m}) = 0, \quad (2)$$

where

$$\chi_m = g_0\,\frac{1}{(\omega_m-\omega_0)\tau}\,\frac{I}{I_{\mathrm{sat}}}; \quad (3)$$

$n_{\mathrm{g}} = n + \omega\mathrm{d}n/\mathrm{d}\omega$ is the group mode refractive index; n is the mode (waveguide) refractive index; $\varDelta_{\pm m}$ are the gain deficits for the side modes, i.e. the differences between the threshold gain g_0, defined below, and the gain for modes;

$$\kappa_m = \frac{2n_{\mathrm{g}}}{c}(2\omega_0 - \omega_m - \omega_{-m})$$

is the parameter characterising the mode nonequidistance;

$$\alpha = \frac{\mathrm{Re}\,(\partial n/\partial N)}{\mathrm{Im}\,(\partial n/\partial N)}$$

is the amplitude – phase coupling coefficient (the Henry factor); N is the carrier concentration in the active region;

$$g_0 = \frac{1}{2L}\ln\frac{1}{R_1R_2}$$

is the threshold mode gain equal to losses at the resonator mirrors with reflectances R_1 and R_2; L is the resonator length; τ is the spontaneous-emission lifetime of carriers; I is the average emission intensity in the active region of the laser;

$$I_{\mathrm{sat}} = \frac{\hbar\omega_0}{(\mathrm{d}G/\mathrm{d}N)\tau}$$

is the characteristic saturation intensity; G is the gain in the active region; and $\mathrm{d}G/\mathrm{d}N$ is the differential gain, or the stimulated recombination 'cross section'.

The system of equations (2) was obtained by assuming that the field interacts with the active medium incoherently, i.e. the medium is characterised by the complex permittivity depending on the concentration of carriers. In turn the carrier concentration is dynamically related to the total field intensity in the resonator containing components oscillating at the intermode frequencies. We assume for simplicity that the coefficients A_m and B_m from [11], characterising the spatial overlap of the profile of oscillations of the carrier concentration with the mode fields, are equal to unity. The effects related to the inhomogeneous distribution of the radiation intensity over the resonator length when the reflectances of mirrors are considerably smaller than unity where neglected, so that, strictly speaking, our analysis is valid only for a high-Q resonator. In addition, we neglect here the contribution from the dynamic grating of carriers with the spatial scale equal to half the wavelength.

The influence of the nonlinearity of the medium in the system of equations (2) is described by the terms proportional to χ_m, i.e. according to (3), to the intensity of the laser-mode field in the resonator. The radiation intensity I is related to the pump current by the approximate expression (see [11])

$$\frac{I}{I_{\mathrm{sat}}} = \theta\eta, \quad (4)$$

where $\theta = (N/G)\,\mathrm{d}G/\mathrm{d}N$ is the dimensionless parameter of the order of unity, characterising the active medium, and $\eta = J/J_{\mathrm{th}} - 1$ is the relative excess of the pump current over the threshold. The intensity I can be also expressed in terms of the output radiation power

$$P_{\mathrm{out}} = ISLg_0, \quad (5)$$

where S is the area of the transverse distribution of the mode field [determined by the function $\upsilon(x,y)$]. The quantity P_{out} in (5) is the total radiation power emerging from both resonator mirrors.

Single-frequency lasing will be stable when the effective gain deficits

$$\varDelta^{\mathrm{eff}}_{\pm m} = \frac{\varDelta_m + \varDelta_{-m}}{2} \pm \mathrm{Re}\left[\left(\frac{\varDelta_m - \varDelta_{-m} - \mathrm{i}\kappa_m}{2} + \alpha\chi_m\right)^2 - (1+\alpha^2)\chi_m^2\right]^{1/2} \quad (6)$$

are positive for all pairs of coupled modes.

For the low-intensity laser radiation (when $\chi_m \ll \Delta_{\pm m}$), the effective gain deficits $\Delta^{\rm eff}_{\pm m}$ coincide with the initial deficits $\Delta_{\pm m}$, and the stability condition is trivial: all $\Delta_{\pm m}$ should be positive, i.e. the gain for all the side longitudinal modes should be lower than the threshold gain. Therefore, for the low output power, single-frequency lasing at the mode with the maximal gain will be always stable because all other modes remain below the threshold due to the gain saturation. Because the mode with the maximal gain always exists (except the degenerate case, when the gains for two or more modes coincide), the single-frequency lasing regime is possible for the mode gain band of an arbitrary shape for the low output power. For high intensities (when χ_m is comparable with $\Delta_{\pm m}$ or exceeds them), the stability condition $\Delta^{\rm eff}_{\pm m} > 0$ is no longer trivial, and, as will be shown below, single-frequency lasing cannot be always achieved.

Consider first the ideal case, when the resonator of a semiconductor laser does not contain longitudinal inhomogeneities producing the coupling of counterpropagating waves in the resonator. In this case, the spectral profile of the mode gain will be a smooth function proportional to the spectral contour of the material gain of the active medium. This function can be represented near its maximum in the form

$$g(\omega) \approx g(\omega_a) - a(\omega - \omega_a)^2, \tag{7}$$

where ω_a is the frequency at which the mode gain is maximal, and $a = -{}^1\!/_2 \partial^2 g/\partial\omega^2$ is the parameter determining the curvature of the gain profile near the maximum.

The intermode distance in the ideal case under study in the zero-order approximation is determined by the group mode refractive index $n_{\rm g}$:

$$\omega_{m+1} - \omega_m \approx \Omega = \frac{\pi c}{n_{\rm g} L}. \tag{8}$$

Thus, $\omega_m = \omega_0 + m\Omega$ and

$$\Delta_m = g(\omega_0) - g(\omega_m) = a\left[(\omega_0 + m\Omega - \omega_a)^2 - (\omega_0 - \omega_a)^2\right]$$

$$= \Delta[m^2 + 2m\delta], \quad \chi_m = \frac{\chi}{m}, \tag{9}$$

where $\delta = (\omega_0 - \omega_a)/\Omega$ is the relative detuning of the laser-mode frequency from the frequency of the gain maximum;

$$\chi = \frac{n_{\rm g}}{\pi c S\hbar\omega_0} \frac{{\rm d}G}{{\rm d}N} P_{\rm out};$$

$\Delta = a\Omega^2$ is the gain deficit for the subthreshold modes adjacent to the laser mode at the lasing threshold, when the laser mode is located at the maximum of the gain band.

The deviation of the modes from the equidistant location in the ideal case under study is determined by the dispersion of the group refractive index $n_{\rm g}$:

$$\kappa_m = m^2\kappa, \tag{10}$$

where

$$\kappa = \frac{2\Omega^2}{c}\frac{\partial n_{\rm g}}{\partial\omega} = -\pi\frac{\lambda_0^2}{n_{\rm g}^2 L^2}\frac{\partial n_{\rm g}}{\partial\lambda} = \pi\frac{\lambda_0^3}{n_{\rm g}^2 L^2}\frac{\partial^2 n}{\partial\lambda^2}.$$

By using equalities (6), (9), and (10), the stability condition $\Delta^{\rm eff}_{\pm m} > 0$ can be represented by the system of inequalities

$$\delta_m^- < \delta < \delta_m^+ \quad (m > 0), \tag{11}$$

$$\delta_m^\pm = \frac{1}{2}\left\{-\alpha\frac{p}{m^2} \pm \left[m^2 + \frac{1+\alpha^2}{1+\beta^2}\left(\frac{p}{m^2}\right)^2\right]^{1/2}\right\}, \tag{12}$$

where $p = P_{\rm out}/P_0$ is the dimensionless output radiation power;

$$P_0 = \frac{\pi c S\hbar\omega_0\Delta}{n_{\rm g}({\rm d}G/{\rm d}N)} = \frac{\pi^2\hbar c^2 S\lambda_0^3}{4n_{\rm g}^3 L^2({\rm d}G/{\rm d}N)}\left|\frac{\partial^2 g}{\partial\lambda^2}\right| \tag{13}$$

is the characteristic output power at which the effect of nonlinearity becomes considerable; and

$$\beta = \frac{\kappa}{2\Delta} = \frac{{\rm Re}\,(\partial^2 n/\partial\lambda^2)}{{\rm Im}\,(\partial^2 n/\partial\lambda^2)} = \frac{4\pi}{\lambda_0}\frac{\partial^2 n/\partial\lambda^2}{|\partial^2 g/\partial\lambda^2|} \tag{14}$$

is the dimensionless nonequidistance of modes caused by the dispersion of the group mode refractive index.

Let us take, for example, the following typical set of parameters of a ridge laser (the values of material parameters presented below are close to those obtained experimentally for the heterostructure described in [12]): $\lambda_0 = 1.06$ μm, $L = 400$ μm, $S = 4 \times 0.5$ μm, ${\rm d}G/{\rm d}N = 5 \times 10^{-16}$ cm^2, $n_{\rm g} = 4$, $\alpha = 3.5$, $\partial^2 n/\partial\lambda^2 = 6$ μm^{-2}, and $|\partial^2 g/\partial\lambda^2| = 8$ μm^{-3}. The calculation with these values gives $P_0 \approx 0.9$ mW and $\beta \approx 9$.

For each $m > 0$, inequalities (11) determine the detuning interval of the laser mode from the maximum of the gain band in which single-frequency lasing is stable with respect to excitation of a pair of modes with indices $\pm m$. Consider first one such interval. For $p \ll 1$, lasing is stable in the detuning interval between $-m/2$ and $+m/2$. This obvious result corresponds to the fact that the continuous frequency tuning near the threshold is possible only within the frequency interval centred at the maximum of the gain curve, whose width is equal to the intermode distance. As the output power increases (with increasing parameter p), this interval shifts to the red and broadens. The strong laser mode induces the additional efficient amplification of the mode with the index $-m$ (with lower frequency) equal to $\alpha\chi_m$ [see the system of equations (2)] and the same (in the absolute value) additional efficient absorption for the mode with the index m (with higher frequency). As a result, the stability region shifts to the red. Another effect taking place in the presence of the strong laser mode is the appearance of coupling between the subthreshold modes. This effect results in the broadening of the stability region. Although both these effects are caused by the same physical mechanism and are described by the same quantity χ_m in the system of equations (2) for mode amplitudes, the second effect can be manifested to a considerably lesser degree due to the nonequidistance of modes which weakens the coupling between subthreshold modes.

One can see from expression (12) that the rate of broadening of the stability region with increasing the output power is determined by the value $(1+\alpha^2)/(1+\beta^2)$. The dependence of the location of the stability region (11) on the output power is determined by the value of the nonequidistance parameter β (Fig. 1). If this parameter is small

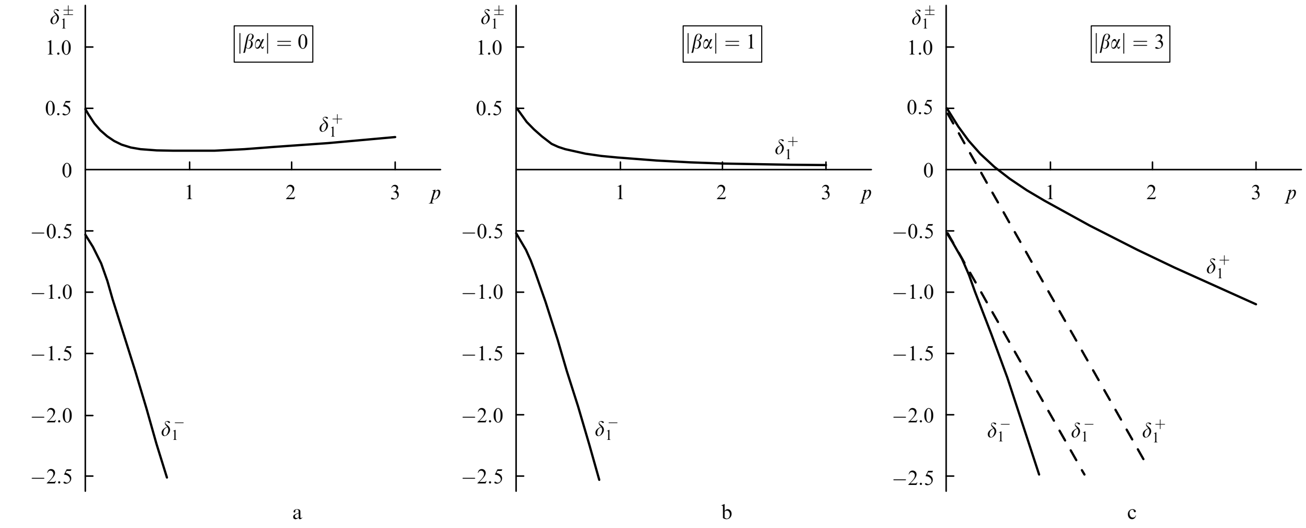

Figure 1. Positions of the boundaries $\delta_1^{\pm}$ of the interval of relative detuning of the laser mode frequency from the gain maximum, in which single-mode lasing is stable with respect to excitation of a nearest pair of side modes, as functions of the dimensionless output power p for the nonequidistance parameter $\beta = 0$ (a), 1/3 (b), and 1 (c) ($\alpha = 3$). The dashed lines show the position of the boundaries of this interval for $|\beta\alpha| \gg 1$, i.e. when the nonequidistance is so high that the interaction between side modes can be neglected.

enough ($|\beta\alpha| \leqslant 1$), the upper boundary δ_m^+ of the stability region will be positive for all p; otherwise, it monotonically (in asymptotics, linearly) decreases with increasing p. Thus, for $|\beta\alpha| \leqslant 1$, the stability interval broadens with increasing p to the low-frequency side, whereas from the high-frequency side this interval always includes at least the point $\delta = 0$ (i.e. single-frequency lasing will be stable for any output power if the position of the laser mode coincides with the maximum of the gain band). If $|\beta\alpha| > 1$, both boundaries of the stability interval shift to the red with increasing the output power.

Consider now the system of inequalities (11). The stability interval of single-frequency lasing is the intersection of intervals corresponding to the different values of m, i.e. system (11) is equivalent to the condition

$$\delta^- < \delta < \delta^+, \tag{15}$$

where

$$\delta^- = \max_{m>0} \delta_m^-, \quad \delta^+ = \min_{m>0} \delta_m^+.$$

The dependence of this resulting interval on the output power p is also determined by β (Fig. 2). It can be shown that for $|\beta\alpha| \leqslant 1$, the stability interval monotonically broadens with increasing p. Therefore, single-frequency lasing is possible for any output power. In turn for $|\beta\alpha| > 1$, the width of the stability region begins to decrease beginning from some value of p and vanishes for $p = p_{\max}$. Thus, for $|\beta\alpha| > 1$, when the nonequidistance of

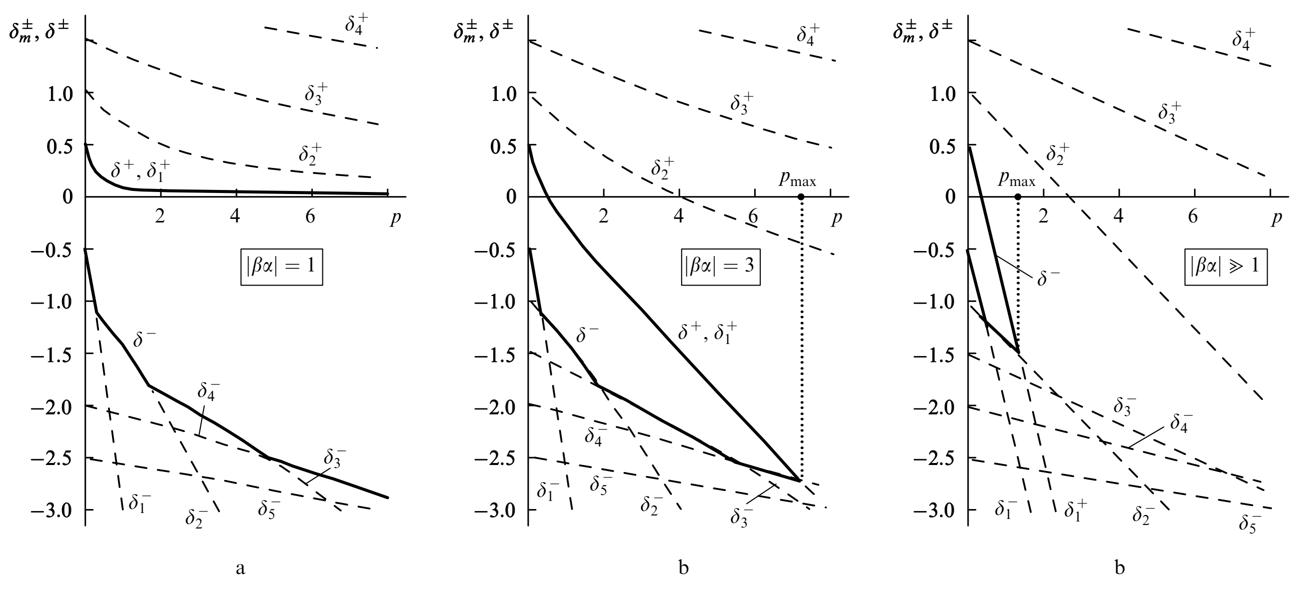

Figure 2. Positions of the boundaries $\delta^{\pm}$ of the stability region of single-frequency lasing as functions of the dimensionless output power p for the nonequidistance parameter $\beta = 1/3$ (a), 1 (b), and $\beta \gg 1$ (c) ($\alpha = 3$) (solid lines). The dashed lines show the dependences of $\delta_m^{\pm}$ on p, each of them representing the restriction of the stability region caused by excitation of one of the subthreshold modes (more exactly, of a pair of coupled modes).

modes is high enough and modes are coupled weakly, the single-frequency output power has a limit. The value of $p_{\max}$ decreases with increasing the nonequidistance parameter β, achieving the minimal value $p_{\max} = 4/|\alpha|$ for $|\beta\alpha| \gg 1$, i.e. when $|\kappa| \gg \Delta$ and the nonequidistance completely breaks the coupling between subthreshold modes with indices $\pm m$. In this case, the nonlinear interaction of the fields splits into the interactions of the strong laser mode with each of the weak subthreshold modes.

The parameters α and β characterise the heterostructure from which the laser is fabricated at the carrier concentration in the active region corresponding to lasing. These parameters are determined by the material properties of the structure layers and by the structure geometry, i.e. the thickness of layers and the ridge shape determining the waveguide properties in the horizontal direction (along the $p-n$ junction). Therefore, they can be different for lasers manufactured from different heterostructures. For typical parameters of a semiconductor laser, the condition $|\beta\alpha| > 1$ is fulfilled, as a rule, i.e. the single-frequency output power has a limit. Thus, calculations performed with the parameters of a ridge laser presented above give $p_{\max} \approx 1.2$, which corresponds to the output power $P_{\rm out}^{\max} \approx 1$ mW. Thus, the single-frequency output power of a laser with parameters presented above and an ideal (optically homogeneous) resonator cannot exceed 1 mW.

As mentioned above, the obtained results are valid, strictly speaking, only for a high-Q resonator. It is difficult to analyse mirrors losses analytically; however, it can be done numerically. In this paper, we will not discuss this question in detail, but note only that the maximal power achievable in the single-frequency lasing regime increases. In particular, for a laser resonator mirrors with reflectances $R_1 = 95\,\%$ and $R_2 = 5\,\%$ and parameters presented above, the calculation gives $P_{\rm out}^{\max} \approx 1.3$ mW. This result was obtained numerically for a more correct consideration of the spatial overlap of the oscillation profile of the carrier concentration with mode fields, i.e. taking into account that the coefficients A_m and B_m differ from unity. In this case, the quantity χ_m becomes complex and is determined by the expression that differs somewhat from (3).

Consider now the real case, when the laser resonator contains longitudinal optical inhomogeneities resulting in the modulation of the gain band. Let us assume that the effective permittivity in the resonator depends on the longitudinal coordinate

$$\varepsilon(z) = \varepsilon_0 + \delta\varepsilon(z), \tag{16}$$

where ε_0 is the average value of the complex effective permittivity; $\delta\varepsilon(z)$ are the fluctuations of the effective permittivity caused, for example, by the deviation of the thickness or the composition of heterostructure layers from their average values. The additions to the gain and the spectral shift of the modes caused a small perturbation $\delta\varepsilon(z)$ can be written in the form

$$\delta g_m = -\frac{\omega}{cn}\,{\rm Im}\,\frac{\int_0^L \delta\varepsilon(z)U_m^2(z){\rm d}z}{\int_0^L U_m^2(z){\rm d}z}, \tag{17}$$

$$\delta\omega_m = -\frac{\omega}{2nn_{\rm g}}\,{\rm Re}\,\frac{\int_0^L \delta\varepsilon(z)U_m^2(z){\rm d}z}{\int_0^L U_m^2(z){\rm d}z}.$$

In this case, the gain deficits and the mode nonequidistance are described by the expressions

$$\Delta_m = \Delta\left|m^2 + 2m\delta\right| + \delta g_0 - \delta g_m,$$
$$\kappa_m = \kappa m^2 + \frac{2n_{\rm g}}{c}\,(2\delta\omega_0 - \delta\omega_m - \delta\omega_{-m}). \tag{18}$$

By using (6), (16), and (17), we can determine the parameter $p_{\max}$, i.e. the maximum output power at which single-frequency lasing is possible. This power will be different for lasing at different longitudinal modes because additions (16) depend on the absolute number of a longitudinal mode.

We used the following model of longitudinal inhomogeneities in the resonator of a semiconductor laser. The real function

$$\delta\varepsilon(z) = 2n_0\delta n_i, \;\; z_{i-1} < z < z_i, \; i = 1, 2, \ldots, M \tag{19}$$

was considered, where $z_i = i\Delta z$; $\Delta z = L/M$; $n_0 = {\rm Re}\sqrt{\varepsilon_0}$ is the average mode refractive index; δn_i are variations in the mode refractive index representing uncorrelated Gaussian real random quantities with the zero average value and the root-mean-square deviation $\overline{\delta n}$. Thus, the random function $\delta\varepsilon(z)$ had a normal distribution and a 'white' spectrum in the region of spatial frequencies from zero to $q_{\max} = \pi/\Delta z$. We considered the two particular realisations of random function (18) with $\overline{\delta n} = 10^{-5}$ and 10^{-4} (note that a change in the mode refractive index can be caused by a change in the thickness of heterostructure layers with the quantum-well active region by the value of the order of the lattice constant); in both cases, Δz was set equal to 0.1 μm.

The longitudinal distribution of the field was described by the threshold distribution

$$U_m(z) = \sqrt{R_1}\exp({\rm i}\beta_m z) + \exp(-{\rm i}\beta_m z),$$
$$\beta_m = \frac{\pi}{L}\,\tilde{m} - \frac{\rm i}{4L}\ln\frac{1}{R_1R_2}, \tag{20}$$

where $\tilde{m} = m_0 + m$ is the 'absolute' mode number; m_0 is the 'absolute' laser mode number; R_1 and R_2 are the reflectivities of mirrors for $z = 0$ and L, respectively. We will consider the case with $R_1 = 95\,\%$ and $R_2 = 5\,\%$.

For a laser with the parameters presented above, we calculated additions to the gain and frequency shifts for a set of longitudinal modes with wavelengths in the vicinity of 1.06 μm from realisations of the random function $\delta\varepsilon(z)$ and expressions (16). Then, the value of $P_{\rm out}^{\max}$ was calculated for each of the modes. Figure 3 presents the results of calculations (additions to the gain and the value of $P_{\rm out}^{\max}$) for the sampling of forty longitudinal modes.

The first considered case ($\overline{\delta n} = 10^{-5}$, Fig. 3a) corresponds to the relatively weak perturbation of the gain band, the root-mean-square addition to the gain being of the order of Δ. The average value of $P_{\rm out}^{\max}$ weakly differs from the maximum output power for the 'ideal' case, however, a scatter comparable with the average value appears. In the second considered case ($\overline{\delta n} = 10^{-4}$, Fig. 3b), the perturbation of the gain band is rather strong, the root-mean-square addition to the gain being an order of

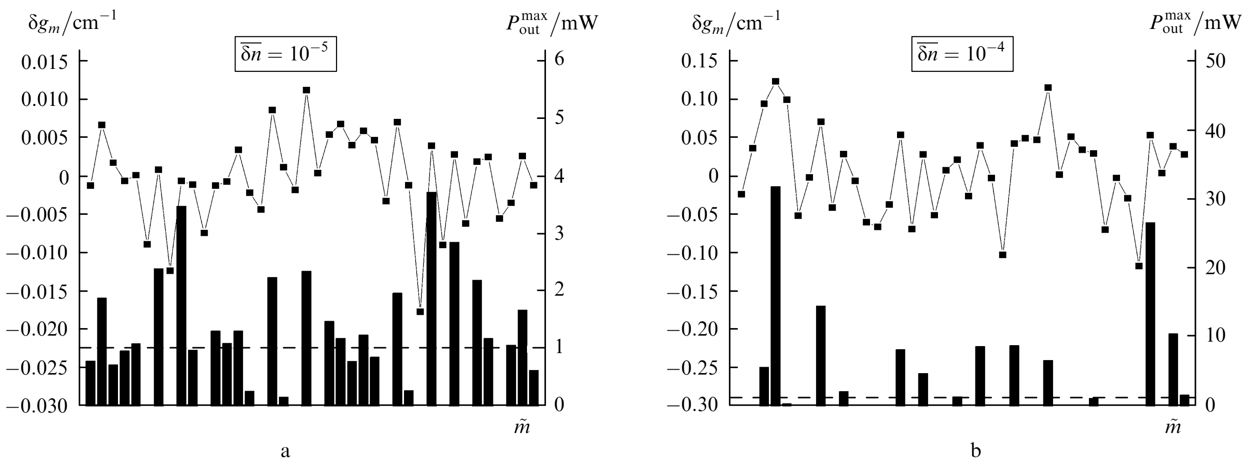

Figure 3. Random modulation of the mode gain δg_m (lines with squares) caused by the presence of longitudinal inhomogeneities in the laser resonator, and the maximum output power $P_{\rm out}^{\rm max}$ at which single-mode lasing can occur at different longitudinal modes (columns). The two presented realisations differ in the value of the root-mean-square fluctuation $\overline{\delta n}$ of the refractive index. The dashed straight line corresponds to the output power $P_{\rm out}^{\rm max}$ for the resonator without inhomogeneities (the resonator parameters are presented in the text).

magnitude higher than Δ. In this case, single-frequency lasing is possible on less than half the longitudinal modes under study; however the output power can be more than an order of magnitude higher than the value corresponding to the 'ideal' case; the single-frequency output power lasing for some modes can achieve ~ 30 mW. Thus, the perturbation of the spectral profile of the mode gain caused by longitudinal inhomogeneities in the resonator leads to the increase of the maximal single-frequency output power. These inhomogeneities can be not only random, as in the case considered above, but can be deliberately introduced into the resonator. As an example, consider a very small (compared to the radiation wavelength) single inhomogeneity, which can be simulated as a jump of the effective permittivity described by the delta function

$$\delta\varepsilon(z) = \rho\delta(z - z_0), \tag{21}$$

where z_0 determines the position of the inhomogeneity. Such a jump corresponds to the reflectance

$$R_{\rm inh} = \left(\frac{\pi\rho}{\lambda_0 n}\right)^2 \tag{22}$$

from the inhomogeneity (this expression is valid for $R_{\rm inh} \ll 1$).

By substituting (18) and (20) into (16), we can easily calculate additions to the gain and the frequency shifts of longitudinal modes:

$$\delta g_m = -\frac{\sqrt{R_{\rm inh}}}{L}\left(\frac{\sqrt{R_1}}{(R_1R_2)^{z_0/2L}} - \frac{(R_1R_2)^{z_0/2L}}{\sqrt{R_1}}\right)\sin\frac{2\pi\tilde{m}z_0}{L},$$

$$\delta\omega_m = -\frac{c\sqrt{R_{\rm inh}}}{2n_{\rm g}L}\left[2 + \left(\frac{\sqrt{R_1}}{(R_1R_2)^{z_0/2L}} + \frac{(R_1R_2)^{z_0/2L}}{\sqrt{R_1}}\right)\cos\frac{2\pi\tilde{m}z_0}{L}\right]. \tag{23}$$

These additions depend periodically on the absolute mode number $\tilde{m}$. Consider the case when an inhomogeneity with the reflectance $R_{\rm inh} = 10^{-4}$ is located at a distance of $L/4$ from the output mirror, i.e. when $z_0 = {}^3/_4L$. Figure 4 presents the calculated additions to the gain and the maximum single-frequency power. The dependence δg_m in Fig. 4a is obtained by using expression (23). In this case, the maximum output power in the presence of the inhomogeneity achieves ~ 60 mW, which is one and a half order of magnitude higher than that in the absence of the inhomogeneity. If random inhomogeneities with $\overline{\delta n} = 10^{-4}$ are also present, which are taken into account as described above, a scatter of in the maximum output powers for different modes appears; however, the average output power remains at the same level (Fig. 4b). Thus, by introducing a longitudinal inhomogeneity into the resonator of a semiconductor laser, we can increase in the controllable way the maximum single-frequency output power.

3. Discussion and conclusions

We have shown in this paper that the single-frequency output power of a semiconductor laser with a built-in horizontal waveguide and typical parameters is restricted from above. This restriction is caused by a change in the effective gain for longitudinal modes adjacent to the laser mode due to the nonlinear interaction of the laser mode with subthreshold modes caused by oscillations of the carrier concentration at the intermode frequencies. The maximum single-frequency output power for a typical ridge laser with the ideal resonator is ~ 1 mW. For invariable material parameters of the active medium, the maximum output power is inversely proportional, according to (13), to the square of the laser length and, hence, can be increased by shortening the laser. The maximum output power can be also increased by increasing the cross section S of the radiation mode (note that in practice this cross section is limited by the necessity of providing the transverse stability of the field). In addition, the maximum output power increases with decreasing the resonator Q factor, i.e. with decreasing the reflectances of resonator

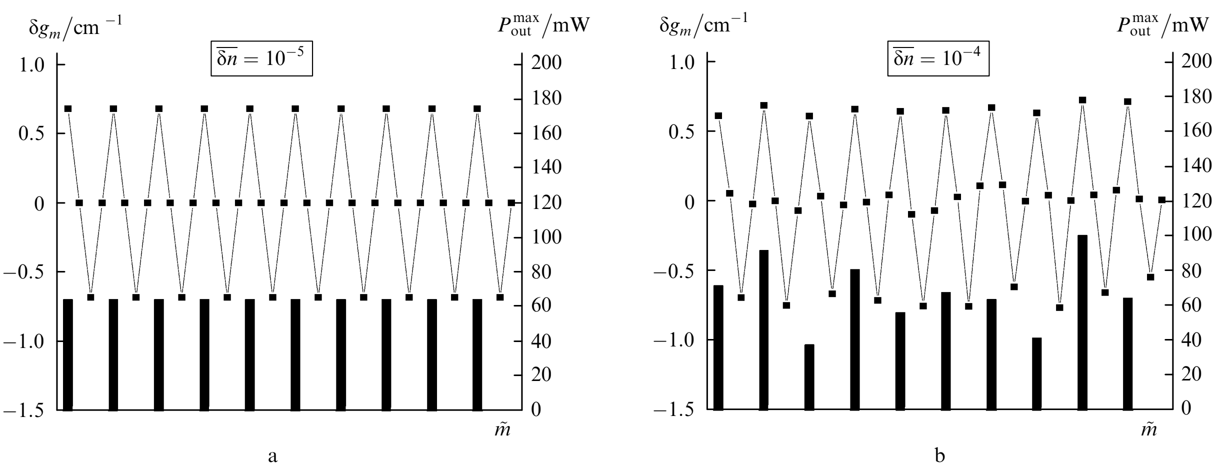

Figure 4. Modulation of the spectral profile of the mode gain δg_m (lines with squares) in the presence of a longitudinal inhomogeneity with the reflectance 10^{-4} in the resonator and the maximum output power $P_{\mathrm{out}}^{\mathrm{max}}$ at which single-frequency lasing can occur at different longitudinal modes (columns) in cases when the resonator does not contain other inhomogeneities (a) and the mode refractive index fluctuates with the root-mean-square value $\overline{\delta n} = 10^{-4}$ (b) (the resonator parameters are presented in the text).

mirrors. The maximum single-frequency output power of the laser under study increases by 30 % when mirrors with reflectances $R_1 = R_2 \approx 100$ % are replaced by mirrors with $R_1 = 95$ % and $R_2 = 5$ %. Note, however, that the applicability of our model for lasers with low reflectivities of mirrors can be restricted due to the spatial inhomogeneity of the gain caused by the inhomogeneous spatial 'burning out' of carriers.

The maximum single-frequency output power considerably depends on the curvature of the mode gain profile near its maximum (characterised by the quantity $|\partial^2 g/\partial\lambda^2|$), the mode nonequidistance caused by the dispersion of the group refractive index (characterised by the quantity $\partial^2 n/\partial\lambda^2$), and the amplitude–phase coupling coefficient α. To increase the maximum power, it is desirable to maximise $|\partial^2 g/\partial\lambda^2|$ and minimise $\partial^2 n/\partial\lambda^2$ and α. Thus, for example, the maximum output power of the laser under study could be increased from 1 to 100 mW either by increasing $|\partial^2 g/\partial\lambda^2|$ from 8 to ~ 90 μm^{-3} and decreasing α from 3.5 to ~ 0.2 or by decreasing $\partial^2 n/\partial\lambda^2$ from 6 to ~ 0.3 μm^{-2} keeping other parameters invariable.

One of the approximations used in our model is the monochromaticity of the laser mode. In reality, the spectral line corresponding to the laser mode always has a finite width caused by the phase fluctuations of the laser mode (amplitude fluctuations can be usually neglected). These fluctuations do not affect the nonlinear interaction of the laser mode with each of the weak modes separately, but weaken, however, the coupling between weak modes, i.e. the influence of the phase fluctuations of the laser mode will be similar to the influence of the nonequidistance of modes. Therefore, the nonmonochromaticity of the laser mode being taken into account, the maximum single-frequency output power should be lower than that obtained within the framework of our model.

If the resonator of a semiconductor laser contains longitudinal inhomogeneities producing the modulation of the spectral profile of the mode gain, the maximum single-frequency output power can be in principle considerably higher (more than by an order of magnitude) than that in the 'ideal' case of the absence of inhomogeneities. This can be achieved if the characteristic modulation 'depth' exceeds the characteristic gain deficits in the absence of inhomogeneities. For a laser with parameters under study, this condition can be fulfilled, for example, in the presence of fluctuations of the effective refractive index along the resonator length with the root-mean-square value $\overline{\delta n} = 10^{-4}$. The increase in the maximum single-frequency output power caused by random inhomogeneities is, however, random, and therefore the experimental output powers can strongly vary from sample to sample. The maximum output power can be controllably increased by deliberately introducing a longitudinal inhomogeneity. Thus, a microscopic inhomogeneity (small compared to the radiation wavelength) with the reflectance $R_{\mathrm{inh}} = 10^{-4}$ present in the resonator causes the increase in the single-frequency output power up to a few tens of milliwatts, while random inhomogeneities can produce only a relatively small scatter in the output power.

As mentioned in Introduction, the results obtained in the paper should be valid not only for ridge lasers but also for any other semiconductor lasers with fixed transverse field distributions.

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