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Simulation of light propagation in waveguides coupled to hexagonal microcavities formed in the GaAs-based photonic crystal

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Abstract. This paper presents the results of numerical simulation of the light-matter interaction in the GaAs-based photonic crystal (PhC). The study focuses on the coupled configurations of waveguides and hexagonal microcavities operating at a wavelength of 1.3 μm. A systematic investigation is conducted into the influence of the diameter of microcavity, its distance from the waveguide and the defect configuration on the distribution of the electric field strength within the PhC structure. It is shown that a spacing of 2 rows between the waveguide and 1.65-μm-diameter cavity allows achieving maximum electric field strength within the cavity. An introduction of a defect into the waveguide leads to a further increase in the electric field strength in the cavity, with an optimal radius of 209 nm.

Keywords: photonic crystal, waveguide, microcavity, GaAs

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Материалы конференции
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Моделирование распространения света в волноводах, связанных с гексагональными микрополостями, сформированными в фотонном кристалле на основе GaAs

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Аннотация. В данной работе представлены результаты численного моделирования взаимодействия света с веществом в фотонном кристалле (ФК) на основе GaAs. Исследование посвящено связанным конфигурациям волноводов и гексагональных микрополостей, функционирующих на длине волны 1,3 мкм. Проводится систематическое исследование влияния диаметра микрополости, ее расстояния от волновода и конфигурации дефекта на распределение напряженности электрического поля в пределах структуры ФК. Показано, что расстояние в 2 ряда между волноводом и полостью с диаметром 1,65 мкм позволяет достичь максимальной напряженности электрического поля в пределах полости. Внедрение дефекта в волновод приводит к дальнейшему увеличению напряженности электрического поля в полости при оптимальном радиусе 209 нм.

Ключевые слова: фотонный кристалл, волновод, микрополость, GaAs

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Introduction

Photonic crystals (PhCs) are a class of optical materials characterized by a periodic modulation of the permittivity in space. When the period of this modulation is comparable to the wavelength of light, it leads to the formation of a complete or partial photonic bandgap (PBG) in the spectrum of electromagnetic states of the material [1]. Due to these unique optical properties, PhCs are considered a promising platform for the development of large-scale optical integrated circuits.

PhCs offer a wide range of potential applications in both fundamental research and applied fields [2–5]. In particular, there are a number of works devoted to the application of waveguide-cavity configurations, such as a pressure sensor based on two-dimensional (2D) PhC structures, which operates by detecting the shift in the resonant wavelength in response to applied pressure [6]. Another work is also of interest, where the novel design of a microring resonator based on a subwavelength grating was presented. The sensitivity acquired in this paper is the highest compared to the previously reported values in the literature [7]. Although the above papers confirm the relevance of PhCs in modern photonics, specific configurations of the waveguide-microcavity systems are yet to be optimized.

In the present study, simulation of light-matter interaction in PhCs containing coupling configurations of waveguides and hexagonal microcavities is carried out. The target wavelength is chosen to be 1.3 μm, which is dictated by its location within the second transparency window of optical fiber, characterized by low attenuation and zero dispersion [8].

Materials and methods

This study focuses on a 2D PhC formed by a hexagonal lattice of air holes embedded within a GaAs matrix. The geometric parameters of the structure were optimized for a wavelength of 1.3 μm: the radius of the air holes and the lattice period were set to 209 and 520 nm, respectively. This selection of parameters ensured that the radiation fell within the complete photonic bandgap of the PhC, applicable to both transverse electric (TE) and transverse magnetic modes. Repositioning of holes within the PhC structure allowed for the design of diverse configurations, including hexagonal cavities coupled to waveguides.

The simulation was carried out in the Comsol Multiphysics 6.1 software package. For the analysis of TE-wave propagation through the PhC, a scalar equation for the transverse component of the electric field (EF) was employed:

$$-\nabla \cdot \nabla E_z - n^2 k_0^2 E_z = 0, \quad (1)$$

where n is the refractive index and k_0 is the free-space wave number.

Results and discussion

Fig. 1 presents the results of numerical simulations of a structure comprising a waveguide and a hexagonal cavity with a diameter (*d*) of 1.65 μm and discretely varying separation between them (*L*). The distance between the waveguide and the cavity varies in increments corresponding to one row of air holes of the PhC.

While Fig. 1, *a*, *b* demonstrates blurred patterns of the EF strength distribution within the cavity, pronounced hexapole modes are observed in Fig. 1, *c*, implying that this waveguide-microcavity configuration is optimal for $d = 1.65$ *μm*. A dip (for the waveguide) and a peak (for the cavity) in the dependences in Fig. 2, *a*, *b* indicate that a significant portion of the radiation from the waveguide is transferred to the microcavity, which is also seen in Fig. 1, *c*. The optimal values of the PhC parameters are marked with green circles in figure 2. Therefore, the waveguide must be positioned two rows from the microcavity to achieve maximum efficiency of the system.

a) *b*) *c*)

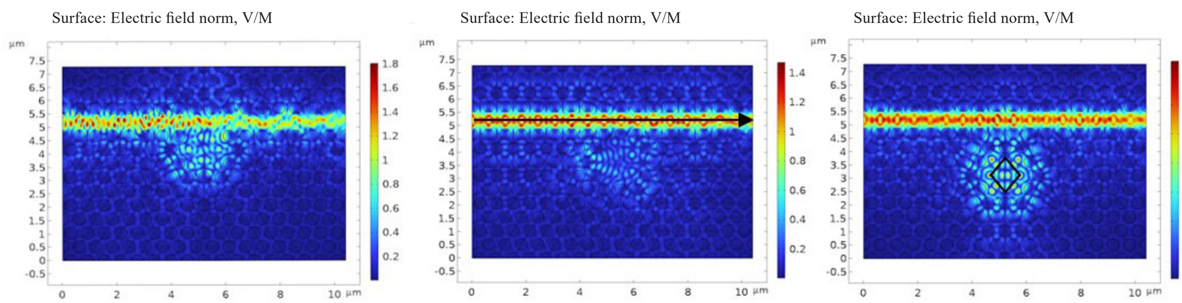

Fig. 1. Distribution of the EF strength in the PhC with a different separation between the waveguide and the cavity ($d = 1.65$ μm): (*a*) $L = 0$; (*b*) $L = 1$; (*c*) $L = 2$. The arrow in Fig. 1, *b* and the rhombus in Fig. 1, *c* indicate a line along which the integrated EF strength was measured

It should be noted that the structure with a microcavity located without a spacing from the waveguide (Fig. 1, *a*) has an even lower integrated EF strength along the waveguide. However, this configuration cannot be considered optimal because increased losses in such a microcavity can lead to a decrease in the quality factor of the hexagonal resonator. Fig. 2, *a* also demonstrates that the structures with $d = 2.69$ μm are optimal when the microcavity is located 1 row from the waveguide. In this case, hexapole modes are also observed in the microcavity, implying that it can operate as a high-quality resonator.

a) *b*) *c*)

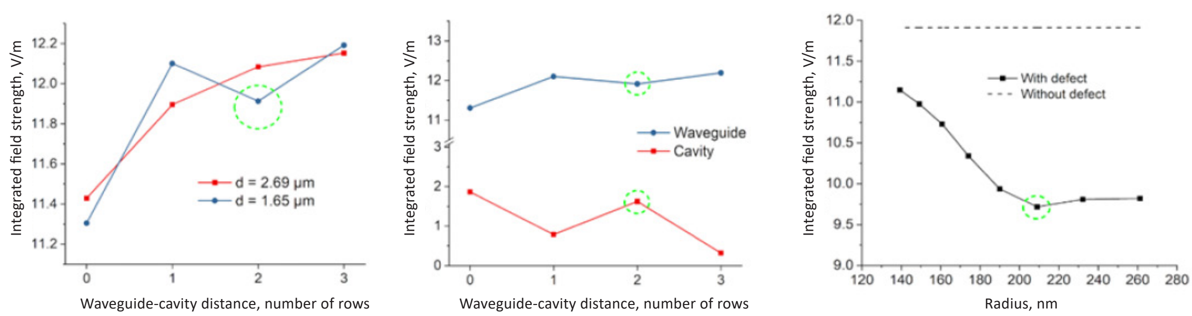

Fig. 2. Dependences of the integrated EF strength along the waveguide (*a*) and within the cavity with a diameter *d* (*b*) on the number of rows of air holes *L* and along the waveguide on the radius of defect in the waveguide (*c*)

In order to improve the penetration of radiation from the waveguide into the hexagonal cavity, a defect was introduced at a distance of 5.2 μm from the left edge of the waveguide (light input). Fig. 3 presents the results of numerical simulations of a structure comprising the hexagonal

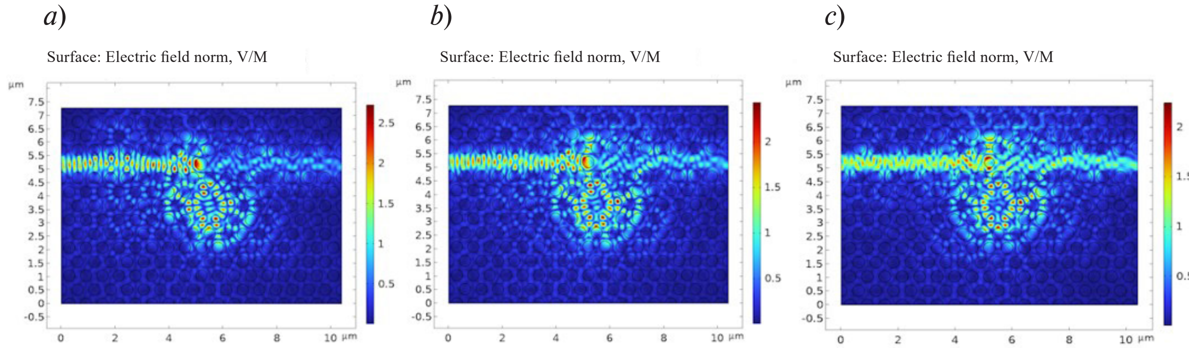

Fig. 3. Distribution of the EF strength in the waveguide-microcavity structure with a defect radius of 232 nm (*a*), 209 nm (*b*) and 174 nm (*c*) obtained as a result of the simulation

cavity located at $L = 1$ from the waveguide with a defect with different radii. Fig. 2, *c* demonstrates a dependence of the integrated EF strength along the waveguide on the defect radius. The results presented suggest that the introduction of the defect allows a reduction of the integrated EF strength along the waveguide. As the defect radius increases, the integrated EF strength along the waveguide decreases until the radius reaches a value of 209 nm. A further increase in the defect radius leads to an increase in the EF strength. This effect indicates that at a defect radius of 209 nm (equal to the pillar radius in the periodic PhC structure), the maximum portion of light from the waveguide is introduced into the hexagonal cavity, which corresponds to Fig. 3, *b*.

Conclusion

The presented work is dedicated to the numerical simulation of the interaction of light with GaAs-based PhCs containing a hexagonal microcavity coupled to a waveguide and operating at a wavelength of 1.3 μm. It is shown that the optimal configuration providing efficient input of light into the hexagonal microcavity is a structure with a 1.65- and 2.69-μm-diameter cavity located 2 and 1 row of air holes from the waveguide, respectively. A structure with a defect having a radius of 209 nm allows further enhancing of the PhC characteristics. The results obtained can be applied in the development of compact optical devices such as optical modulators and switches.

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