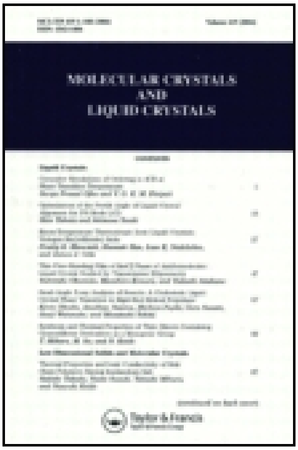

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Photonic Crystals based on Cholesteric Liquid Crystals

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Photonic Crystals based on Cholesteric Liquid Crystals

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Bragg reflection for the circularly polarized light is one of the most attractive properties of Cholesteric Liquid Crystal (CLC), which results in its intrinsic 1D chiral structure [1]. This property has been already exploited in various applications such as reflective displays, with leading contributions from Kent State University. It is also possible to use the CLC ordered structure (in the planar Grandjean configuration) to create 2D diffraction gratings, by applying electric field to the material [2]–[3].

We propose a new application for this material: by applying a periodic electric field, we generate 2D periodic structures in the bulk, which result in a photonic crystal (PCLC). Such a structure has some decisive advantages with respect to photonic crystals obtained by common holographic methods [4]. High efficiency is one of them, due to the intrinsic efficiency of CLC Bragg mirrors. Another is the reconfiguration capability, as the optical response of PCLC changes as a function of the period and of the applied electric field value.

Keywords: cholesteric crystals; photonic crystals

INTRODUCTION

We present preliminary results on a first PCLC, which was produced by applying periodic electric fields to a thick sample of CLC (30 μm), creating a transmission grating. The period of the grating, CLC pitch length and incidence angle are chosen to be as close as possible

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to the photonic crystal resonance. We demonstrated polarization dependence, as well as the spectral selectivity of the diffracted orders, which origin lies in the resonance between both gratings: the CLC Bragg reflection grating and the thin transmission grating induced by the electric field. To our knowledge, it is the first attempt of creating photonic crystals using CLC in such a way.

Liquid crystals have been extensively used to create diffraction gratings on the base of nematics, and most recently based of cholesterics [2]. Our approach is a step further proposing to match the CLC pitch and the period of an induced thin grating similar to what is used in a photonic crystal [4,5]. In this paper we demonstrate the validity of this approach by observing the interaction and the resonance between the two gratings. Photonic CLC presents a number of advantages over existing solutions, due to polarization dependence, used as a control parameter, high birefringence, and reconfiguration capability.

PHOTONIC CHOLESTERIC LIQUID CRYSTAL (PCLC)

The CLC in planar Grandjean configuration exhibits reflective modes with circularly polarized light of the same handedness as the CLC helix [1]. Reflection occurs at wavelength $n_oP < \lambda < n_eP$, where P is the CLC pitch and n_e, n_o extraordinary and ordinary refraction indexes. For a thin 1D grating operating in transmission, the Bragg diffraction angle θ_B and the diffraction wavelength are related as follows:

$$\sin\theta_B = \frac{\lambda_R}{2n\Lambda_X} \tag{1}$$

where λ_R is the diffraction wavelength, n is the average refraction index and Λ_X is the modulation period. When we combine both modulations, as shown on Figure 1, the picture becomes more complex, as the CLC anisotropy should be taken into account. The device principle is shown Figure 1. Between two glass plates we confine the CLC in planar configuration. The thickness L is controlled by the spacers. On both glass plates we have the indium-titan oxide (ITO) transparent conducting layer enabling the application of an electric field to the CLC. One of the electrodes (the bottom one on the figure) is etched to create the periodic one-dimensional grating. The incoming light interacts with both gratings and diffracts after passing through the material.

The 2D periodic modulation of dielectric tensor is of a complex form, and from a theoretical view point it is difficult to provide a relevant modeling of the director orientation as a function of the applied

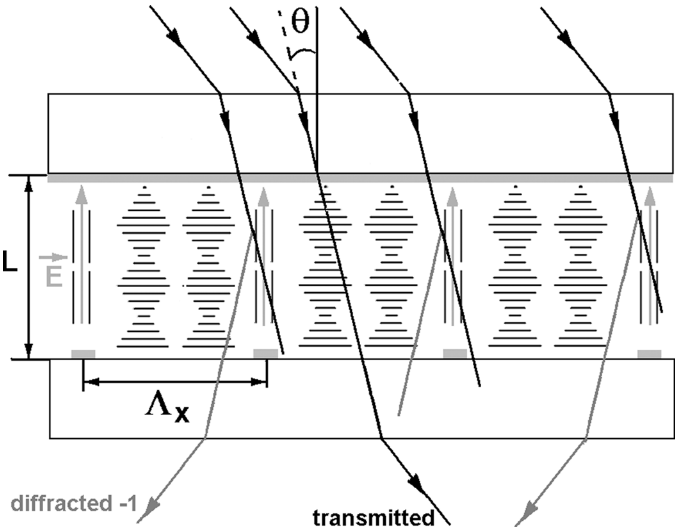

FIGURE 1 Cross-section of the switchable Photonic CLC device.

electric field. Instead, we assume that there exists the resonance similar to that observed in photonic crystals for a proper choice of the parameters (periods and voltage values). For the scaling of the device we assume that order of magnitude of the relevant parameters is similar to that of the ones occurring in the simplest case of a 2D sinusoidal modulation:

$$n(\mathrm{x},\mathrm{y}) = n_0 + \Delta n_X \cos\left(\frac{2\pi x}{\Lambda_X}\right) + \Delta n_Y \cos\left(\frac{2\pi y}{\Lambda_Y}\right) \tag{2}$$

Λ_X, Λ_Y are the modulation periods along X and Y, Δn_X, Δn_Y the corresponding modulation indices.

As we are interested in telecommunication applications, the device scaling has been done assuming the resonance wavelength close to $\lambda_\mathrm{R} = 1{,}55\,\mu\mathrm{m}$. The thickness of the CLC layer L will define the resonance width and is chosen equal to $30\,\mu\mathrm{m}$, resulting in a width of half height of a few nanometers. We etched three different periods of $\Lambda_\mathrm{X} = 8\,\mu\mathrm{m}$, $15\,\mu\mathrm{m}$ and $30\,\mu\mathrm{m}$, to investigate how thickness variations with respect to the period ratio impact the outcomes. For the sinusoidal modulations like (2) estimates according to [6] give us the following values, for the corresponding parameters: pitch of CLC $\mathrm{P} \approx 1\,\mu\mathrm{m}$ and $\theta_\mathrm{B} \approx 1^\circ \div 4^\circ$ depending on the grating period. The last critical step is the CLC stabilization by a polymer network, with a concentration of polymer of about 5%.

EXPERIMENTAL DEMONSTRATIONS

We used a CLC mixture from Merck: MDA-00-1444 – host, and MDA-00-1445 – cholesteric mixture, with an ordinary index of 1.5 and an extraordinary of 1.68 (measured for the visible wavelengths). For stabilization we used the monomer RM-257 supplied by Merck. The measurements have been carried out using a tunable laser with a tunable range over 1500–1620 nm. We control the incidence angle of the incoming light and its polarization state. For controlling the polarization we used a linear polarizer coupled with a quarter-wave plate. Our setup enables us to measure the output polarization.

We present the results for a 30 μm grating. We start from the CLC planar Grandjean structure and we distort it by applying an increasing electric field through the stripe electrodes. The measurement were carried out using the right-handed circularly polarized (RCP) light. Figure 2 shows a diffraction resonance spectrum, taken for the -1

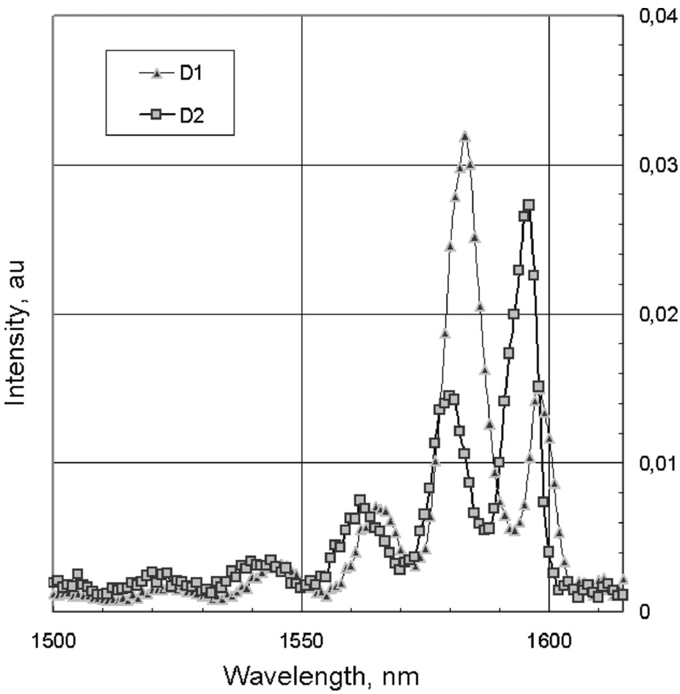

FIGURE 2 Resonance diffraction spectra for a 30 μm grating, -1 diffraction maximum. Voltage and angle chosen for a larger intensity in the 1st or 2nd order. D1: 0.5 V/μm, 10° incidence angle. D2: 0.2 V/μm, 6° incidence angle.

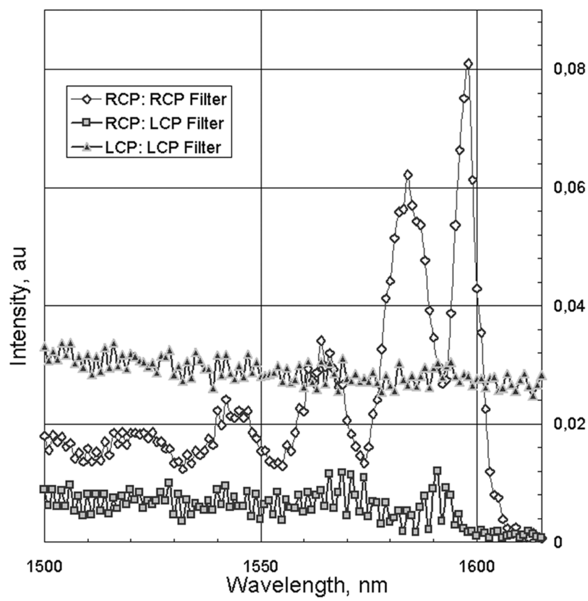

FIGURE 3 Diffraction spectra for 30 μm grating, −1 diffraction order. Spectrums are taken for the same applied voltage of 0.5 V/μm. The input and output polarizations only change. Rhombs correspond to RCP input and RCP output filter. Squares to RCP input and LCP output filter. Triangles for LCP input and LCP filter.

diffraction order. The incidence angle and the applied voltage are tuned to clearly show the possibility of having a higher intensity in the first or second resonance peaks. We clearly see a resonance which is similar to what is observed with photonic crystals. Near the bandedge of the reflection grating (in our case the CLC Bragg) we observe an increase in the transmission intensity.

The polarization dependence has been measured. In all cases, we do not observe any wavelength selectivity for LCP light (left-handed circularly polarized). It can be easily understood, as the LCP light does not interact with the right-handed CLC Bragg grating. So we observe only the diffraction due to the transmission linear grating. Results for different incoming polarizations and different output filters are shown on Figure 3. We see that the output light has almost the same polarization as the input light, the intensity of RCP incident light with LCP filter is very low. (LCP incident light with RCP output filter gives even lower intensity and not shown.) The top curve on the Figure 3 corresponds to the RCP incoming light with a RCP filter. It

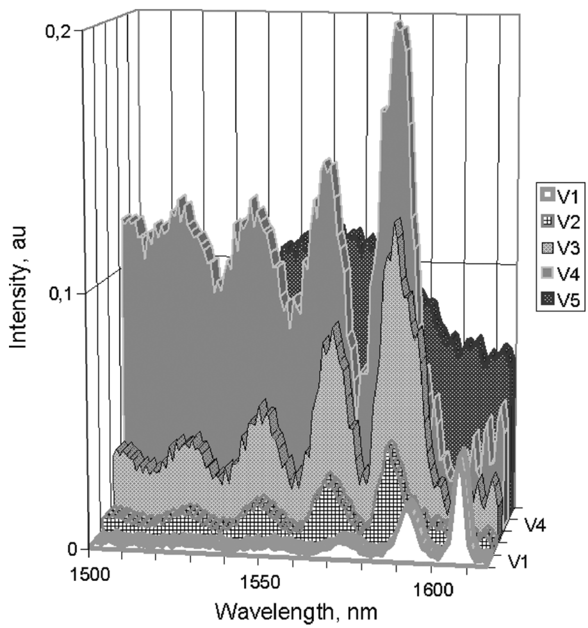

FIGURE 4 3D representation of resonant diffraction spectra for a 30 μm grating, −1 diffraction order. Axis Z corresponds to intensity in arbitrary units, axis Y to the wavelength, axis X to the applied voltage. The curves profiles are marked by the corresponding voltage: V1: 0.25 V/μm; V2: 0.5 V/μm; V3: 1 V/μm; V4: 3 V/μm; V5: 5 V/μm;.

clearly shows the resonance effect. The middle curve corresponds to the LCP with a LCP filter, and does not show wavelength selectivity. The bottom curve corresponds to a RCP incoming light and LCP filter.

When we increase the applied voltage the curve shapes change significantly (Fig. 4). As the voltage increases, the diffraction intensity increases, but the contrast of the resonance curves deteriorates simultaneously. For high voltages >4 V/μm we no longer see the spectral selectivity. We understand the phenomenon as follow: we assume that as the applied voltage increases the modulation depth of linear gratings increases as well, leading to an increase in diffraction efficiency, while at the same time the CLC planar structure quality deteriorates, leading to a decrease of the spectral selectivity. The experiments on the gratings with smaller period confirm this point. For these grating we don't observe any spectral selectivity due to a stronger distortion of the CLC structure.

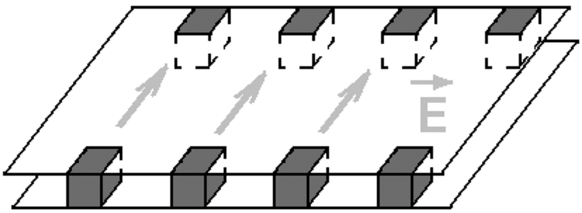

FIGURE 5 Thick electrodes design. Electric field is applied between the thick electrodes.

These experiments confirm the existence of a resonance between the CLC reflective Bragg and transmission gratings. The structure also shows a strong polarization dependence. The ratio of thickness to the modulation period is the main critical factor in determining the performance of the photonic CLC.

FUTURE DEVELOPMENTS

Although we have been able to make a proof of concept of a photonic CLC, several issues should be resolved before it can be used for practical applications. The main issue is the relatively low efficiency of the diffraction orders. Theoretically, it can be increased by increasing the applied voltage, but with the consequence of lowering the contrast of the resonance peaks. A possible improvement would be to use an etched counter electrode, which should increase the contrast of resonance peaks, but it is more technologically demanding, as it requires an accurate positioning of electrodes during assembling. Another option is to create a modulation by a transverse electric field as shown Figure 5, but it is also technologically demanding with respect to the used cell thickness.

Another approach which looks promising is to record a linear transmission grating by UV curing techniques of a monomer into the CLC structure, as it is done for holographic polymer dispersed liquid crystal (Holo-PDLC [7]). The problem in this case is to find chemically compatible mixtures. Preliminary investigations indicated several difficulties such as phase separation for the high concentrations of polymer. One of the advantages of using fixed polymer grating is a better modulation profile, compared to the electric field induced profile, the counterpart is a loss of the reconfiguration or switching capability which is presented when using the electric field. The polarization dependence is still present and can be used as a control parameter for applications.

CONCLUSION

We have demonstrate grating resonance in a photonic CLC device where the interaction occurs between the Bragg CLC structure and a transmission grating induced by an electric field. We determined the critical parameters, in particular the thickness to modulation period ratio, which impacts the PCLC performance. Based on these experiments we suggest some possible improvements, which would facilitate the implementation of practical applications. Finally, we state an interesting theoretical issue which goes beyond the scope of this paper. Namely, if any periodic 2D modulation of the dielectric tensor would lead to appearance of resonance for certain wavelengths, polarization and incidence angle of the incoming light.

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