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Partial Coherence of Laser Diode Radiation as a Cause of Generation Channels Formation

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Abstract—The modeling of high-power wide-contact laser diodes is discussed taking into account the limitations imposed by the short coherence length of radiation. The relationships between coherence, spectrum, and nonlinear properties of a laser resonator are considered.

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INTRODUCTION

The modeling of high-power laser diodes (LDs) became especially relevant upon the creation of quantum-sized semiconductor structures in which the spectral line of the optical gain was two orders of magnitude narrower than in bulk semiconductors, and the optical gain was itself greater by about the same amount [1]. The first works on the mathematical modeling of dynamic processes in LDs [2, 3], which served as the basis for creating today's basic models, appeared in the 1980s. New devices with quantum wells (QWs) and wide active regions (wide contacts) now produced require fundamentally new approaches to the mathematical modeling of the dynamics and statics of their radiation during their design.

BASIC MODEL

A basic model describing the self-consistent interaction between radiation and nonequilibrium carriers in a multilayer semiconductor structure was described in, e.g., [4, 5]. Kinetic (velocity) equations that describe the concentration balance of carriers and photons in the active region of the laser are the basis of all self-consistent LD models. The spatially inhomogeneous interaction between laser radiation and carriers is considered in distributed LD models. Effective dielectric constant $\varepsilon(N(y))$ depends on the concentration of nonequilibrium carriers N at a specific point in the active layer [4]. The system of kinetic partial differential equations for concentrations N of carriers and S of photons, which forms the kinetic part of the model, is the basis of the self-consistent LD model. The wave equation transformed into the Helmholtz equation with allowance for the dependence of the field amplitude on time and axial coordinate z in the form $E(y,z,t) = \psi(y)\exp(i(\omega t - \beta z))$ is the optical part of the model:

$$\frac{d^2\psi_j(y)}{dy^2} + \left(\frac{\omega_j^2}{c^2}\varepsilon(y) - \beta^2\right)\psi_j(y) = 0, \tag{1}$$

where ω_j is the frequency of the optical radiation (the eigen values of the equation); β is the longitudinal (along the z axis) constant of propagation; and $\psi_j(y)$ represents the lateral eigen functions. The dependence on transverse coordinate x is considered using the effective refractive index in [6].

LIMITATIONS OF THE BASIC MODEL

In a laser (resonator) problem, the eigen values of Eq. (1) are either the complex frequencies of modes ω_j or effective refractive indices $n_{\mathrm{eff}\,j} = c\beta/\omega_j$. In such a problem, constant β_M of longitudinal propagation is usually selected for a single longitudinal mode with number M. It is determined by resonator length L and coefficients of reflection R_1 and R_2 of the mirrors:

$$\beta_M = \frac{M\pi}{L} + \frac{i}{2}\left[\alpha_0 + \frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right)\right], \tag{2}$$

where α_0 is the nonresonant loss in a cold resonator. The solution to Eq. (1) yields the gain of transverse modes $G_j(t) = -2\,\mathrm{Im}(\omega_j)$ and their profiles $\psi_j(y)$.

Some possible approaches to solving the self-consistent LD model were described in [4, 5]. Such a scheme can be considered the basic configuration of a self-consistent distributed dynamic LD model. The basic model assumes the use of a quasi-continuous incoherent approximation. Quasi-continuity refers to kinetic equations and implies that the iterative calcu-

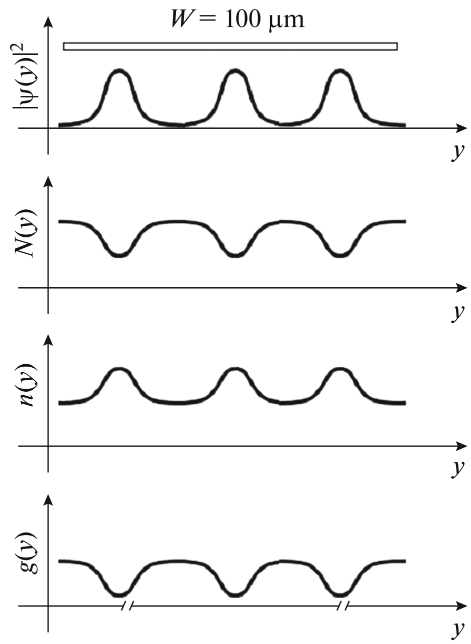

Fig. 1. Formation of channels of generation in wide contact LDs.

lation is performed using time steps that exceed the optical travel time between the mirrors of the Fabry–Perot resonator, while agreeing with the Routh–Hurwitz stability criterion. This time is several fractions of a picosecond. In an incoherent approximation, we believe the optical oscillation phase of the forward and backward waves in the planar resonator of the LD manages to stray during several passes of radiation through the resonator, which corresponds to the operation of a real LD. This allows us to use Eq. (1) to calculate the transverse profile shape of the radiation field. In the context of electrodynamics, the incoherent approximation justifies transitioning to a complex value of the dielectric constant and the refractive indices of the LD layers.

In addition, the basic model does not fully or even partially consider effects of a thermal, polarization, or spectral nature, such as the Joule heating, the nonresonant absorption of radiation, spectral hole burning, intraband energy relaxation, and competition between the polarization modes.

In the basic model, the spatial separation of amplification and optical limitation in LDs with quantum wells is considered by introducing coefficients of optical filling for the quantum wells and the extended waveguide [7, 8].

BASIC MODEL WITH ALLOWANCE FOR THE LENGTH OF COHERENCE

An important circumstance that demands modernization of the basic model is the transition to wide contact LDs, in which the width of the active region is more than 50 μm [8]. The maximum radiation power of such devices can be more than 20 W.

The basic model of an LD with an incoherent approximation works well in structures with narrow contacts (less than 50 μm), but ceases to work in wide-contact LDs. Experiments show that the radiation in wide contact LDs decays into unphased channels of generation [9]. The radiation decays into channels because the wavefront (beam) must make several trips from mirror to mirror without losing coherence so that the part of the optical radiation that propagates at the edge (along the lateral coordinate *y*) of the active region can be phase-locked with radiation at the opposite edge of this region.

Figure 1 schematically illustrates the distribution of the parameters of an active layer along lateral coordinate *y* for developed generation in three channels. We can see the phenomenon of radiation self-focusing as a result of two effects: the spatial hole burning of nonequilibrium carriers by stimulated emission in regions with maximum intensity of the optical field and nonlinear refraction, which ensures self-focusing of radiation in those places of the active layer of wide contact LDs, where the concentration of nonequilibrium carriers has local minima. The relationship between the width of the channel and the hole spatial burning of nonequilibrium carriers in the basic model is due to nonlinear refraction parameter $\left|\frac{dn'}{dN}\right|$ being on the order of 10^{-20} cm^3.

Calculations according to the theory of diffraction and allowing for the curvature of the wavefront yield an estimate of number N_{chan} of the channels of generation, depending on the length L_{coh} of the coherence of laser radiation:

$$N_{chan} \approx W\sqrt{\frac{2\pi n}{\lambda L_{coh}}}, \quad (3)$$

where n is an effective refractive index of the fundamental transverse mode of the laser waveguide; W is the full width of the active region; and λ is the wavelength of the radiation in a vacuum.

With (3), we can estimate the LD's length of coherence if we know the number of channels:

$$L_{coh} \approx \frac{2\pi n}{\lambda}\left(\frac{W}{N_{chan}}\right)^2. \quad (4)$$

Relation (4) reflects the relationship between the transverse and longitudinal lengths of coherence in a laser active layer . We can see that the transverse length of coherence, which is approximately equal to the optical width of the channel of generation, is associated with the longitudinal quadratic dependence.

Measurements of the LD's length L_{coh} of coherence, made using a Michelson interferometer, showed it was around 1–5 cm [10, 11]. In addition, the authors of [12] showed that the length of LD radiation's coherence does not obey familiar relations from the theory of solid-state and gas lasers, since LDs have an energy band structure.

Let us consider the characteristic quantities for the structure of a powerful wide-contact LD with QW [8]. The structural parameters are: resonator length $L = 2$ mm; wavelength of radiation in a vacuum $\lambda = 0.964$ μm; contact width $W = 100$ μm; effective refractive index $n = 3.6$; length of coherence $L_{coh} =$ 5 cm; and mirror coefficients of reflection $R_1 = 0.02$ and $R_2 = 0.98$. Formula (3) with these parameters yields a value of 2.16; i.e., number of channels $N_{chan} = 2$. We would therefore expect two channels of generation in wide contact LDs with the above parameters, as was observed in [9, 13].

For the above LD parameters, length of coherence $L_{coh} = 5$ cm also allows us to approximate the line width of one electronic state in the QW subbands $\Delta\lambda_{level} = 0.017$ nm, which corresponds to energy level width $\Delta E_{level} = 2.6 \times 10^{-5}$ eV. The spectral width between working subbands 1_{ee} and 1_{lh} (electrons and heavy holes) in the QW of the wide contact LDs in this case corresponds to width of gain line $\Delta\lambda_{1ee-1lh} = 6$ nm [13], which fits into the range of energy $\Delta E_{1ee-1lh} =$ 9.3×10^{-3} eV. Below, we present calculated data on the spectral characteristics of laser resonator of the considered device. The distance between the longitudinal modes of the resonator of such an LD is $\Delta\lambda_{long} =$ 0.06 nm ($\Delta E_{long} = 9.3 \times 10^{-5}$ eV), while the width of the Fabry–Perot resonance is $\Delta\lambda_{res} = 0.07$ nm ($\Delta E_{res} = 1.1 \times 10^{-4}$ eV) (i.e., slightly more than the inter-mode distance). We can see that a 2-mm-long wide contact LDs resonator is not a good frequency-selective element. First of all, the emission spectrum of such an LD is determined by the gain contour of the QW, and not by the Q-factor of the resonator, as is the case with less powerful LDs. This ratio of the spectral characteristics of a resonator plays an important role in the formation of unphased channels of generation. It ensures weak non-uniformity of the gain spectrum of the LD. This in turn results in clear spectral and spatial separation of the wide contact LD radiation between the channels of generation. In wide contact LDs with an even longer cavity with the same mirror parameters, we would expect the emergence of new LD effects, which means a new category of lasers.

If there are several channels of generation, the basic self-consistent distributed model ceases to work, since using the incoherent approximation which is the basis of this model becomes impossible.

One way of solving the difficulties in creating an adequate model of wide contact LDs is to use a hybrid model. In such a model, we must consider that the spatial width of the channels of generation in wide contact LDs depends on the length L_{coh} of coherence and nonlinear coefficient of refraction $\left|\frac{dn'}{dN}\right|$ of the active layer associated with it.

RELATIONSHIP BETWEEN SELF-FOCUSING AND COHERENCE IN WIDE CONTACT LDs

Let us consider a simplified model in which each channel of generation of wide contact LDs has a unique lateral fundamental mode $\psi_0(y)$. According to wave theory and the effective refractive index approach [6], this mode is the solution to Eq. (1) for mode number $j = 0$. The value of β_M in form (2) is calculated from the given central frequency of the gain spectrum of the wide contact LDs. We therefore find the mode gain and profile of the $\psi_0(y)$ mode.

The energy balance of lateral modes in LDs was considered in [14], where the following relation was derived:

$$\frac{2\omega_j''}{\omega_j'} = \frac{2\beta_M''}{\beta_M'} - \frac{\overline{\varepsilon}_j''}{\overline{\varepsilon}_j'}, \quad (5)$$

where $\overline{\varepsilon}_j''$ and $\overline{\varepsilon}_j'$ are the imaginary and real parts of the effective dielectric constant of the lateral modes. Expression (5) is the equation of energy balance in a laser resonator. The reciprocal of the Q-factor of the j-th generated mode is on the left side of Eq. (5). The difference between the inverse Q-factor of a cold laser resonator and the gain of the active medium per lateral mode (the effective tangent of the gain angle) is on the right side.

The equation of dispersion in this notation is

$$\frac{\omega_j'^2}{c^2}\overline{\varepsilon}_j' = \beta_M'^2 + \varkappa_j^2. \quad (6)$$

Effective complex dielectric constant $\overline{\varepsilon}_j$ and lateral propagation constant $\varkappa_j$ have the form

$$\overline{\varepsilon}_j = \frac{1}{D_y}\int_{-\infty}^{+\infty} \varepsilon(y)\left|\psi_j(y)\right|^2 dy; \quad (7)$$

$$\varkappa_j = \sqrt{\frac{1}{D_y}\int_{-\infty}^{+\infty}\left|\frac{\partial\psi_j(y)}{\partial y}\right|^2 dy}, \quad (8)$$

where D_y is the interval of normalization, which we assume below to be equal to width w_0 of the channel of generation at zero lateral mode. We assume that eigen functions $\psi_j(y)$ are normalized to unity by the quadratic norm

$$\frac{1}{D_y}\int_{-\infty}^{+\infty}\left|\psi_j(y)\right|^2 dy = 1. \quad (9)$$

Let us consider expressions (5) and (6). At the contінous wave (CW) generation, relation (5) takes the form

$$\frac{2\beta_M''}{\beta_M'} = \frac{\overline{\varepsilon}_m''}{\overline{\varepsilon}_m'}. \quad (10)$$

Let us consider the fundamental lateral mode. In a weak waveguide that is a channel of generation, the profile of this mode is well approximated by the normalized Gauss function

$$\psi_0(y) = \pi^{-1/4}\exp\left(\frac{y^2}{2w_0^2}\right), \quad (11)$$

where normalization condition (9) is considered.

Using expressions (2), (5), (6), and (11), we find the relation connecting the width of channel of generation with the other characteristics of the LDs

$$\frac{\omega_0'^2}{c^2}\overline{\varepsilon}_0' = \left(\frac{M\pi}{L}\right)^2 + \frac{1}{2w_0^2}, \quad (12)$$

where ω_0' is the central frequency in the fundamental mode spectrum of a channel of generation.

As a result, spatial width w_0 of a channel of generation and width $\Delta\lambda$ of its spectral line are interconnected. In terms of wavelengths from (12), we obtain

$$w_0 = \frac{\lambda}{2\pi n_{\text{eff}\,0}}\sqrt{\frac{\lambda}{\Delta\lambda}}, \quad (13)$$

where λ is the central wavelength in the fundamental mode spectrum of a channel of generation; $n_{\text{eff}\,0}$ is the effective refractive index of the fundamental mode in the channels of generation (see Fig. 1).

Comparing expressions (3), (4), and (13) when there is experimental data, we can estimate the magnitude of the relationship between the radiation coherence length and the nonlinear properties of the active medium.

CONCLUSIONS

It was shown that the relationship between coherence and nonlinear refraction can be considered when modeling LDs. This allow us to explain the decomposition of radiation in wide contact LDs into unphased channels of generation from physically different viewpoints.

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