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Output losses in semiconductor laser resonator formed by a photonic crystal

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Calculations of the distribution of electromagnetic field and output losses for a semiconductor laser resonator based on a two-dimensional photonic crystal are performed. For a constant Γ-factor, the size of the holes affects the localization of laser radiation in the center of the resonator, reduces parasitic lateral losses and increases output losses from the crystal surface.

Keywords: semiconductor lasers, photonic crystal, optical losses in the resonator, distributed feedback.

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High-power semiconductor lasers are in high demand due to their record-high efficiency, but the growth of optical power from an aperture of $100\,\mu$m has reached saturation over the past ten years [1,2]. The main current concept behind increasing the output optical power is to increase the emission area and form bars and arrays of emitters [3,4]. These assemblies of semiconductor lasers are characterized by low spatial beam quality with different radiation divergence at different axis, a wide divergence in the far field, and a multimode regime. This hampers their use significantly. One way to solve this problem is to develop new approaches to the formation of a semiconductor laser resonator that provide a large symmetrical region of emission from the chip surface. A resonator of this kind may be based on a two-dimensional (2D) photonic crystal (PC) formed in heterostructure layers. On the one hand, 2D periodicity of the refraction index provides distributed feedback, establishing resonator properties; on the other hand, it may provide surface emission output in the direction perpendicular to the heterostructure layers [5–8]. The mentioned studies were focused on the theoretical investigation of optical output losses for an infinite PC-based resonator as functions of the size of holes that form it. However, insufficient attention was paid to the influence of distributed feedback, which forms the resonator directly, and to the presence of parasitic optical losses that reduce the efficiency of lasing. The dependences of total optical losses of the resonator and parasitic lateral losses on the emitting aperture size were presented, but it remained unclear how these quantities depend on the size of holes in the case of a finite PC. The dependence of radiation localization in the PC center on the size of holes was not analyzed. In the present study, we calculate the electromagnetic field distribution in the region of emission from the chip surface for a PC-based resonator and demonstrate the mechanism behind parasitic losses in this resonator that limits the radiative efficiency of a laser.

Calculations for resonators based on finite-size PCs were carried out using a semi-analytical method that is based on the three-dimensional theory of coupled modes [5,9] and was discussed in detail in [10]. In accordance with Bloch's theorem, the field is represented in this method as a sum of waves, and periodic modulation of the refraction index in the PC layer is expanded into a Fourier series

$$E_i(\mathbf{r}) = \sum_{m,n} E_{i,m,n}(x,y)U(z) \times \exp\left[-i(m\beta_0 x + n\beta_0 y)\right], \quad i = x, y, \tag{1}$$

$$n^2(x,y) = n_{av}^2 + \sum_{m\neq 0, n\neq 0} \xi_{m,n} \exp\left[-i(m\beta_0 x + n\beta_0 y)\right]. \tag{2}$$

Here, $U(z)$ is the distribution of the electromagnetic field along the direction of heterostructure growth; $E_{i,m,n}(x,y)$ is the electromagnetic field amplitude in the PC plane with its dependence on coordinates (x,y) specified by the finite size of the PC and, consequently, the presence of boundary conditions; $\beta_0 = 2\pi/\Lambda$ is the component of the reciprocal PC lattice vector; Λ is the PC lattice period; m and n are arbitrary integer numbers; $n_{av} = \sqrt{n_{air}^2 f + n_{em}^2(1-f)}$ is the average PC refraction index, where $f = S_{air}/\Lambda^2$ is the fill factor that characterizes the size of holes, $n_{air} = 1$ is the refraction index of air, and n_{em} is the refraction index of the emitter in which the PC is formed; and $\xi_{m,n}$ are the Fourier expansion coefficients that differ from zero only in the PC layer and do not depend on variable z if the walls of holes are vertical. In the present study, we consider the TE polarization of field $\mathbf{E} = (E_x, E_y, 0)$.

Waves in the electromagnetic field decomposition may be divided into groups: basic waves $\sqrt{m^2+n^2} = 1$, higher-order waves $\sqrt{m^2+n^2} > 1$, and radiative waves $\sqrt{m^2+n^2} = 0$. Inserting expressions (1) and (2) into the wave equation and collecting terms with the same (m,n), we obtain a system of coupled equations for the amplitudes

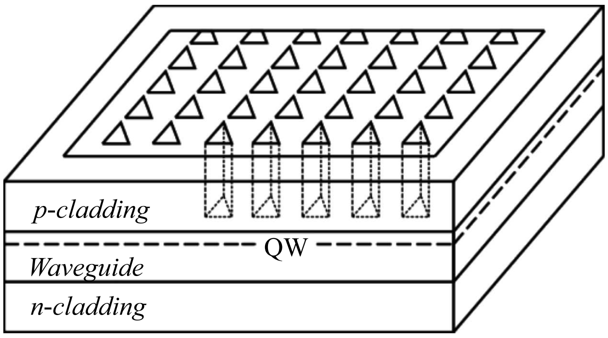

Figure 1. Schematic diagram of a semiconductor laser with a PC-based resonator.

Heterostructure design

Layer	Material	Refraction index n	Thickness d, nm
n-emitter	$Al_{0.35}Ga_{0.65}As$	3.347	1500
Waveguide layer	$Al_{0.15}Ga_{0.85}As$	3.432	250
Quantum well	$In_{0.21}Ga_{0.79}As$	3.560	9
Waveguide layer	$Al_{0.15}Ga_{0.85}As$	3.432	50
Residual p-emitter layer	$Al_{0.20}Ga_{0.80}As$	3.410	h
PC	$Al_{0.20}Ga_{0.80}As$/Air	n_{av}	1900

of basic waves $E_{(y,1,0)}$, $E_{(y,-1,0)}$, $E_{(x,0,1)}$, and $E_{(x,0,-1)}$ that have the distribution along axis z corresponding in shape to the fundamental waveguide mode. This system may be reduced to a differential matrix equation form (see [10] for details):

$$(\delta + i\alpha)\begin{pmatrix} E_{(y,1,0)} \\ E_{(y,-1,0)} \\ E_{(x,0,1)} \\ E_{(x,0,-1)} \end{pmatrix} = C\begin{pmatrix} E_{(y,1,0)} \\ E_{(y,-1,0)} \\ E_{(x,0,1)} \\ E_{(x,0,-1)} \end{pmatrix} + i\begin{pmatrix} \partial E_{(y,1,0)}/\partial x \\ -\partial E_{(y,-1,0)}/\partial x \\ \partial E_{(x,0,1)}/\partial y \\ -\partial E_{(x,0,-1)}/\partial y \end{pmatrix}, \quad (3)$$

where δ is the deviation of the radiation wave vector from the Bragg condition, α is the electromagnetic wave loss/gain, and C is the coupling matrix consisting of the coupling coefficients between waves in (1). The search for eigenvalues and eigenvectors was carried out using the numerical finite difference method on a staggered grid. This system is transformed into an $(\delta + i\alpha)$ eigenvalue and eigenvector problem of dimension $4K$, where K is the number of partition nodes.

Quantity α specifies the output losses in the laser resonator (in the approximation of zero internal optical losses). In the case of a finite-size PC, these losses may be divided into two groups: useful ones, which are associated with radiation output from the resonator through the crystal surface, and parasitic losses associated with the propagation (leakage) of electromagnetic radiation in the plane of heterostructure layers outside of the emission aperture. Thus, on the one hand, this quantity governs the magnitude of the threshold lasing gain; on the other hand, it does not characterize fully the radiative efficiency of a laser due to radiation output from the chip surface.

In the present study, the distribution of electromagnetic field intensity and output losses for a semiconductor laser resonator based on a PC were calculated. The laser was formed based on an AlGaAs/AlGaAs/InGaAs heterostructure with a three-layer optical waveguide. Holes forming a PC with square symmetry were etched in its top emitter (Fig. 1). A strained InGaAs quantum well, which served as a source of laser radiation with a wavelength of $\sim 1.045\,\mu$m, was formed in the waveguide. The heterostructure design is presented in the table. Thickness h of the residual p-emitter layer, which is the distance from the waveguide/p-emitter interface to the bottom of etched holes, was varied in calculations. The PC period was $\Lambda = 300$ nm, holes had the shape of a right triangle, and the emitting aperture size was $200 \times 200\,\mu$m.

One of the primary differences in optimization of the designs of infinite and finite PCs consists in the presence of parasitic lateral losses that affect the electromagnetic field distribution in the resonator. The fill factor of a finite PC was optimized in the present study. Varying the fill factor, we also change the effective refraction index in the PC layer, which affects the distributions of the waveguide mode and the Γ-factor of the PC ($\Gamma = \int_{\text{PhC}} |U(z)|^2 dz / \int_{-\infty}^{+\infty} |U(z)|^2 dz$, where the PhC region is the PC layer). To perform single-parameter optimization and find out how does the fill factor affect the distribution of useful and lateral losses, we fixed the Γ-factor value. With this aim in view, we performed a series of calculations for structures where the same Γ-factor was maintained in the PC layer by adjusting the residual p-emitter layer thickness. Increasing the fill factor, we brought the PC closer to the waveguide layer to keep the Γ-factor at a constant level of 1.5 %. To do this, we adjusted the value of h within the range of $0.78-0.05\,\mu$m and varied the fill factor from 5 to 30 %. The upper limit of 30 % is set by the process capabilities of lithography and etching of triangular-shaped holes.

Patterns of laser intensity distribution in the PC-based resonator were obtained for these designs (Fig. 2). From the calculations it is clear that for a small fill factor, most of the radiation intensity is concentrated at the boundaries of the PC region, which indicates that the distributed feedback does not work and the PC loses its resonator properties. An increase in fill factor leads to localization of laser radiation in the center of the aperture, and the distribution of the electromagnetic radiation intensity in the near field assumes the shape of a bell (Fig. 2, d).

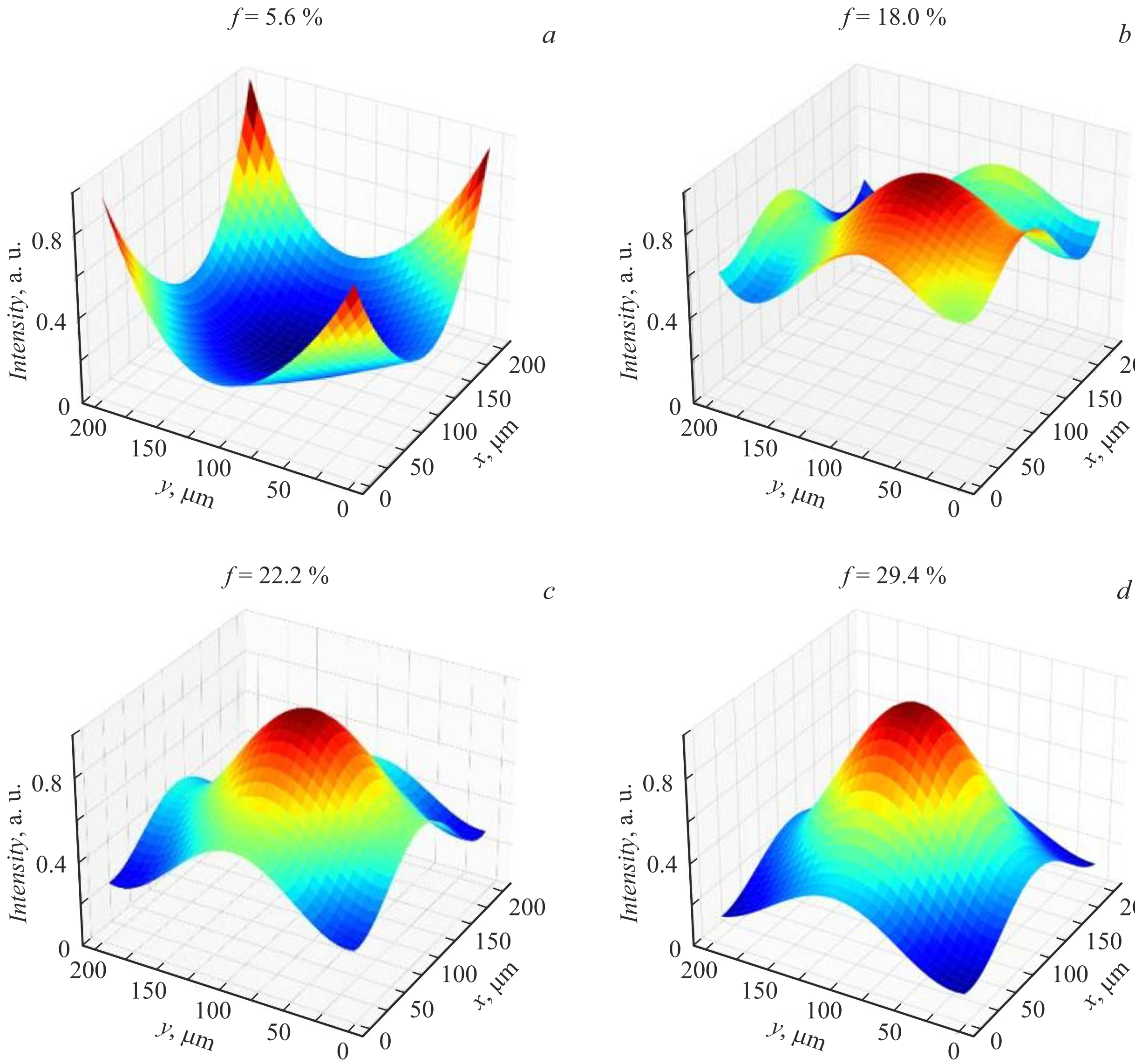

Figure 2. Patterns of laser intensity distribution in a PC-based resonator with different fill factors: 5.6 (*a*), 18 (*b*), 22.2 (*c*), and 29.4 % (*d*).

Calculations of total output losses revealed that their magnitude decreases with an increase in fill factor (Fig. 3, *a*), decrease the threshold conditions. This makes for a stark contrast with the infinite PC model, where the resonator output losses increase as holes grow in size [9]. In order to separate useful and parasitic losses, we calculated the relative power emitted from the chip surface (P_{rad}) and in the waveguide plane (P_{edge}) [10]. It turned out that P_{rad} increases monotonically with increasing fill factor, while P_{edge} decreases accordingly (Fig. 3, *b*). Thus, an increase in fill factor translates into a stronger distributed feedback and localization of laser radiation in the center of the emission aperture (provided that the shape of the waveguide mode is maintained). The reduction in total output losses with an increase in fill factor for the finite PC is associated precisely with this localization of laser radiation in the resonator. When the fill factor increases at a constant Γ-factor, the distributed feedback gets stronger, leading to an increase in radiative efficiency of the finite PC resonator, and this is fundamentally different from the model case of an infinite PC, for which there are no lateral losses.

The results of additional calculations for an overgrown PC located inside the waveguide layer, which allows for a significantly higher value of the Γ-factor, were similar. The reduction in optical output losses at high values of the fill factor for an infinite PC is associated precisely with a lower level of the average refraction index of the PC layer; however, in the case of a finite PC, parasitic lateral losses and the degree of localization of laser radiation in the resonator play a decisive role. As holes grow in size, total losses decrease due to a significant reduction in lateral losses, while useful losses associated with radiation output from the PC surface increase and the distribution of the electromagnetic field becomes localized in the center of the resonator.

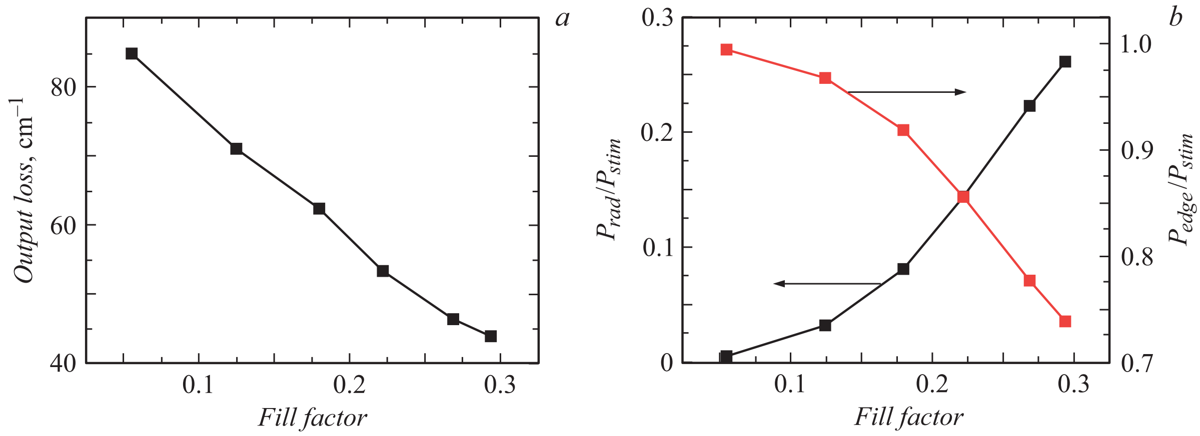

Figure 3. Dependences of the resonator output losses (a) and the relative power of emission from the chip surface and in the waveguide plane (b) on the PC fill factor.

Thus, when optimizing the design of a PC, one needs to take into account not only the influence of geometric parameters of holes on the value of total losses, but also their influence on the distribution of electromagnetic radiation in the waveguide and the ratio of lateral and vertical losses.

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Conflict of interest

The authors declare that they have no conflict of interest.

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