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# Microsecond-range optical shutter for unpolarized light with chiral nematic liquid crystal

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A fast electro-optic shutter is fabricated and demonstrated. The device works independently of the polarization state of the incoming light beam. Modulation between 3% transmission and 60% transmission is obtained within a wavelength range of 50 nm with a response time of 20 μs. The device consists of two partly polymerized chiral nematic liquid crystal layers separated by a half wave plate. The transmission modulation is due to a 50 nm wavelength shift of the photonic band gap of the chiral liquid crystal realized by applying an electric field over a mixture of photo-polymerized LC and non-reactive nematic LC containing a chiral dopant. The shutter features high reflectivity in the photonic band gap. We investigate the influence of the amplitude of the applied voltage on the width and the depth of the reflection band.  [http://dx.doi.org/10.1063/1.4918303]

Chiral nematic liquid crystals (CLC) have attracted considerable attention from both a fundamental and a practical point of view due to the spontaneous arrangement into a helical structure. In addition, organic materials are interesting for photonic applications due to the relative ease of synthesis, characterization and processing. In CLCs the average molecular direction (i.e. the director) twists and forms a helical arrangement. The periodicity of this helical structure can range from few hundred nanometer to several micrometers and results in a modulation of the index ellipsoid along the helical axis.[1] Similar to a distributed Bragg reflector (DBR), the periodicity of a CLC acts as a 1D Photonic Band Gap (PBG). The width of the PBG is given by $\Delta\lambda = \Delta n P$ with $\Delta n$ the LC birefringence and $P$ the pitch, which is equal to the distance which the director rotates over 360°. When an unpolarized light beam is incident on a uniform CLC layer along the helical axis, the circularly polarized light of the same handedness as the chiral helix is reflected in our case Right handed Circular Polarization (RCP). While the polarization with opposite handedness can propagate unhindered.[1,2] Thus, a CLC cannot reflect more than 50% of normally incident unpolarized light.

A CLC layer can be an optical rotator, a notch filter, a polarizer, or a reflector.[3] Also CLCs have been used in applications such as lasers and displays.[4–9] Direct control and wavelength tuning of the PBG are crucial for several applications such as lab- on-a-chip devices and switchable optical devices: reflectors, diffraction gratings, polarizers, shutters, reflective displays, lasers and sensors.[10] The PBG of the CLC can be tuned by using external stimuli such as heat,[11–14] light,[15–17] mechanical stress[18] and electricity.[19–31]

Most of the reported CLC devices exhibit relatively slow switching characteristics in the order of several ms or a small tuning range which encumbers the use in practical applications. The most

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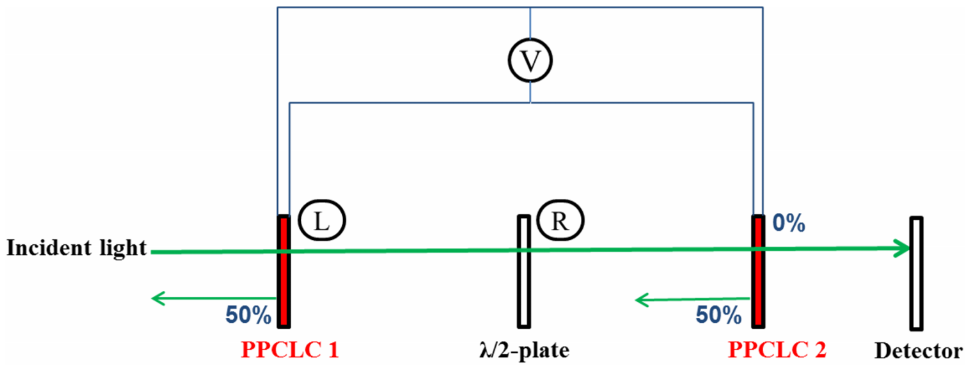


FIG. 1. Schematic drawing of the device operation to modulate unpolarized incident light.

common technique for tuning the PBG is changing the pitch P.[10–22] Direct electronic control of the PBG is difficult because the periodic structure may deform non-uniformly and the Bragg reflection may be disrupted under the application of an electric field.[2,27,30] To overcome the problem of losing the uniform CLC structure the liquid crystal may be polymer-stabilized.[24,32–37] Finding a solution to avoid deterioration of the structure while maintaining a fast response remains an issue.

In previous work we have demonstrated wavelength-tuning of the PBG of a CLC layer using an applied voltage. This resulted in a fast response of tens of microseconds and tuning over a broad wavelength range, with high reproducibility and without deformation or degradation.[31] For many applications however it is unacceptable that the device only reflects about half of the unpolarized light. It is desirable to have a switchable photonic band gap with fast response irrespective of the polarization state of the incoming light beam.

In this work, we demonstrate a polarization-independent electro-optic switch with a shift of the PBG of up to 50 nm and response time of 20 µs, with transmission modulation between 3% and 60%. The device includes two partly polymerized chiral nematic liquid crystals (PPCLC) and a half wave plate. The influence of the thickness of the PPCLCs and of the amplitude of the applied electric field on the switching features is investigated.

The CLC mixture is prepared by mixing 50 wt% non-reactive nematic LC (MDA-00-3536, Merck), 3.47 wt% right handed chiral dopant (BDH1305, Merck), photo initiator (Irgacure 819, BASF) and 46.5 wt% reactive LC (Mixture of mono-acrylate and di-acrylate monomers-Merck). It is possible to make devices for different operation wavelengths by selecting the appropriate chiral dopant concentration. The full procedure of making the mixture, the cell fabrication and the UV polymerization is explained in previous work.[31] The resulting PPCLC film consists of a polymer layer filled with nano-pores of unpolymerized LC which reacts to an applied electric field. In order to obtain switching from full reflection to full transmission in a certain wavelength range, we have used the method which is depicted in Figure 1. The set up includes two PPCLCs and one half wave plate. RCP light with wavelength in the PBG is reflected by PPCLC1 and the LCP light is transmitted. LCP light is converted to RCP by the zero order half wave plate centered at 850 nm. Due to the fact that this is not a broadband half wave plate, LCP light at other wavelengths will be converted into slightly elliptically polarized light. The relative retardation error for 800 nm for example is about 6%. Then the RCP light is reflected by PPCLC2. This reflected light travels through the first PPCLC as it is converted to LCP. The photonic band gap is tuned by applying the same voltage signal over both PPCLCs.

Two PPCLCs with 4 µm thickness and a central wavelength λ0 of 850 nm are implemented in the setup of Fig. 1. The cells are driven by a function generator and amplifier with a sine wave voltage (0 to 132 V/µm, 1 kHz). By applying an electric field, the nematic LC inside the voids is oriented and aligned parallel to the electric field due to the positive dielectric anisotropy of the LC. As reported before[31] for a single PPCLC cell, the application of a voltage results in a blue shift of the PBG. The pitch is fixed by the CLC polymer template, which means that the average refractive index seen by RCP light decreases. The transmission spectra of the samples are measured by a

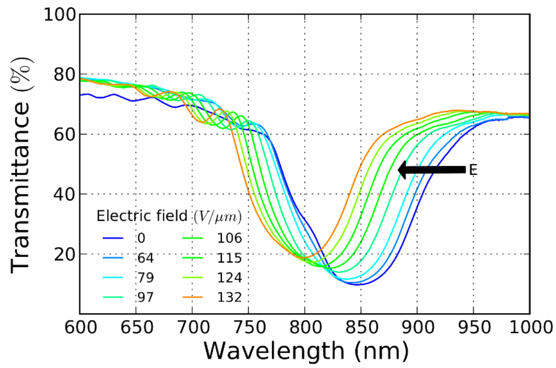


FIG. 2. Transmission spectra for unpolarized light for a full PPCLC-λ/2-PPCLC device with two 4 μm thick PPCLCs for eight applied electrical fields.

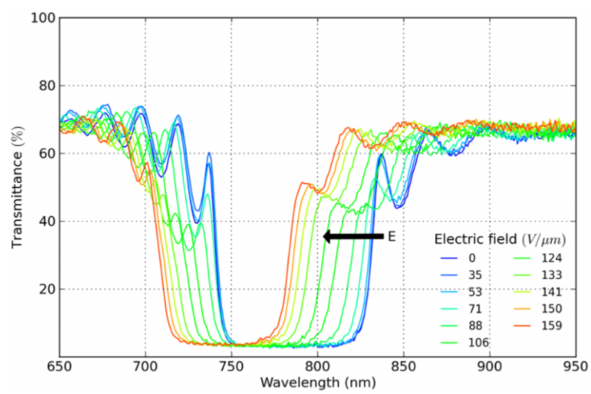


FIG. 3. Transmission spectra for unpolarized light for a full PPCLC-λ/2-PPCLC device with two 8 μm thick PPCLCs for eight applied electrical fields.

dual-beam spectrophotometer (Perkin Elmer) as a function of the electric field. To avoid problems with the polarization dependency of the spectrophotometer, the measurements are performed with a linear polarizer before the device under test. Measurements are performed for different orientations of the linear polarizer. No noticeable difference is measured in the transmission spectrum when varying the angle of the linear polarizer, which means that the device works for unpolarized light. The blue shift of the PBG is shown in Fig. 2. The device shows a blue shift of 50 nm. Instead of using the device as a wavelength tunable reflector, we believe that the most interesting application is a fast shutter for a particular wavelength. For this device we select the wavelength of 850 nm to switch between NIR and visible light and we obtain a contrast ratio (the ratio between the transmissions of a full PPCLC-λ/2-PPCLC device for zero and high electric field for specific wavelength) of 5. To reach higher contrasts it is essential to achieve high reflectivity and low transmittance in the PBG of the PPCLC. One option is to increase the thickness of the PPCLC layers to 8 μm.

Figure 3 shows the transmission spectra of the thicker device for unpolarized light. The contrast ratio increases to 20 while the transmission in the center of the PBG is practically independent of the applied electric field and less than 3%. The transmission in the PBG of samples with 8 μm thickness is not zero which means that there is a contribution from scattered light.[31] These measurements confirm that the field-tuning of the PBG keeps the uniform helical order which is usually not the case for polymer-based CLC switches.[24] The applied electric field can be generated by commercially available amplifiers. Due to the very limited current, the power consumption is low.

The response time of the device with PPCLCs of 8 μm thickness and right band edge at 875 nm is measured with a set of light emitting diodes (850 nm wavelength, FWHM 35 nm) and a silicon photodiode for the detection. When the voltage is off, the wavelength of the light emitting diodes is inside the photonic band gap and the incident unpolarized light is strongly reflected by the device as

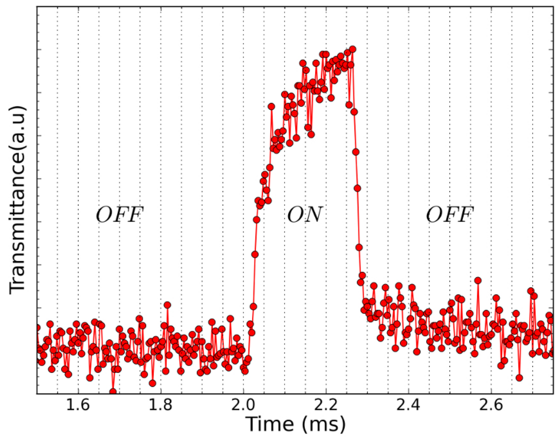


FIG. 4. Switching of the transmission for light with 850 nm wavelength for a device with two PPCLCs of 8 μm thickness for a block wave electric field with amplitude 150 V/μm and frequency 2 kHz.

shown in Figure 4. By applying an electric field, the PBG shifts to smaller wavelengths. In this state the wavelength of the light emitting diodes (850 nm) is above the PBG and the light can propagate through the device. The 10–90% response time is 20 μs for switching between zero and a block wave electric field signal with amplitude 150 V/μm and frequency 1 kHz. These switching times are much shorter than in previously reported work.[22,23,25] The fact that the switching off time is shorter than the switching on time is due to speed limitations of the voltage amplifier. The slew rate of the amplifier (Trek model 50/750) is 125 V/μs which limits the driving frequency and response time.

In conclusion, a fast polarization-independent optical switch with a 50 nm shift of the photonic band gap has been demonstrated. The switch consists of two partly polymerized chiral nematic liquid crystal layers and is driven by applying an electric field. The optical response time is 20 μs and the wavelength range of the switching is 50 nm. The device shows contrast ratios up to 20. Due to the self-assembly of chiral liquid crystal with the pitch determined by the dopant concentration, the fabrication of the switch is inexpensive and the working wavelength can be chosen.

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