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Observation of light-induced reorientational effects in periodic structures with planar nematic-liquid-crystal defects

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We report on the experimental studies of the light-induced reorientational effects in a one-dimensional periodic photonic structure with an embedded planar nematic-liquid-crystal defect. We demonstrate that in the presence of a periodic structure, the self-action of light in a liquid-crystal layer demonstrates sharp power-dependent characteristics for the intensity-dependent optical transmission. Robustness of the effect suggests its applications for all-optical tunable photonic devices. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2936085]

Nonlinear optics of liquid crystals has been studied for more than twenty years.[1,2] Liquid crystals are very attractive for applications in tunable optical devices, since they demonstrate nonlinear optical behavior arising from molecular reorientation and/or thermal effects. Molecular reorientation has been studied theoretically and demonstrated experimentally in different geometries,[3] and also with[4–6] and without[7] external electric fields. While many theoretical papers studied the light-induced Freedericksz transition in planar structures (see, e.g., Refs. 8 and 9), no clear experimental results have been reported so far.

In this letter, we report on the experimental studies on light-induced nonlinear transmission of one-dimensional periodic structures with an embedded planar defect infiltrated with a nematic liquid crystal. We observe that in the presence of a periodic structure the self-action of light leads to a sharp power-dependent change in the transmission characteristics of the structure.

We study the transmission of a one-dimensional periodic structure composed of alternating layers of SiO_2 and TiO_2 with a nematic-liquid-crystal (NLC) defect infiltrated into a middle layer, see Figs. 1(a) and 1(b). The periodic structure is fabricated by means of the e-beam evaporation technique; the refractive indices of SiO_2 and TiO_2 are 1.46 and 2.41, respectively, (at 532 nm), and the thickness of all layers is 140 nm. Both right and left Bragg mirrors have $N=10$ periods, which generate a photonic gap from 520 to 560 nm [see Fig. 1(c)]. However, such relatively large number of layers makes it impossible to observe clearly defect modes inside the bandgap due to mirror losses,[3] and usually smaller number of layers is used with $N=5$ (see Refs. 4 and 5). The design of our structure follows the earlier theoretical predictions[10] for the reduction in the threshold power for light-induced reorientational effects in periodic structures. The 6CHBT NLC possesses low absorption and high nonlinear response,[11,12] with the refractive indices $n_e=1.6718$ and $n_o=1.5225$ in the visible frequency range. The NLC is sandwiched between two equivalent periodic structures, and the thickness of this NLC defect layer is about 12 μm. The edge surfaces of each periodic structure are rubbed along the x axis in order to achieve the planar alignment of the NLC molecules along the x axis.

The experimental setup is shown in Fig. 2. A linearly polarized monochromatic laser beam with the wavelength $\lambda=532$ nm is focused on the NLC layer by the lens with $f=100$ mm. It gives a spot of about $w_o=25$ μm at the sample. The beam is normally incident on the structure along the z axis. In the experiment, the transmission of the structure is measured versus the input power.

In our experimental geometry, the liquid-crystal molecules experience mostly the twist deformation and rotation in the xy plane only. Therefore, we can introduce the angle θ describing the director orientation in the NLC layer as $\mathbf{n}=\{\cos\theta,\sin\theta,0\}$ (see Fig. 1). Strong anchoring of molecules at the surfaces of dielectric implies that θ is fixed at the boundaries ($\theta=0$).

In our experiments, we use normally incident linearly polarized light. The angle β of the incident polarization is measured from the y axis, so that $\mathbf{E}^{\mathrm{in}}=E_0^{\mathrm{in}}\{\sin\beta,\cos\beta,0\}$. Therefore, the case $\beta=0$ corresponds to the orthogonal polarization of light relative to the orientation of molecules at the boundaries. The different incident angles β cause different molecular distributions inside the NLC slab resulting in a variation of the refractive indices. Because of the sample birefringence, the beam polarization changes as it propagates through the NLC slab. The characteristic length l_c over which the polarization state changes significantly is $l_c \simeq \lambda/(n_e-n_o)$.[13] In our case, the slab thickness $L\simeq 12$ μm is three times larger than the critical distance $l_c\simeq 3.5$ μm. According to Mauguin theorem,[13] the polarization of the linearly polarized light impinged normally onto a NLC layer should follow adiabatically the changes of the director and emerge from the NLC slab with the same incident angle of polarization, being still linearly polarized. Thus, at small powers, we expect no variations in the polarization inside the NLC medium. However, above the threshold, higher-order nonlinear effects will affect the birefringence making it stronger and, subsequently, leading to larger variations in the director orientation.

When the polarization angle coincides with the director orientation ($\beta=90°$) no orientational effects should be observed. Therefore, this case can be employed for testing

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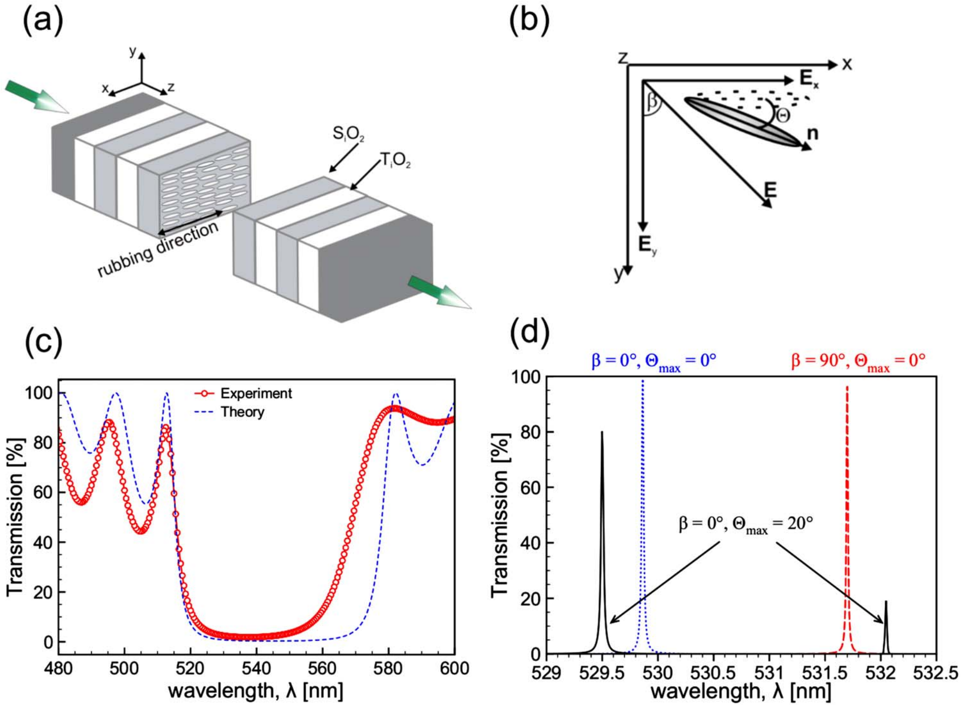

FIG. 1. (Color online) (a) Schematic of the one-dimensional periodic structure with a liquid-crystal defect layer. (b) shows a sketch of molecular alignment in the liquid crystal; schematically shown molecular reorientation in the (x,y) plane; θ is the orientational angle, β is the angle between the direction of the electric field and the y coordinate. (c) Experimental (red) and theoretical (blue) transmission spectrum of the periodic structure with LC defect layer. (d) Zoom of the theoretical spectra near the pumping wavelength $\lambda = 532$ nm showing the existence of ordinary ($\beta = 0°$) and extraordinary ($\beta = 90°$) defect modes. In addition to this, we plot the variation of the transmission after reorientation, by assuming that $\Theta(z) = \Theta_{\max} \sin(\pi z/L)$.

other (rotationless) phenomena, e.g., the effect of thermal nonlinearity. In fact, we verify experimentally that for the input powers up to 6 mW, no significant thermal effects are observed. Moreover, we estimate the initial pretilt angle θ_0 inside the structure to be $\theta_0 \sim 3°–4°$.

For the light polarized perpendicular to the director (at $\beta = 0$), we expect to observe orientational effects when the input power exceeds some threshold value, as was suggested earlier.[14] The light propagation through a NLC slab is accompanied by spatially nonuniform phase retardation as a result of the intensity-dependent change in the refractive index. For a radially symmetric beam incident normally on the NLC slab, the reorientation process depends on the beam radius, and it is the strongest at the beam center. As a result, for the input Gaussian beam, the transmitted light exhibits clear diffraction rings in the far field. The reorientation-induced change in the effective refractive index experienced by light beams leads to the redshift of the defect modes, so that one of the mode frequencies coincides eventually with that of the pumping light resulting in a strong variation in the intensity of the transmitted light.

The main results of our experiments are summarized in Figs. 3(a)–3(d) presenting the transmission spectra for the incident light polarized along the y axis. The insets show the corresponding spatial intensity patterns registered by the change-coupled device (CCD) camera. For registration of reorientation, we use a precise method based on measuring the on-axis intensity. The central part of the beam (an inner part of the diffraction pattern) is isolated using the aperture located in front of the detector. Changes in the transmitted intensity detected in the center of the outgoing beam give us an evidence of reorientation of the molecules and the existence of a defect mode. As can be seen in Fig. 3, at the input power of 1.1 mW, the first peak in transmission appears, and it indicates the appearance of the defect mode of the periodic structure at the wavelength $\lambda = 532$ nm coinciding with that of the incident beam [see Fig. 1(d)]. The power necessary to reorient the liquid-crystal molecules and, consequently, excite the defect state is *much lower* than that needed to obtain the same rate of orientation in the pure liquid-crystal slab, which is estimated to be about 10 mW.[10]

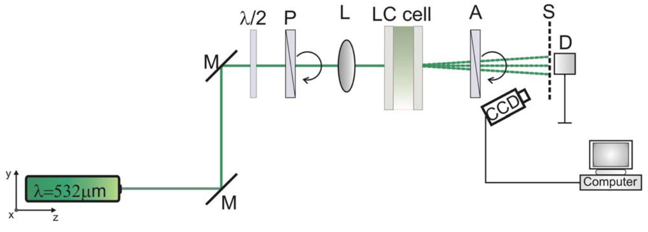

FIG. 2. (Color online) Experimental setup: M, mirrors, λ/2, waveplate, P, polarizer, L, lens, A, analyzer, S, screen, D, detector, and CCD camera. Linearly polarized light after polarizer and waveplate is focused on the front facet of the structure by means of lens with $f = 100$ mm. Polarizer and waveplate allow to control the polarization and input power.

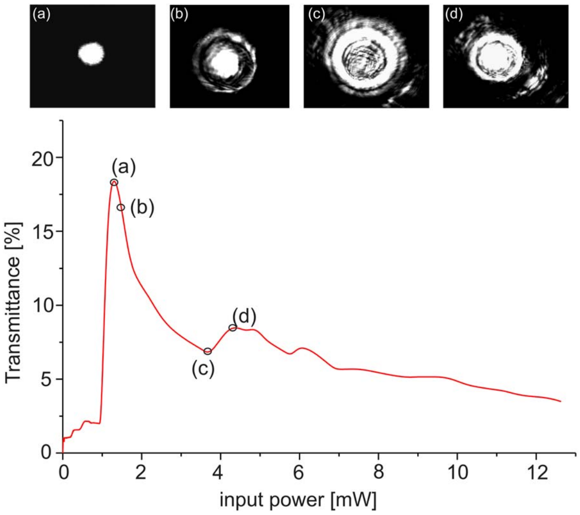

FIG. 3. (Color online) Transmission of the y-polarized light as a function of the input power. The insets show the light intensity distribution in the far field for the input power: (a) P 1.1 mW, (b) P 1.4 mW, (c) P 3.7 mW, and (d) P 4.2 mW.

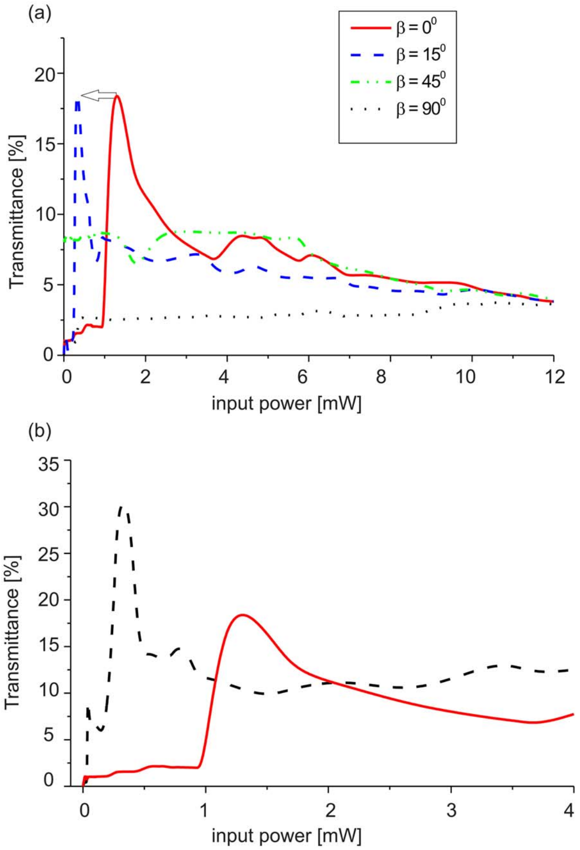

FIG. 4. (Color online) (a) Transmission for different angles of the initial linear light polarization (different values of β) vs the input power. The arrow indicates the shift of the transmission peak; (b) transmission spectra for periodic structure with 50 μm (dashed -black) and 12 μm (solid -red) thick liquid-crystal defect layer.

Further increase in the input power leads to a decrease in the transmission. This occurs because the higher power leads to further increase in the effective refractive index and, consequently, the further redshift of the defect mode. As the plot in Fig. 3 indicates, there appear two additional transmission peaks at the input powers of 4 and 6 mW, respectively, which are likely caused by the presence of other defect modes. Usually, the formation of diffraction rings in the transmitted light indicates the appearance of a nonuniform molecular reorientation inside the NLC slab.[15,16] Hence, we claim that the appearance of the first ring in our experiments provides a proof that the observed effects are solely due to the reorientational nonlinearity of the NLC defect slab.

We also measure the polarization of the transmitted light and find that it changes from linear to elliptic for the input power higher than that of the first threshold.

Figures 4(a) and 4(b) summarize the dependence of the light transmission on various experimental parameters. Figure 4(a) shows the transmission for different values of the input polarization angle β. The power threshold of the nonlinear transmission, as indicated by the first peak, depends strongly on the polarization angle. The threshold is higher when the input polarization is perpendicular to the long axes of molecules of the liquid crystal ($\beta = 0°$), and it decreases with decreasing β. From our measurements, we estimate the changes in the orientational angle θ. In particular, we find that the first peak of 18% of transmission corresponds to $\theta_{\max} = 19°$ [see Fig. 1(d)]. Increasing the polarization angle leads to changes in the effective refractive index and, consequently, the power needed to reorient molecules up to $\theta = 19°$ is lower, as the relative angle of reorientation ($|\theta - \beta|$) becomes smaller. For even larger polarization angle ($\beta = 45°$) the first transmission peak disappears, but the overall low-power transmission is now higher due to the changes in the effective refractive index.

For the powers larger than 6.0 mW, thermal effects start to play a significant role, as is estimated in the case of the x-polarized light. However, the changes in the refractive index due to thermal nonlinearities are smaller than those produced by the reorientational nonlinearity.

We have also found that the width of the NLC defect layer significantly affects the nonlinear transmission characteristics. In Fig. 4(b), we compare two cases of thin ($L = 12$ μm) and thick ($L = 50$ μm) LC layers. In the latter case, we observe sharper and higher peak with 30% of transmission at 480 μW. We also observe the transmission peak for even lower power of about 280 μW. This behavior is consistent with the standard dependence $\sim 1/L^2$ of the threshold power for reorientational effects.[2]

In conclusion, we have experimentally demonstrated intensity-dependent transmission in a one-dimensional periodic structure with a nematic liquid-crystal defect, based on reorientational nonlinearity. We have shown that the periodic structure reduces dramatically the threshold power for nonlinear transmission. This effect can be potentially useful for all-optical switching and nonlinear transmission.

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