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PHYSICS

Optical Bistability in a Photonic Crystal with a Liquid-Crystal Defect

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Abstract—We investigate experimentally the nonlinear transmission of a photonic crystal with a nematic liquid-crystal defect upon reorientation of the director in a field of cw laser radiation propagating at a certain angle to the sample. At different detunings, we observed the regimes of bistability, differential gain, and optical limiting. The resonance transmission peaks were detuned from the laser radiation wavelength by changing the angle of light incidence onto the sample. The value of nematic nonlinear constant n_2 determined from the experimental data is in good agreement with the theoretical estimate.

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One of the priority directions of modern applied photonics is the development of controlled devices based on structures with periodical modulation of permittivity in one, two, or three dimensions on a spatial scale comparable with the wavelength of light. Such structures are called photonic crystals (PCs) [1, 2]. An important feature of these structures is the presence of band gaps in the spectrum of their eigen electromagnetic states, where incident radiation reflects almost completely [1–3]. The defect breaking periodicity of the dielectric properties leads to localization of light of certain wavelengths in the defect and the occurrence of narrow passbands (defect modes) in the band gaps. Optical properties, including nonlinear ones, of the PCs can be effectively controlled by using as a defect media sensitive to an external electric, temperature, or light field. Media highly promising in this respect are liquid crystals (LCs) with a vast variety of nonlinear optical phenomena [4–6]. In particular, the nematic LCs are characterized by orientational optical nonlinearity, which makes it possible to control the refractive index through the distortion of the director field by an electric field of the laser beam [4, 6]. The self-action of light in the LC placed into the resonator manifests itself, in particular, in optical bistability [5]. In study [7], bistability was observed in the low-Q optical resonator with a nematic LC irradiated by a cw laser with an input power of hundreds of milliwatts; in [8], multistability of several orders and regenerative pulsations were observed under approximately the same conditions. The photonic crystals can significantly decrease the power at which the optical bistability is observed. Due to, probably, localization of light in the defect layer, the bistability effect in a PC can be observed at a much lower intensity of the input radiation as compared to the case of the macroscopic optical resonator, where introduction of the LC cell causes additional loss and, thus, decreases the Q factor. This idea was analyzed theoretically in study [9], in which the possibility of all-optical switching in a one-dimensional PC with an LC defect was demonstrated. According to the results of the calculation, the threshold intensity in the PC can be lower by four orders of magnitude than in the case of the same crystal without the resonator. In addition, the possibility of fabricating an optical diode on the basis of this structure was demonstrated. Further investigations in this direction are promising for the development of all-optical switches and transistors.

In this study, we investigate the effect of orientational nonlinearity of the LCs on the light-induced transmission of a one-dimensional PC with a homeotropically oriented nematic as a defect. We demonstrate the optical bistability, differential gain, and optical confinement at different detunings of the defect mode from the laser radiation wavelength that were performed by choosing the angle of light incidence onto the sample.

We consider the geometry of the interaction between the laser radiation and the PC with the LC defect. Let the linearly polarized laser radiation fall at

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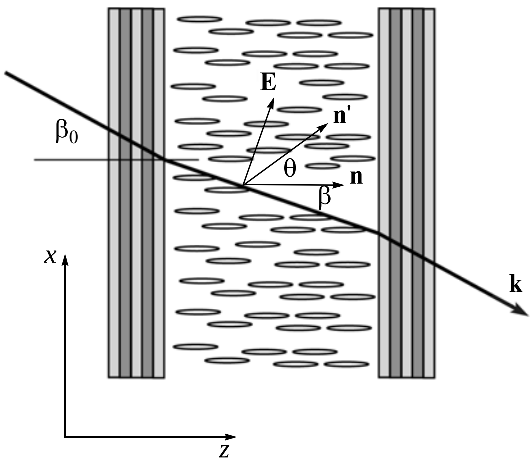

Fig. 1. Transmission of the linearly polarized laser radiation through a periodic photonic structure with the defect filled with the homeotropically aligned nematic LC.

angle β_0 to director **n** of the homeotropically oriented nematic LC with thickness L (Fig. 1). Wave vector **k** of the laser radiation makes the angle $(\beta + \theta)$ with director **n'** excited by the light field; θ is the reorientation angle, and **E** is the laser field strength.

Using the minimization of the free energy of the LC in the approximation of small angles of reorientation of **n** $(\theta \ll 1)$, the equation for θ can be written as

$$\frac{d^2\theta}{dz^2} + 4CE_0^2\sin^2\frac{m\pi z}{L} = 0, \quad C = \frac{\Delta\varepsilon}{8\pi K_3}\sqrt{\frac{\varepsilon_\perp}{\varepsilon_\parallel}}\sin\beta_0. \quad (1)$$

Here, $\Delta\varepsilon = \varepsilon_\parallel - \varepsilon_\perp$ is the permittivity anisotropy at the optical frequency (the indices correspond to the permittivity values measured along (‖) and perpendicular (⊥) to director **n**), K_3 is the elastic constant for the B deformation, m is the integer corresponding to the defect mode number, and E_0 is the field amplitude in the resonator cavity. Unlike [6], Eq. (1) takes account of the light waves inside the resonator being standing waves.

Under the boundary conditions $\theta(z = 0) = \theta(z = L) = 0$ and $m \gg 1$, the solution of Eq. (1) coincides with the analogous solution for the LC layer [6], so the effective refractive index caused by the optical reorientation can be written as $\langle\Delta n\rangle = n_2 I$ where the angle brackets indicate averaging over the LC layer thickness, I is the maximum value of the intensity in the defect layer, and nonlinear constant n_2 has the form

$$n_2 = \frac{(\Delta\varepsilon)^2}{2K_3 c\varepsilon_\parallel}\sqrt{\frac{\varepsilon_\perp}{\varepsilon_\parallel}}\frac{L^2}{6}\sin^2\beta\cos^2\beta. \quad (2)$$

The radiation incidence angle is related to the internal angle: $\sin\beta_0 \approx \sqrt{\varepsilon_\parallel}\sin\beta$. Note that the orientational nonlinearity is an effect similar, to a great extent, to the Kerr nonlinearity.

The intensity of the light field in the nonlinear resonator can be written as [10]

$$I = I_0\frac{1+R}{\varepsilon_\perp^{1/2}(1-R)}\frac{1}{1+F\sin^2(\Phi/2)}, \quad F = \frac{4R}{(1-R)^2}, \quad (3)$$

where I_0 is the input intensity, R is the reflection coefficient of the mirrors, and $\Phi = \Phi_0 + \delta\Phi$ is the total optical field phase delay in the cavity of the resonator filled with a medium with refractive index n_0. Here, $\Phi_0 = \frac{4\pi}{\lambda}n_0 L\cos\beta - 2m\pi$ is the detuning of the linear phase incursion from the nearest resonance and $\delta\Phi$ is the nonlinear phase delay caused by the light-induced reorientation of the LC director

$$\delta\Phi = \frac{4\pi}{\lambda}\langle\Delta n\rangle L\cos\beta = \alpha I, \quad (4)$$

where the coefficient $\alpha = \frac{4\pi}{\lambda}n_2 L\cos\beta$. Near the resonance $|\Phi| \ll 1$, formula (3) can be written as

$$I = I_0\frac{1+R}{\varepsilon_\perp^{1/2}(1-R)}\frac{1}{1+F\Phi^2/4}. \quad (5)$$

The transmission of the resonator filled with the medium whose refractive index depends on the intensity, $n = n_0 + n_2 I$, can be in the hysteretic dependence on the intensity of the input radiation (bistability) [11]. Bistability arises when there is a region with the derivative $\frac{dI_0}{dI} < 0$ [12]. From the condition $\frac{dI_0}{dI} = 0$, we can obtain the relation

$$\alpha I = -\frac{2}{3}\Phi_0 \pm \frac{1}{3}\sqrt{\Phi_0^2 - \frac{3(1-R)^2}{R}}, \quad (6)$$

which allows us to determine the boundary of the bistability region. There is bistability when expression (6) has two real solutions, i.e., at $\Phi_0^2 - \frac{3(1-R)^2}{R} > 0$.

The investigated sample was a periodic structure consisting of two multilayer mirrors forming the micro-resonator with a gap of 10 μm filled with the nematic LC 4-*n*-pentyl-4'-cyanobiphenyl (5CB). To obtain homeotropic alignment of director **n**, the mirror surface was treated with a 0.6% alcohol solution of lecithin. The mirrors consisted of six 55-nm-thick ZrO_2 layers with a refractive index of 2.04 and five 102-nm-thick SiO_2 layers with a refractive index of 1.45, alternately sputtered onto the surface of the glass substrate.

The experimental setup is shown schematically in Fig. 2. The sample was irradiated by a Millennia Pro 5sJ (Spectra-Physics) single-mode cw Nd: YVO_4 laser with the operating wavelength λ_L = 532.2 nm. The

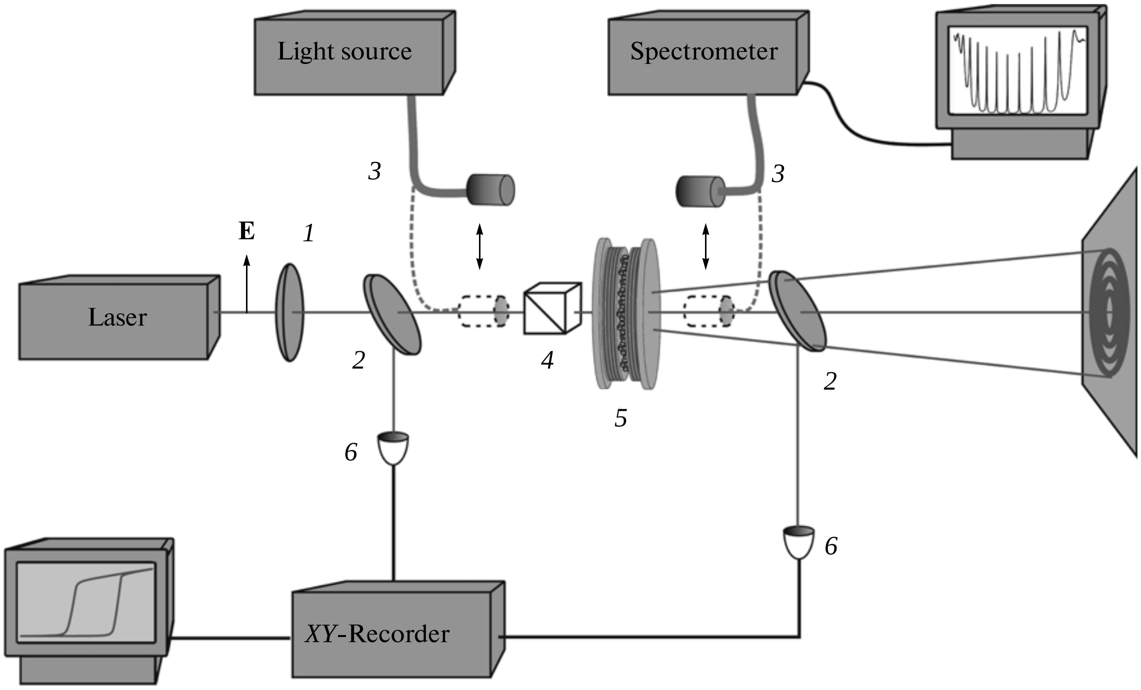

Fig. 2. Schematic of the experimental set-up: (*1*) focusing lens, (*2*) beam splitters, (*3*) light guides with collimating objectives, (*4*) Glan prism, (*5*) sample in the temperature-controlled cuvette, and (*6*) photodiodes.

laser radiation was focused by a lens with a focal distance $f = 27.5$ cm to the sample center. The beam waist in the focal plane measured with an intensity level of $\frac{1}{e^2}$ of the maximum was $d = 50$ μm. The temperature-controlled cuvette in which the sample was placed ensured a stabilization accuracy of ±0.1°C. All the measurements were performed at the fixed temperature $T = 23$°C. The cuvette construction allowed rotating the sample relative to the axis perpendicular to the probe radiation direction (axis y in Fig. 1). The error of setting tilt angle β_0 of the incident beam was ±0.05°.

The spectral position of the defect mode relative to laser line λ_L was controlled using an Ocean Optics HR4000CG spectrometer equipped with fiber optics. The Glan prism was fixed so that the polarization direction of the incident light (axis x in Fig. 1) lay in the incidence plane (plane xz in Fig. 1) at any orientation of director **n**. In such a configuration, the transmission spectrum component corresponding to the e-wave is recorded. After tuning, the fibers were removed from the optical channel and the dependence of power P_{out} of the laser radiation passing through the periodic structure with the LC defect on input power P_{in} was measured. The radiations were detected by recording photodiodes connected with a digital two-coordinate recorder based on an NI PXI 1042 (National Instrument) programmable unit. The laser beam passed through the sample was observed on the screen.

The transmission spectrum of the PC is a set of resonance peaks corresponding to the modes localized in defect. Optical bistability was observed using the mode with $\lambda_m = 533$ nm ($\beta_0 = 0°$) closest to the laser wavelength. Its spectral position was controlled by choosing the angle of light incidence onto the sample [13] from the range 3°–10° (Fig. 3). Power P_{out} of the laser radiation passing through the structure with gradual increasing and subsequent decreasing of input power P_{in} was measured for detunings $\delta\lambda = \lambda_L - \lambda_m$ presented in Fig. 3. The dependences P_{out} (P_{in}) for these detunings are shown in Fig. 4. As is known, observation of the bistable behavior of the transmission of the nonlinear system placed into the Fabry–Perot resonator is possible at the long-wavelength detuning of the input radiation frequency from the resonance transmission frequency [11]. In the angle range $\beta_0 = 6°–10°$ corresponding to the detunings $\delta\lambda = 1–3$ nm, the experimental dependences P_{out} (P_{in}) demonstrate the regime of the optical bistability caused by the orientational nonlinearity of the nematic LC. The transition of the system from the low- to the high-transmission state has a threshold character and is accompanied by strong laser beam divergence in the far-field. The system returns to the initial state by the other portion of the dependence, forming the hysteresis loop. With a decrease in the detuning, the threshold of the transi-

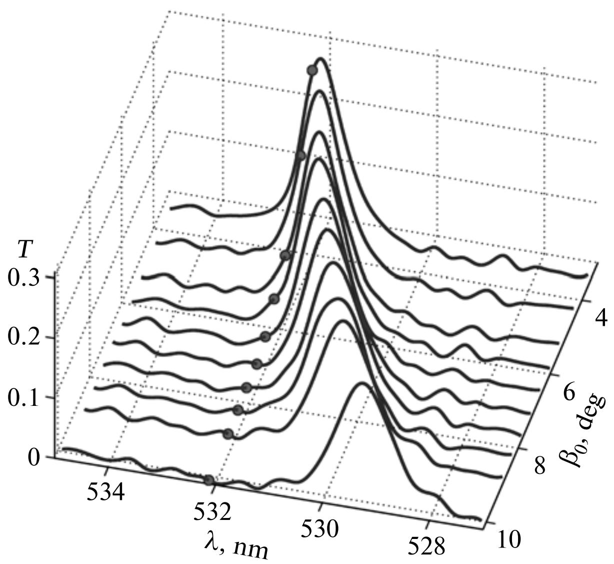

Fig. 3. Spectral position of the peak of mode λ_m vs. incidence angle β_0 in the vicinity of the laser wavelength λ_L = 532.2 nm (shown by dots).

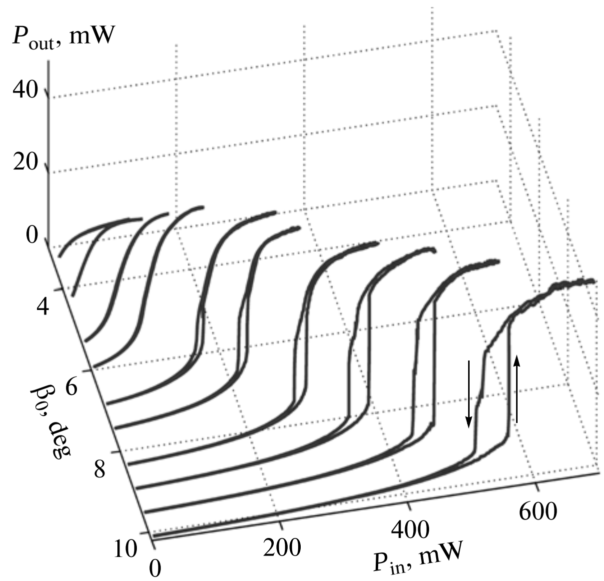

Fig. 4. Dependences of power P_{out} of light passing through the periodic structure on laser input power P_{in} at different detunings. The arrows show the direction of the transition of the nonlinear transmission of the sample.

tion of the system to the high-transmission state lowers and the hysteresis loop narrows. Note that the nonlinear medium (5CB) in itself is not characterized by intrinsic bistability. At the incident angles $\beta_0 = 5°–6°$, the detuning is decreased down to the values $\delta\lambda \sim 0.5$ nm. The threshold power of the transition decreases considerably, and the width of the hysteresis loop approaches zero, leading to the occurrence of the differential gain regime [11]. At smaller angles $\beta_0 < 5°$, the regime of the laser radiation power limiting is established, which is demonstrated by the corresponding dependences $P_{out}(P_{in})$ in Fig. 4.

Let us estimate nonlinear constant n_2 for the 5CB nematic from expression (2). For the layer with the thickness $L = 10$ μm and the parameters $\Delta\varepsilon \approx 0.611$, $K_3 = 10^{-6}$ dyne, $\varepsilon_\parallel = 2.989$, and $\varepsilon_\perp = 2.378$ [14] at the internal angle $\beta = 5.85°$ corresponding to the maximum detuning of the defect mode, we obtain $n_2 = 3.1 \times 10^{-8}$ cm²/W. In addition, the value of n_2 can be found from the experimental data with the use of relation (6), taking into account that the transmittance of the structure under study is related to intensity I in the defect layer and the input power as [10]

$$T = \pi d^2 I\sqrt{\varepsilon_\perp}\frac{1-R}{4(1+R)P_{in}}.$$

The transmittance at the laser radiation wavelength is $T = 3.86 \times 10^{-2}$ (Fig. 3). This value corresponds to the initial phase detuning $\Phi_0 = -0.31$ determined from the dependence $T(\Phi_0)$ [15]. The threshold power of the transition of the system to the high-transmission state corresponds to the value $P_{in} = 560$ mW (Fig. 4). Then, with the account for the Gaussian profile of the beam intensity for the parameters $R = 0.94$, $d = 50$ μm, and $\varepsilon_\perp = 2.378$, we obtain the intensity of the light field inside the nematic layer $I = 3.1 \times 10^4$ W/cm². For the given structure, the factor $\frac{3(1-R)^2}{R}$ has the fixed value 0.01. The coefficient $\alpha = 9.72 \times 10^{-6}$ cm²/W from (6) allows us to determine the nonlinear constant $n_2 = 4.1 \times 10^{-8}$ cm²/W, which is in good agreement with the theoretical estimate.

CONCLUSIONS

We demonstrated experimentally the effects of optical bistability, differential gain, and limiting of the power of the laser radiation propagating in a PC with the nematic LC defect. As the detuning is decreased, the hysteresis loop narrows and the threshold radiation power necessary for switching decreases. Using the experimental data, we determined nonlinear nematic constant n_2, which is in good agreement with the theoretical estimate.

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