

Coupling of a microdisk laser to a photonic crystal waveguide

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The paper presents the model of a microdisk laser photonic crystal defect waveguide coupling system. Different finite dimensions of photonic crystals are taken into account. It is shown that coupling to a photonic crystal waveguide allows to increase the output power while maintain quality factor, which is not what a traditional coupling to a planar waveguide allows. The influence of the photonic crystal cavity modes coupling to the resonator mode on the efficiency of the power output is also pointed out.

Keywords: Microdisk laser, whispering gallery modes, photonic crystal, planar waveguide, photonic integrated circuit.

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Microlasers with disk and ring microresonators several tens of micrometers in diameter (microdisk lasers) that support whispering gallery modes (WGM) arouse interest in reseachers due to their small size, low threshold current (10 mA for a diameter of 30 μm), high performance (modulation frequency greater than 5 GHz) and ability to operate at high temperatures (up to 100 °C without cooling) [1]. On the other hand, photonic integrated circuits (PIC) draw attention of researchers and are supposed to be used for future computing machines, biosensors, etc. [2,3]. Either external lasers or stripe-contact lasers with a sufficiently long (compared with other PIC elements) resonator generally serve as light sources for the schemes of interest. Passive disc and ring resonators have been already used in the schemes of interest generally as filters [4]. Therefore, it is interesting to incorporate microdisk lasers directly into PIC, but this is, at first sight, hindered by their radiation isotropy resulting from their centrally-symmetric geometry. It is proposed to solve the radiation pattern problem through a modified resonator geometry: convex limaçon of Pascal, etc. [5,6], as well as disc microlaser arrays [7]. Modes of such resonators actually have a far-field pattern, however, they always contain a significant portion of radiation output in the reverse direction. In addition, in any case there is still a radiation divergence together with the problem of radiation routing in the scheme plane. Microlaser coupling with a planar waveguide is an alternative solution. In this case, there is a challenge of providing a sufficient coupling force while maintaining the resonator's Q factor, which requires a very small gap between the microdisk and waveguide (about 100–200 nm) [8]. However, the disc also emits radiation into a free space where it is not coupled with the waveguide, which represents a loss in terms of routing.

This study investigates a new technique of disc microlaser coupling with a surrounding PIC. For this, a photonic crystal (PC), a dielectric with periodic refractive index variation, is proposed [9]. Variation is generally provided either by

hole etching or by formation of mesas (pillars). Thus, a photonic band gap (PBG) is formed — a region of wavelengths, for which propagation of light through PC is impossible; the central PBG wavelength is on the order of two to three PC periods. The PBG width varies depending on a lattice configuration. Moreover, depending on light polarization, PBG can exist in different spectrum areas or can be absent for one of polarizations, allowing PBG to be used for microlaser mode filtering. Finally, a linear defect in PC is a waveguide, in which propagation of waves with a wavelength falling into PBG is allowed [10].

The paper describes simulation of disc microlaser coupling with such waveguide and comparison with a traditional planar waveguide coupling configuration. A model of properties of the selected PC and simulation of response of the microdisk–PC system with a waveguide to point excitation depending on a PC size are described first. Then this system is compared with a traditional microdisk-planar waveguide coupling scheme. For quantitative comparison of schemes, response intensity peak FWHM and a proportion of energy output into the waveguide are calculated. We demonstrate that a PC layer, whose size is close to the microdisk diameter, is sufficient for very efficient radiation output. Q factor of WGM is maintained and the loss is not greater than 5%.

A 2D finite element method implemented in COMSOL package was used for simulation. Resonator diameter was 4 μm , refractive index $n = 3.5$ as for GaAs at a wavelength of about 1 μm . Such resonator is chosen because microlasers with high density quantum dots for this wavelength have been studied for quite a long time [1], moreover, the obtained results can be easily scaled up to other ranges. For clarity, a smaller diameter than that generally used for experimental research was chosen to provide a sufficiently large mode spacing ($\Delta\lambda \approx \lambda^2/2\pi nR$ for WGM), not too high Q factor ($Q \propto \exp R/\lambda$) and sufficiently high radiation output loss.

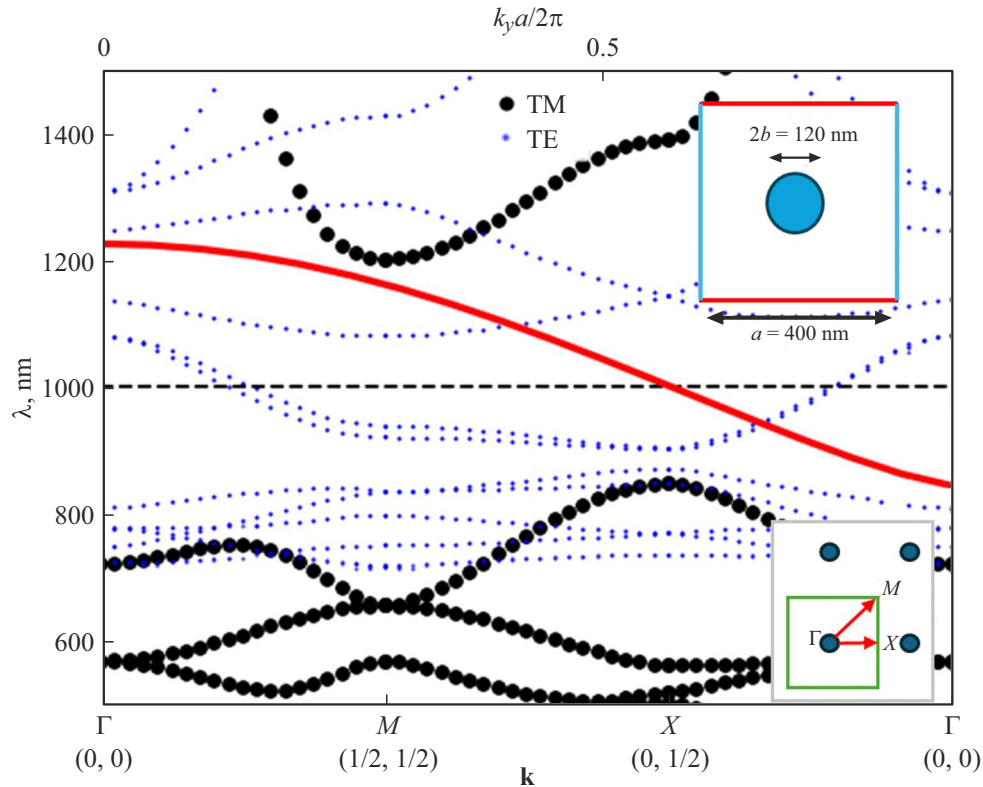


Figure 1. PC dispersion (lower axis, vector notations in PC reciprocal lattice vector units) for TM modes (circles) and TE modes (dots) near the $1\ \mu\text{m}$ wavelength and fundamental waveguide mode dispersion (solid line, upper axis, vector k_y is oriented along the waveguide). The upper inset shows a photonic crystal lattice cell, the lower inset shows a PC reciprocal lattice and Brillouin zone (green square) and high symmetry points. For a color version of the figure, see the online version of the paper.

A square lattice of cylindrical mesas with the same refractive index as that of the resonator was chosen for PC. Such lattice provides partial PBG (only for TM modes), allowing for investigation of modes with and without confinement in a single model. Note that there are PCs with a total PBG for all types of modes: for example, with a triangular lattice of cylindrical holes with a specified period or a hexagonal lattice of mesas (similar to a graphene lattice); a triangular lattice of mesas with a partial PBG can be also selected for TE modes [10]. Lattice parameters (length of a square lattice cell side $a = 400\ \text{nm}$ and radius of mesa $b = 60\ \text{nm}$) were selected so that a wavelength of $1\ \mu\text{m}$ falls within PBG for TM modes (modes whose electric field is perpendicular to the substrate plane). Waveguide is a PC without one row of mesas. As the PC itself, the waveguide provides confinement only for TM modes and its cutoff frequency is near the center of PBG. Dispersion of an infinite PC and dispersion of a fundamental waveguide mode are shown in Figure 1. The shown results were obtained by stipulating periodic boundary conditions with the Bloch vector $\mathbf{k}$ for each of the pairs of opposite lattice cell sides. The vector ran over a set of values in the first Brillouin zone with eigen energies calculated for each of the values. Waveguide mode dispersion was calculated in the same way, for this a lattice cell was chosen that consisted of 21 PC cells arranged in line with a mesa

removed in the central cell. A periodic boundary condition with the one-dimensional Bloch vector k_y now only links the fields on long faces, and the field on short faces is set to zero. Note that there is a certain region of possible lattice periods and mesa diameters, which contains a waveguide mode for this WGM. Thus, relative positions of the waveguide and resonator can be adjusted. For example, a microdisk diameter in the given model is exactly equal to ten PC periods, so that in a symmetric mesa arrangement a microdisk edge coincides with the center of the waveguide. By increasing the PC period a by 5%, we will still have a PC with a PBG containing a wavelength of $1\ \mu\text{m}$, however, the microdisk will account for 9.5 PC periods and its edge will now coincide with the wavelength edge. For effective output, it appears to be correct to couple the waveguide and microdisk in such a way that the spatial region of the WGM maximum approximately coincides with the waveguide mode maximum. Possibility of such adjustment is another benefit of the proposed structure: in case of traditional coupling, the waveguide cannot overlap the microresonator.

After calculating the PC and waveguide dispersion, microdisk eigen modes were determined. For further study, two WGMs of the first radial order with a wavelength of $1016.8\ \text{nm}$ for the TM mode and of $1018.1\ \text{nm}$ for the TE mode were chosen. PC–microdisk system response was

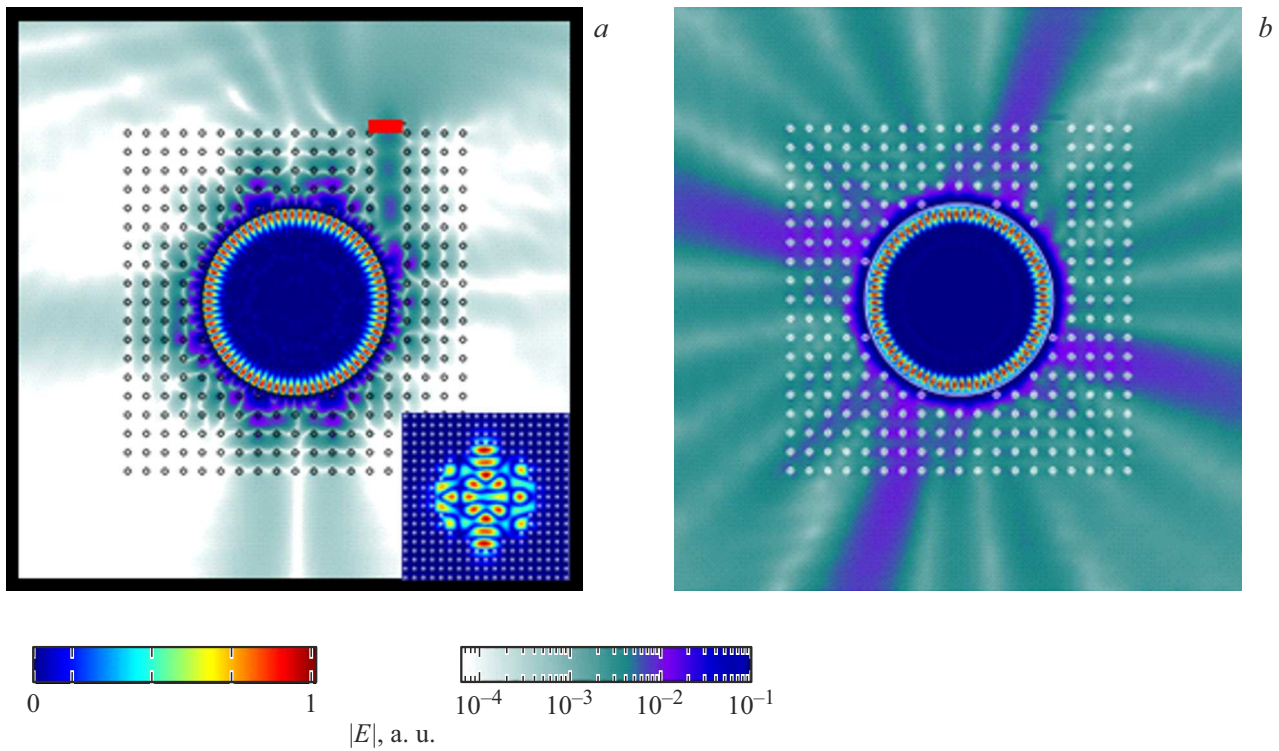


Figure 2. Distribution of the electric field modulus of the TM mode (*a*) and TE mode (*b*) in the microdisk resonator (linear scale) and in the surrounding area with the PC-based waveguide (logarithmic scale). The inset shows the response of a cavity produced in PC by the microdisk resonator to radiation-induced excitation at the WGM wavelength. Integration contour for determining the total energy flux Φ_0 is marked in black, energy flux through the waveguide Φ_{WG} is marked in red.

simulated as follows: a point dipole with a moment oriented perpendicularly (for the TM mode) or parallel (for the TE mode) to the substrate was positioned at a distance about 100 nm from the microdisk boundary, then a stationary solution to Maxwell's equations was sought for in a frequency-domain representation. System response was defined by the energy density integral of the electric field within the disc $W_{WGM} = \frac{1}{4\pi} \iint_{MD} \epsilon |E|^2 ds$ (where ϵ is the permittivity, E is the field strength), the output power was defined by the Poynting vector integral $\mathbf{S}$ across the waveguide width $\Phi_{WG} = \int_{WG} \mathbf{S} \cdot \mathbf{n} dl$, and the scattered power was defined by $\Phi_0 - \Phi_{WG}$ (where $\Phi_0 = \oint \mathbf{S} \cdot \mathbf{n} dl$ is the Poynting vector integral along the whole boundary). Electric field modulus distribution is shown in Figure 2, *a, b*, where integration regions are also shown. Note that the TM mode decays quickly within PC, but propagates in the waveguide, and the TE mode, on the contrary, is linked to the PC's TE mode and scattered when leaving the PC. When another PC lattice is selected, a reverse situation can be implemented: TM mode scattering and optical confinement of the TE mode.

For this, select, for example, a PC with a triangular lattice, which contains a band gap only for TE modes for the mesa radius ratio to the period $b/a \approx 0.4$ (see [10], Appendix C). It is important to note that an electric field decays much slower in specific directions. This is due to the interaction

between WGM and a cavity formed in the PC, which is occupied by the microresonator [10]. Such modes have a lower Q factor than WGM, therefore they are quite easily linked to WGM even with a noticeable wavelength offset. Inset in Figure 2, *a* shows the cavity response to similar excitation at the WGM frequency without a microresonator. Resultant field distribution is a linear combination of field distributions of several cavity's TM modes, the nearest of which are at 1009.3 nm and 1018.1 nm.

Interaction between WGM and cavity modes drives into using a larger PC to prevent release of the microdisk mode outside the waveguide confinement. The first simulation was performed for PC with four lattice periods of the lattice separating the microdisk from the free space, and the next simulation used ten periods, which provided a considerably better confinement as it follows from Figure 3, *a* and will be shown below. However, ten periods exactly meet the microdisk diameter; thus, an overall size of the whole system is only three times as much as the microdisk diameter.

To compare the proposed structure with the traditional coupling technique, a microdisk–planar waveguide system was also simulated, where the waveguide was made from the same material as the resonator (Figure 3, *b*), with a minimum gap between the disc and waveguide equal to 200 nm, and the waveguide width equal to 400 nm, which coincides with PC period and, consequently, with the

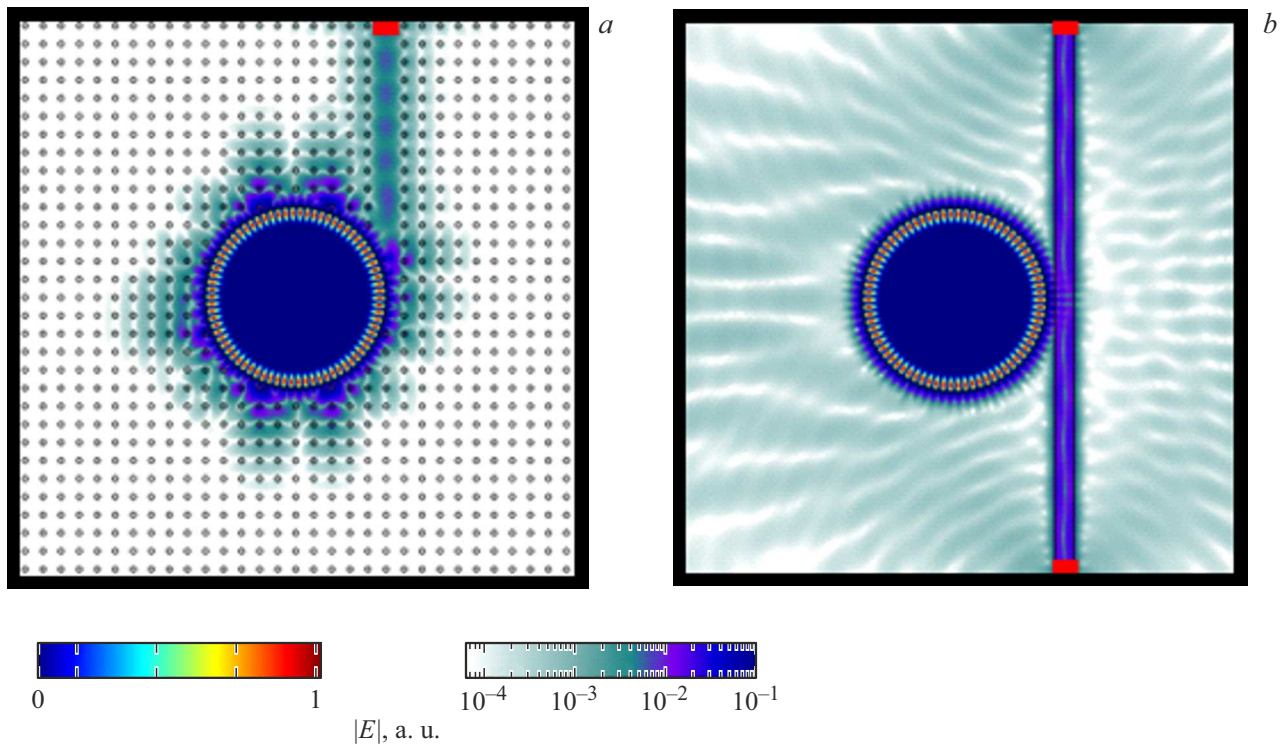


Figure 3. Electric field modulus distribution (TM polarization) in a structure with ten PC periods and a waveguide (a) and in a structure with a traditional planar waveguide (b). Designations of scale and contours are the same as in Figure 2.

waveguide width in it. Such parameters were chosen to ensure the same power output to the waveguide as that in the ten-period PC structure. Note that the planar waveguide is installed on both sides to avoid scattering at its end. There is no such problem in a scheme with PC because full optical confinement is provided at the waveguide end. Figure 3 suggests that PC provides considerable decay of electromagnetic radiation, while in a traditional scheme with a planar waveguide, radiation is scattered in space.

Figure 4 shows a comparison of responses of three radiation output schemes: the waveguide in a four-period PC (a „small“ scheme), the waveguide in a ten-period PC (a „large“ scheme) and the planar waveguide in free space (a „traditional“ scheme). Figure 4, a compares the integral energy of the mode's electric field W_{WGM} within the microdisk. As can be seen, a peak width in schemes with PC virtually coincides with a peak width for the free resonator, while a peak in the scheme with the planar waveguide broadens, which indicates that the mode Q factor decreases. However, strong interaction with the PC cavity mode (the nearest of which is on the long-wavelength side as specified above) leads to a long-wavelength shift of WGM by 74 pm (or about $7 \cdot 10^{-5} \lambda$) and to splitting at 8 pm. There is no shift for the traditional scheme.

Figure 4, b shows Φ_{WG} — the integral of energy flux (Poynting vector) through the waveguide cross-section. For the large and traditional schemes, values of Φ_{WG} are close to each other (divergence of about 20%) due to the gap

selected in the traditional scheme. The output energy can be obviously increased in the traditional scheme by reducing the gap, however, this will reduce the mode Q factor even more [8].

A reason why the Q factor is maintained in the PC schemes and reduced in the traditional scheme is clearly explained in Figure 4, c, which shows a scattered energy flux spectrum equal to the full (in all directions) energy flux Φ_0 less Φ_{WG} . It can be seen that the scattered energy for the traditional scheme is three times as high as that for the large scheme with PC and is close to that for the small scheme. However, the full energy flux in the small scheme is still smaller than in the traditional one and approximately coincides with that for the large scheme. Thus, there are two power output channels in the traditional scheme: via the waveguide and scattering into the free space. While the link with free space modes is stronger due to the fact that the free space fits tightly to the disc and also due to the presence of the waveguide that breaks the WGM symmetry. While the waveguide in the photonic crystal schemes is the only strong channel (stronger than in the large scheme) and the link with the free space modes (stronger in the small scheme) is suppressed by PBG.

Response peak FWHMs $\delta\lambda$ for all given models and corresponding Q factors calculated as $Q = \lambda/\delta\lambda$ as well as proportions of power output into the waveguide at the resonance wavelength are compared in the table. For the small scheme, the power output into the waveguide is lower.

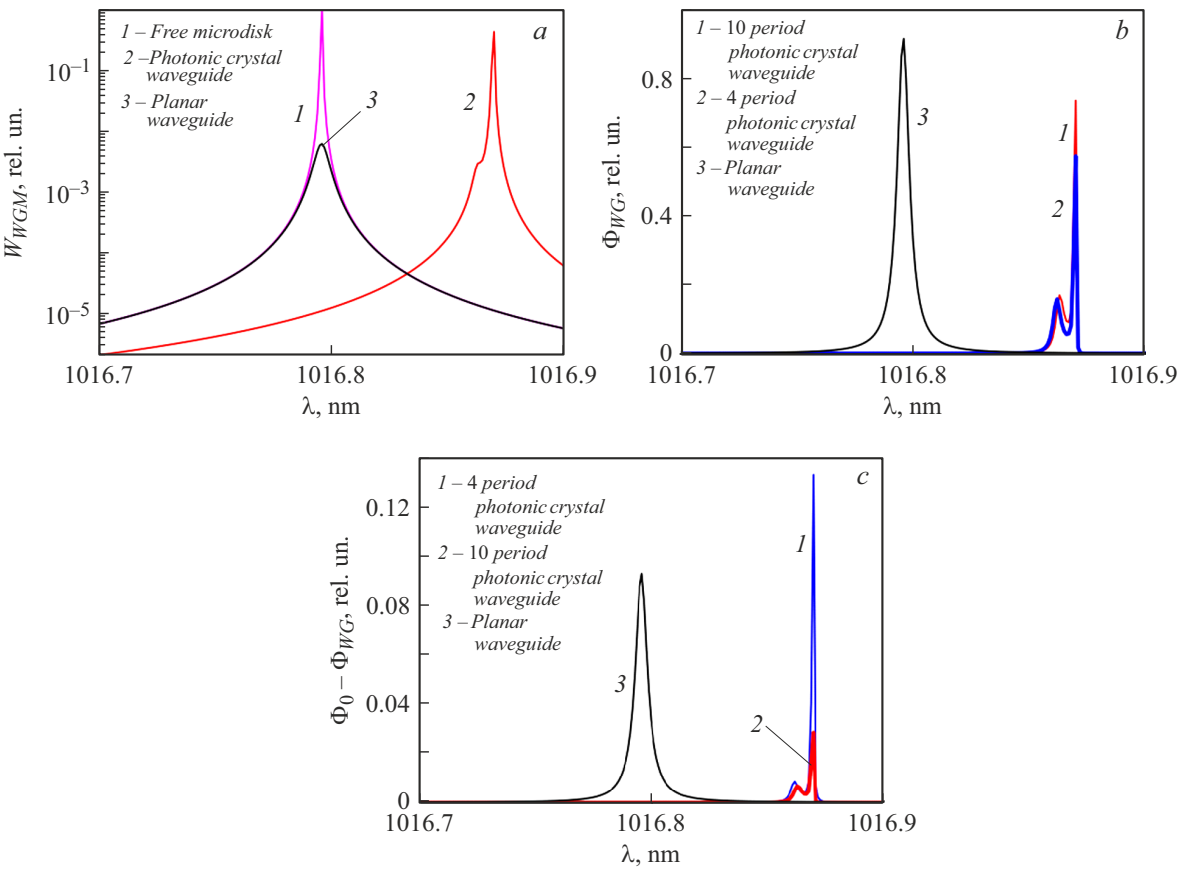


Figure 4. *a* — electric field energy within the microdisk (normalized to the maximum energy in the free microdisk); *b* — energy flux through the waveguide cross-section; *c* — scattering energy flux. Fluxes in parts *b* and *c* are normalized to the maximum full flux Φ_0 in the traditional scheme.

WGM properties in the studied coupling schemes (the full flux Φ_0 in the traditional scheme (at the WGM wavelength)) is taken as the relative flux unit

Model	FWHM peak $\delta\lambda$, pm	Q factor Q	Relative power flux in the waveguide Φ_{WG}	Relative power flux scatterd $\Phi_0 - \Phi_{WG}$	Proportion of power output into the waveguide Φ_{WG}/Φ_0 , %
Free microdisk	1.0	$9.4 \cdot 10^5$	—	—	—
Coupling with the planar waveguide	6.3	$1.6 \cdot 10^5$	0.91	0.09	91
Connection with the waveguide in the four-period PC	1.2	$8.5 \cdot 10^5$	0.57	0.13	81
Coupling with the waveguide in the ten-period PC	1.2	$8.3 \cdot 10^5$	0.73	0.03	96

This is due to a weaker link with the waveguide mode: the waveguide is very short in this scheme, which results in a nonuniform (along the y axis) field distribution in it and reduction of the overlap integral. Q factors for the small and large schemes virtually coincide due to the balance of scattering suppression and waveguide link (see above).

Thus, the work describes a technique for implementing directional output and routing of initially isotropic radiation of a microlaser with a disc resonator via a photonic crystal waveguide. It is shown that a photonic crystal with dimensions only three times as large as the microdisk diameter almost completely suppresses radiation scattering into the free space, and the waveguide arranged in the photonic crystal by means of removal of one period provides the power output. At the same time, there is no significant reduction of the microresonator mode Q factor. Confinement can be degraded in a smaller photonic crystal due to a link between the microresonator mode and the photonic crystal cavity mode.

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Conflict of interest

The authors declare that they have no conflict of interest.

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