DEFECT MODES IN REAL PHOTONIC CRYSTALS

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Abstract: It is demonstrated experimentally that amplitudes of defect modes of one-dimensional photonic crystal have maximal value near edges of the photonic band gap while at the centre of the stop-band they are reduced, moreover than more number of layers in photonic crystal, the less the amplitude of defect mode at the center of the PBG. We explain such behavior of defect modes presence of losses at propagation of light in real photonic crystal structures.
Keywords: photonic crystal, defect mode, photonic band gap, liquid crystal

One-dimensional photonic crystals (PCs) represent multilayer periodic structures consisting of alternating layers of two dielectric materials with different refractive indices (multilayered thin-film structures) [1, 2]. In contrast to three-dimensional PCs, they do not have a complete PBG; however, they attract considerable interest in view of their multifunctionality. The production technique of such structures for the optical range is well developed [2]. Multilayered thin-film structures have long been investigated and widely used as interference filters, light polarizer's, multilayer dielectric Bragg reflectors, and antireflecting coatings [3]. At present, multilayer periodic structures are investigated within the concept of PCs. This approach provides a new insight into the optical properties of such structures and allows one to increase their applicability, including the applications to the observation of new physical effects and phenomena. The big interest represents PCs with micro-or nanodefects which can be considered as micro-and nanocavity [4, 5].

In this paper we study experimentally and theoretically some features of defect modes (DMs) in one-dimensional PCs. The structure of PC under investigations is expressed as $(HL)^N H(D)H(LH)^N$. Here, H and L are optically isotropic dielectric layers with high and low refractive indices n_1 and n_2 and thicknesses t_1 and t_2, respectively; the period of the lattice is $t = t_1 + t_2$; D is the defect layer with refractive index n_d and thickness t_d; N is the number of bait-layers HL and LH (the number of periods). The defect layer is filled with an air or a 4-n-pentyl-4'-cyanobiphenyl (5CB) planarly oriented nematic liquid crystal (LC). Investigated PC represented the structure consisting of two identical mirrors are assembled into a sandwichlike plane-parallel cell and are placed in a temperature-controlled chamber. The gap between the mirrors (the thickness of the defect layer) is specified by teflon spacers. Each mirror consists of $N+1$ layers of zirconium dioxide with the refractive index of n_1=2.04 and N layers of silicondioxide with the refractive index of n_2=1.45, which were deposited by turns on the surface of a glass substrate. The values of the refractive indices $n_{1,2}$ (and of the liquid crystal n_{LC} below) correspond to a wavelength of λ=589 nm.

Figure 1 represents the transmission spectra for two PCs with the air defect layer recorded under the normal incidence of light. Fig. 1a corresponds to the first sample, which has the following parameters: t_1=55 nm, t_2=102 nm, and N=10; Fig. 1b corresponds to the second sample, which has the parameters t_1=52nm, t_2=102 nm and N=5. In both cases these parameters allow one to form photonic band gaps in the visible spectrum with defect modes whose amplitudes, number, and position depend on the thickness and the refractive index of the defect layer, the number of layers in the multilayer mirrors, and the losses in the mirrors. Note that the defect modes attain their maximal amplitude near the edges of the band gap. The increase of the number of layers in the mirrors leads to the decrease of the optical transmission in the PBG.

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The similar result takes place in a case when the defect layer is filled with the liquid crystal (Fig. 2).

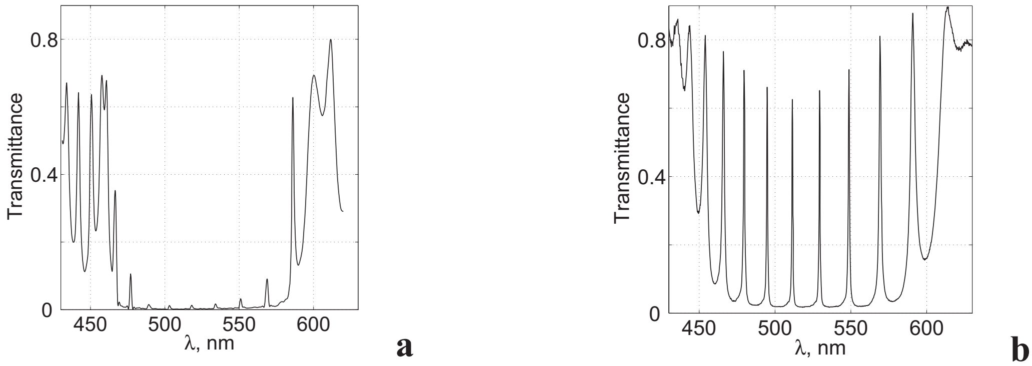

Fig.1. The transmission spectrum of the photonic crystal with air defect layer. **a**) The number of bi-layers in the mirror N=10, t_d=2.5 mkm; **b**) N=5, t_d=2.3 mkm.

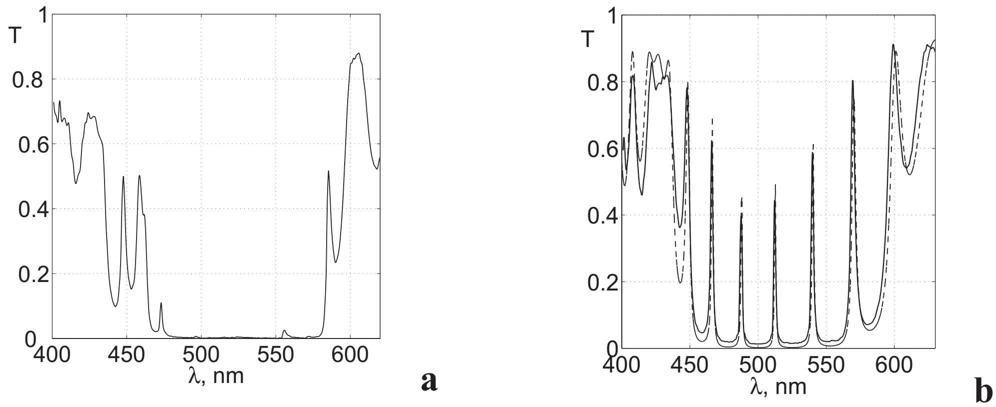

Fig. 2. Transmission spectra of a PC with an LC (5CB) defect layer: (a) N = 10 and (b) N = 5; the solid line represents the experimental data and the dashed line, the results of calculations

The behavior of defect modes in Fig. 1 and 2 can be qualitatively understood by using the analogy with a Fabry–Perot interferometer (FPI). It is well known that the transmission of an interferometer depends substantially on the transmittance T_m (reflectivity R_m) and the loss factor A_m of the mirrors [6]. The coefficients T_m, A_m, and R_m depend on the wavelength of light and $R_m+T_m+A_m=1$. In the case of identical mirrors, the transmittance of FPI is $T = 1/(1 + A_m / T_m)^2 < 1$ on resonance frequency. The parameter A_m strongly influences at the transmittance T of the interferometer. In the absence of losses (A_m=0), T =1 at the transmission maximum for all modes of the resonator. Due to the losses (A_m> 0), T decreases. At the center of the band gap, where T_m is less than at the edges, the transmittance of the interferometer attains its minimal value, while the reflectivity attains its maximal value. In this case the larger the number of layers in the mirrors, the smaller the transmittance T. Thus, losses in PC structures may significantly reduce the amplitudes of defect modes. In real PCs, losses may be caused by various factors. The most important role is played by the roughness of the interface between layers; nonparallelism and irregularity of layers (fluctuations of the layer thickness), which lead to the scattering of light; nonresonant absorption in the layers; and other factors. These factors may be crucial for the determination of the spectral properties of defect modes in PCs.

We have calculated the transmission spectrum of PC, using a method of recurrent relations [7], which allows us to easily take into account losses in the PC by introducing complex refractive indices in each layer. The values of the imaginary parts of the refractive indices (or the extinction coefficients) can be chosen by comparing experimental data with the results of calculations. Figure 2b shows the calculated and experimental transmission spectra of PC with LC defect layer. Good agreement between the calculated and experimental spectra is obtained for the values $\mathrm{Im}(n_{1,2})=2\ 10^{-3}$ and $\mathrm{Im}(n_{LC})=1.5\ 10^{-4}$.

We also investigated the transmission spectra of PC for different angles of incidence of light on the crystal. Figure 3 shows, as an example, the transmission spectra of the PC for TM (Fig. 3a) and TE (Fig 3b) polarizations of light as a function of the tilt angle θ of incident radiation.

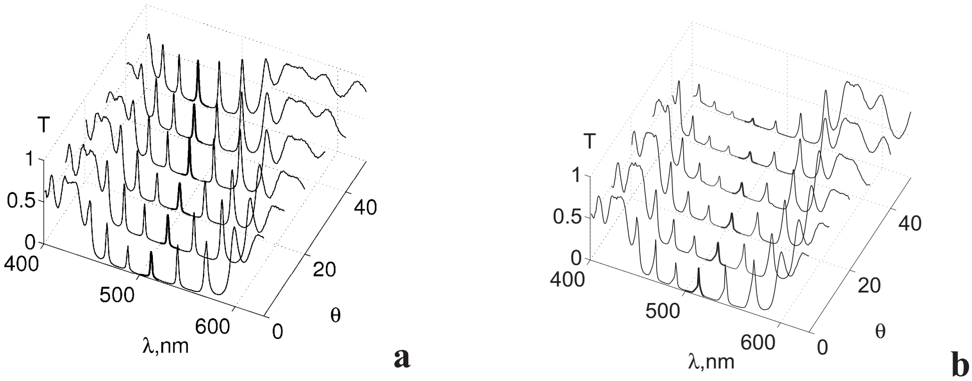

Fig. 3. Transmission spectra of a PC with a planarly oriented layer of 5CB nematic LC for various angles of incidence θ for (**a**) TM- (*XX*-) and (**b**)

In conclusion, we have established experimentally that defect modes attain their maximal amplitude near the edges of the band gap, while at the center of the stop band the optical transmission in the defect modes decreases.

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