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CONDENSED-MATTER SPECTROSCOPY

Control of the Transmission Spectrum of a Photonic Crystal with Lattice Defects

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Abstract—The transmission spectrum of a one-dimensional photonic crystal with structural defects is investigated. An anisotropic layer of a nematic liquid crystal is considered as a defect. The possibility of effective external control of the transmission spectrum of the photonic crystal by changing either the orientational state of the defect liquid crystal layer (for example, using an electric field) or the angle of incidence of light is shown. It is established that the spectral properties of the photonic crystal change radically with a change in the optical characteristics of the defect layer in the vicinity of the temperature phase transition of the nematic liquid crystal to the isotropic state.

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INTRODUCTION

Interest in photonic crystals [1] (structures with a periodic change in the dielectric properties on a spatial scale of the same order of magnitude as the optical wavelength) is related to the prospects for their practical use and the possibility of observing various physical phenomena with their help. A new electromagnetic effect can be realized by introducing defects into a photonic crystal. This is the phenomenon of light localization in defect modes with discrete frequencies lying in the band gaps of the unperturbed photonic crystal [1–5]. Defect modes can be used to design narrowband filters [6] and low-threshold lasers [7], develop information and communication technologies [8–12], and increase the efficiency of nonlinear optical interactions [13, 14]. For many practical applications, it is expedient to have the possibility of restructuring the photonic gap structure by electro- and thermo-optical effects. This possibility may provide flexible control of signal routing through an optical communication network. The spectra of photonic crystals can be modified by controlling the anisotropy of electro-optical materials. It is well known that liquid crystals (LCs) are characterized by high sensitivity to external fields and a strong anisotropy of permittivity.

The transmission spectrum of a one-dimensional (1D) photonic crystal with lattice defects was investigated in [15]. An anisotropic layer of a nematic LC (NLC) was considered as a defect. Taking into account the NLC specificity, it was shown that the transmission spectrum of a photonic crystal can be effectively controlled by changing the orientation of the nematic director using, for example, an external electric field. The transmission spectrum was studied for the case of normal incidence of light on the sample at a planar or homeotropic orientation of the nematic director. The dependence of the transmission spectra of the photonic crystal on the thickness of the defect layer and its position in the sample and on the number of layers of the photonic crystal structure was also studied.

In this paper, we report the results of a theoretical investigation of the specific features of the transmission spectrum of a 1D photonic crystal with lattice defects recorded at oblique incidence of light on the sample with continuous variation in the orientation of the NLC director from homeotropic to planar. The modification of the transmission spectrum of the photonic crystal with a change in the LC dielectric characteristics under the action of temperature fields, especially in the vicinity of the phase transition from the nematic to the isotropic phase (where the refractive index is rather sensitive to variations in temperature), was also studied.

TRANSMISSION SPECTRA

The photonic crystal structure considered by us consists of alternating layers of two materials with a structural defect (Fig. 1).

An NLC layer (denoted as d) with a thickness W_d was chosen to be the defect layer. θ is the angle between the nematic director and the z axis. The NLC layer is embedded between two superlattices with a unit cell composed of materials a and b with the layer thicknesses W_a and W_b, respectively. The structure under

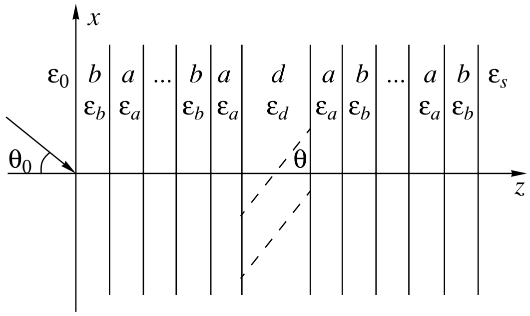

Fig. 1. Structure of a one-dimensional photonic crystal with a lattice defect.

consideration is characterized by the permittivities ε_a and ε_b of layers a and b, respectively, and the permittivity tensor of the NLC layer

$$\hat{\varepsilon} = \begin{bmatrix} \varepsilon_\perp \cos^2\theta + \varepsilon_\parallel \sin^2\theta & 0 & \frac{1}{2}\sin 2\theta \Delta\varepsilon \\ 0 & \varepsilon_\perp & 0 \\ \frac{1}{2}\sin 2\theta \Delta\varepsilon & 0 & \varepsilon_\perp \sin^2\theta + \varepsilon_\parallel \cos^2\theta \end{bmatrix}, \quad (1)$$

where $\varepsilon_\perp = \varepsilon_{xx} = \varepsilon_{yy}$ and $\varepsilon_\parallel = \varepsilon_{zz}$ are the components of the dielectric tensor in the principal axes and $\Delta\varepsilon = \varepsilon_\parallel - \varepsilon_\perp$. The Maxwell equations for the case of an anisotropic defect layer in a photonic crystal on the class of H-type fields with a frequency ω

$$\{E_x, E_z, H_y\} = \{E_x(z), E_z(z), H_y(z)\}e^{i(kx - \omega t)} \quad (2)$$

with the propagation constant $k = k_x$ have the form

$$\left[\frac{d^2}{dz^2} + 2ik\frac{\varepsilon_{xz}}{\varepsilon_{zz}}\frac{d}{dz} - \beta\left(k^2 - \frac{\varepsilon_d\omega^2}{\beta c^2}\right)\right]E_x = 0, \quad (3)$$

where $\beta = \beta_{xx}/\varepsilon_{zz}$,

$$\varepsilon_d = (\varepsilon_{xx}\varepsilon_{zz} - \varepsilon_{xz}^2)/\varepsilon_{zz} = \varepsilon_\perp\varepsilon_\parallel/(\varepsilon_\perp \sin^2\theta + \varepsilon_\parallel \cos^2\theta), \quad (4)$$

$$H_y = -\frac{ic}{\omega}\left(\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x}\right), \quad (5)$$

$$E_z = \frac{1}{\left(k^2 - \frac{\omega^2}{c^2}\varepsilon_{zz}\right)}\left[\frac{\omega^2}{c^2}\varepsilon_{zx}E_x - ik\frac{dE_x}{dz}\right]. \quad (6)$$

The Maxwell equations for the case of isotropic layers in a photonic crystal are derived from (3)–(6) using the replacements $\varepsilon_{xx}, \varepsilon_{zz} \longrightarrow \varepsilon_a$ or $\varepsilon_{xx}, \varepsilon_{zz} \longrightarrow \varepsilon_b$ at $\varepsilon_{xz} = 0$. We will investigate the transmission spectrum of the photonic crystal with lattice defects as in [15], using the transfer matrix method. Let the layer permittivities have the form

$$\varepsilon = \begin{cases} \varepsilon(0) = \varepsilon_0, & z < z_0, \\ \varepsilon(1) = \varepsilon_b, & z_0 < z < z_1, \\ \varepsilon(2) = \varepsilon_a, & z_1 < z < z_2, \\ \dots \\ \varepsilon(l_1) = \varepsilon_d, & z_{l_1 - 1} < z < z_{l_1}, \\ \dots \\ \varepsilon(N) = \varepsilon_b, & z_{N-1} < z < z_N, \\ \varepsilon_s = 1, & z > z_N. \end{cases} \quad (7)$$

For the structure under consideration, the distribution of the electric field in the layers can be written as

$$\begin{aligned} E_x(n, t) &= A(n)\exp[i\alpha(n)(z - z_n) - i\omega t] \\ &+ B(n)\exp[-i\alpha_1(n)(z - z_n) - i\omega t], \end{aligned} \quad (8)$$

where $A(n)$ and $B(n)$ are, respectively, the amplitudes of the incident and the reflected waves in the nth layer,

$$\alpha(l) = -k\frac{\varepsilon_{xz}}{\varepsilon_{zz}} + \sqrt{\varepsilon_d\left(\frac{\omega^2}{c^2} - \frac{k^2}{\varepsilon_{zz}}\right)}, \quad (9)$$

$$\alpha_1(l) = k\frac{\varepsilon_{xz}}{\varepsilon_{zz}} + \sqrt{\varepsilon_d\left(\frac{\omega^2}{c^2} - \frac{k^2}{\varepsilon_{zz}}\right)},$$

$$k = \frac{\omega}{c}n_0 \sin\theta_0. \quad (10)$$

The magnetic field distribution in the layers is given by the expression

$$\begin{aligned} H_y(n, t) &= \{q(n)A(n)\exp[i\alpha(n)(z - z_n) - i\omega t] \\ &- q(n)B(n)\exp[-i\alpha_1(n)(z - z_n) - i\omega t]\}, \end{aligned} \quad (11)$$

where $q(n) = [\varepsilon_d\varepsilon_{zz}(n)/(\varepsilon_{zz}(n) - n_0^2 \sin^2\theta_0)]^{1/2}$ and θ_0 is the angle of incidence of light on the sample from the medium characterized by the refractive index $n_0 = \sqrt{\varepsilon_0}$.

According to the boundary conditions, the tangential components of **E** and **H** must be continuous at the boundary. The continuity of E_x and H_y at the interfaces $z = z_{n-1}$ between the media yields a system of equations, which can be represented as the matrix equation

$$\begin{pmatrix} A(n-1) \\ B(n-1) \end{pmatrix} = T_{n-1,n}\begin{pmatrix} A(n) \\ B(n) \end{pmatrix}. \quad (12)$$

Here, the transfer matrix $T_{n-1,n}$ has the form

$$T_{n-1,n} = D^{-1}(n-1)D(n)P(n). \quad (13)$$

For an anisotropic layer,

$$D(n) = \begin{pmatrix} 1 & 1 \\ q(n) & -q(n) \end{pmatrix}, \tag{14}$$

$$P(n) = \begin{pmatrix} e^{-i\alpha(n)\gamma(n)} & 0 \\ 0 & e^{i\alpha_1(n)\gamma(n)} \end{pmatrix}, \tag{15}$$

$\gamma_n = z_n - z_{n-1}$; and $n = 1, 2 \ldots N$. It follows from (12) that the amplitudes $A(0)$ and $B(0)$ are related to $A(s)$ and $B(s)$ as

$$\begin{pmatrix} A(0) \\ B(0) \end{pmatrix} = \hat{M}\begin{pmatrix} A(s) \\ B(s) \end{pmatrix}, \tag{16}$$

where

$$\hat{M} = \hat{T}_{01}\hat{T}_{12}\ldots\hat{T}_{N-1,N}\hat{T}_{N,s}, \tag{17}$$

$s = N + 1$, and $\gamma_{N+1} = 0$. When the reflection of electromagnetic waves from the right side of the photonic crystal sample is absent, the reflectance $\rho(\omega)$ is determined by the expression

$$\rho(\omega) = \left|\left(\frac{B(0)}{A(0)}\right)_{B(s)=0}\right|^2. \tag{18}$$

Using (16), we obtain

$$\rho(\omega) = \left|\frac{\hat{M}_{21}}{\hat{M}_{11}}\right|^2, \tag{19}$$

where $\hat{M}_{21}$, and $\hat{M}_{11}$ are elements of the matrix $\hat{M}$.

Obviously, the transmittance is determined by the expression

$$\tau(\omega) = 1 - \left|\frac{\hat{M}_{21}}{\hat{M}_{11}}\right|^2. \tag{20}$$

RESULTS AND DISCUSSION

Let us investigate the specific features of the transmission spectrum of the photonic crystal with structural defects by numerical solution of the equation obtained for the transmittance (20). The calculation will be performed for a photonic crystal with a number of layers $N = 85$, including the defect layer located at the center of the layered medium. In addition, we assume below that the layer thicknesses are $W_a = W_b = 1$ µm; the permittivities are $\varepsilon_a = 4$, $\varepsilon_b = 2.25$, and $\varepsilon_0 = 1$, respectively; and the defect layer thickness $W_d = 5.2$ µm. We will investigate primarily the frequency dependence of the photonic crystal transmittance within the second band gap of an ideal photonic crystal for different orientations of the nematic director.

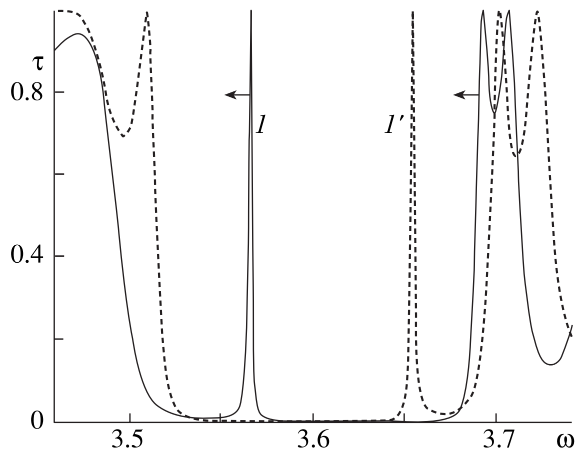

Fig. 2. Frequency dependences of the transmittance of the photonic crystal at different angles θ of orientation of the nematic director. The angle of incidence $\theta_0 = 0$. The curves of defect modes *1* and *1'* are given for the values $n_d(0) = n_\perp = 1.5$ and $n_d(\pi/2) = n_\parallel = 1.665$, respectively; ω is in units of c/W. The arrows indicate the direction of shift of the dashed curve with increasing θ from 0 to π/2.

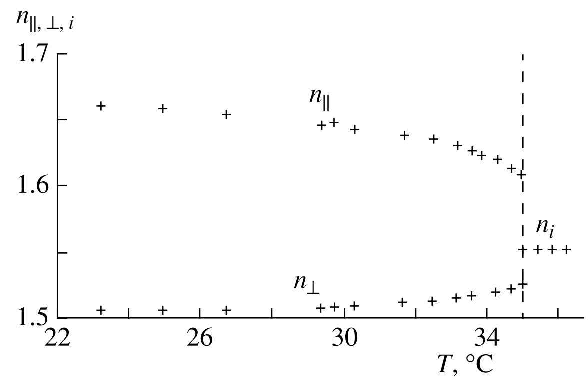

Fig. 3. Temperature dependences of the refractive indices of NLC 5TCB for a wavelength λ = 3.12 µm [16].

Figure 2 shows the frequency dependence of the transmittance of the photonic crystal at different angles of orientation of the nematic director and the normal incidence of light. The values of the refractive indices of the defect layer in the IR range for the tangential and normal orientations of the nematic director,

$$n_d\left(\frac{\pi}{2}\right) = \sqrt{\varepsilon_\parallel} = n_\parallel = 1.665$$

and

$$n_d(0) = \sqrt{\varepsilon_\perp} = n_\perp = 1.5$$

correspond to NLC 5TCB at room temperature (Fig. 3). The intermediate values of the refractive indices are determined by expression (4). The plots for defect modes *1* and *1'* in Fig. 2 correspond to the angles of the

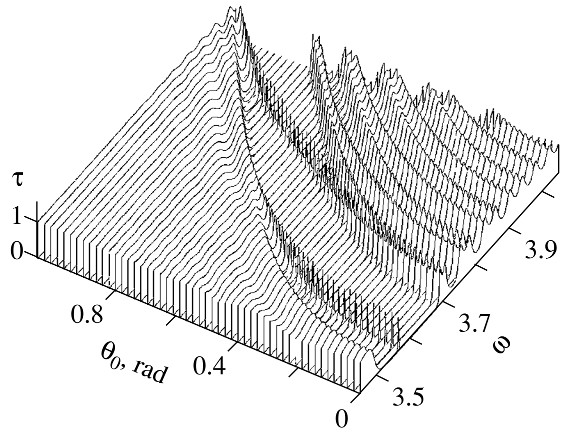

Fig. 4. Dependence of the transmittance of the photonic crystal with a structural defect on the frequency ω and the angle of incidence θ_0 (the case of normal orientation ($\theta = 0$) of the nematic director; the other parameters are the same as in Fig. 2).

director orientation $\theta = 0$ and $\pi/2$. We will trace the evolution of mode *1* with increasing θ. It turns out that the plot of defect mode *1* shifts with increasing θ to lower frequencies and, at $\theta = \pi/2$, merges with the continuous spectrum. In this case, the curve for the defect mode, split off in the high-frequency region from the continuous spectrum at $\theta = \pi/2$, coincides with curve *1*'. The spectral width of the lines of defect modes *1* and *1*' is about 10 Å and the band gap is 180 nm.

Figure 4 shows the possibility of controlling the transmission spectrum of the photonic crystal by changing the angle of incidence of light on the sample. As an example, we will consider the case of normal orientation of the NLC director ($\theta = 0$).

It can be seen that an increase in the angle of incidence θ_0 leads to a shift of the band gap boundaries and peculiar behavior of the position of the defect mode in this band gap. A change in θ_0 from 0 to $\pi/3$ leads to a shift of the band gap boundaries by approximately 570 nm. With an increase in the angle of incidence, beginning with $\theta_0 = 0$, the plot for the defect mode (Fig. 2, curve *1*) shifts to the low-frequency boundary of the band gap, merging with the continuous spectrum at $\theta_0 = 0.65$. In addition, at the angle of incidence $\theta_0 = 0.2$, the second defect mode splits off from the continuous spectrum in the high-frequency region and behaves like the first defect mode with increasing θ_0.

It is noteworthy that, for light of the given polarization incident from the medium with the refractive index $n_0 = n_b$ (irrespective of the orientation angle of the nematic director), the band gap reduces to zero at $k = (\omega/c)n_b\sin\theta_B$, where $\theta_B = 53.1°$ is the Brewster angle. At this angle, the Fresnel reflection from the interfaces disappears.

Figure 5 shows the reconstruction of the transmission spectrum of the photonic crystal occurring as the temperature approaches the temperature of the phase transition from the nematic to the isotropic state. In the vicinity of this transition, the changes in the refractive indices are most significant (Fig. 3). At $T = 28°C$, a new defect mode (*2*) becomes pronounced in the band gap of the transmission spectrum of the photonic crystal. The arrows in Fig. 5 indicate the direction of shift of defect modes *1* and *2* and new defect mode *2*' with increasing temperature. Note that new defect modes may arise not only with a change in the optical characteristics of the defect layer but also with a change in the

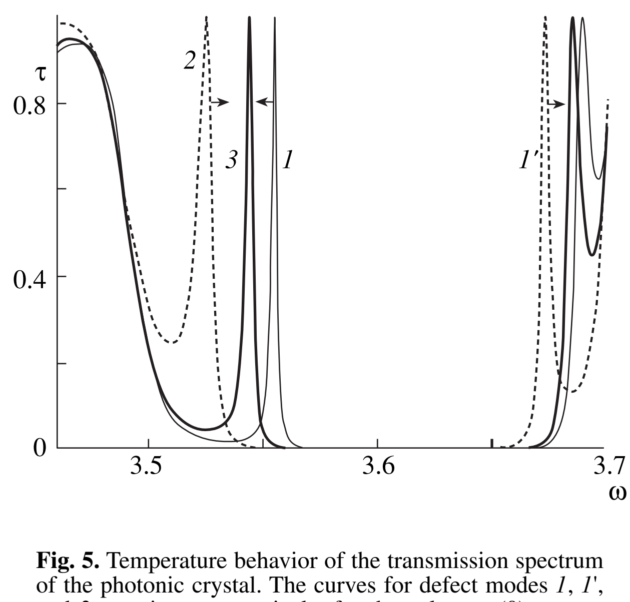

Fig. 5. Temperature behavior of the transmission spectrum of the photonic crystal. The curves for defect modes *1*, *1*', and *2* are given, respectively, for the values $n_d(0) = n_\perp = 1.449$ and $n_d(\pi/2) = n_{||} = 1.65$ measured at $T = 28°C$; the other parameters are the same as in Fig. 2. The arrows indicate the direction of shift of the curves for defect modes with increasing temperature.

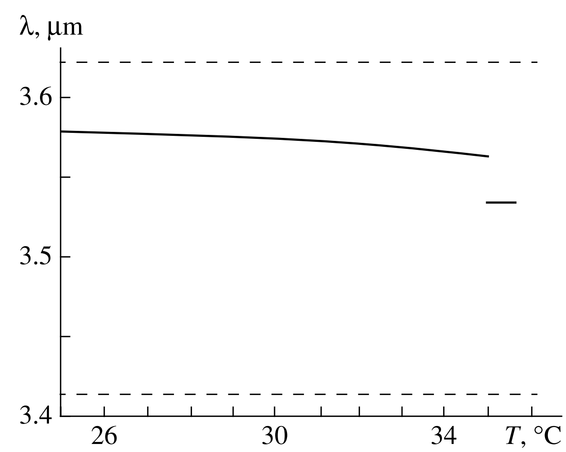

Fig. 6. Temperature dependence of the position of the maximum of the photonic crystal defect mode. The dashed lines indicate the boundaries of the second band gap of the crystal.

geometric sizes of layers [15]. In other words, changing the optical thickness of the defect layer, we can introduce new defect levels into the band gap of the photonic crystal. The transmission spectrum of the photonic crystal undergoes a stepwise reconstruction at the temperature of the NLC phase transition to the isotropic state ($T = 35°C$) and is described by a continuous curve in the isotropic phase. In this case, curve *1'* merges with the continuous spectrum and curves *1* and *2* reach stepwise the level of defect mode *3*.

Figure 6 shows the temperature dependence of the frequency of defect mode *2* (Fig. 5), which is related to the temperature dependence of the refractive index $n_{\parallel}$. The jump in the wavelength of the defect mode at the phase transition temperature is about 30 nm.

CONCLUSIONS

It is shown that the transmission spectrum of a 1D photonic crystal with lattice defects has a number of specific features, related primarily to strong anisotropy of the permittivity and the high sensitivity of the NLC layer (considered as a structural defect) to external fields.

A change in the orientation of the nematic director leads to significant frequency shifts of the defect modes within the band gap of the photonic crystal almost without changes in the width of the transmission curves of the defect modes and the transmittance of the photonic crystal at the defect mode frequencies. It is also shown that the position of the band gap and the defect modes in the band gap can be effectively controlled by changing the angle of incidence of light on the photonic crystal.

It is established that the temperature phase transition of the NLC to the isotropic phase may lead to qualitative changes in the transmission spectrum of the photonic crystal—a change in the number and the position of the defect modes in its band gap.

In practical applications, the photonic crystals considered here may be promising, for example, for design of tunable narrowband filters and temperature-sensitive elements.

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