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Light Sensitive Liquid Crystals for All-Optical Photonic Devices

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We report our recent efforts on the fabrication and characterization of light responsive devices realized in soft composite materials. Periodic microstructures obtained by means of a photolithographic technique and a chemical etching process have been used to micro confine a light responsive liquid crystal stabilized through a self-organization processes. The high quality, light responsive, periodic microstructures have been exploited for realizing different all-optical, fast and low power applications. An overview of the realized photonic devices is presented.

Keywords Diffraction gratings; holography; liquid crystals

Introduction

In photonics, switching devices play a key role in the control of light [1]. In particular, in the last decades, much attention has been paid to elements in which light can be controlled by light as a stimulus for a future technology towards high-speed information processing [2]. In this framework, the development of Photoresponsive Liquid Crystals (PLCs) has provided interesting solutions for all-optical switching applications [3]. In the last years several kind of PLCs have been synthesized such as photochromic dendrimers forming Liquid Crystals (LCs) phases [4]; Bacteriorhodopsin photo-driven LC [5] and azobenzene based chromophore [6]. In particular, PLCs containing an azo group in their structure have been widely exploited; they exhibit both the photosensitivity of azobenzene compounds and the high birefringence of LCs. By exposing PLCs to blue-green light, they undergo a conformational transformation (trans-cis photoisomerization), followed by a dramatic change in the macroscopic optical properties of the material [7].

It has been demonstrated [8,9] that LC compositions with a high concentration of PLCs of the series CPND [1-(2-Chloro-4-N alkylpiperazinylphenyl)-2-(4-nitrophenyl) diazene]and homologues are uniquely promising for the realization of all-optical effects;

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indeed, they enable CW, as well as nanosecond pulsed, laser induced fast switching of a large refractive index anisotropy (∼0.2), by means of low power/low energy density beams of visible light (∼1 mW/cm^2 for CW and 10 mJ/cm^2 for pulsed radiation).

The performances of LC based optical devices are determined both by the director orientation of the LC and by the confinement topology. In fact, we have recently shown [10] that it is possible to realize a polymeric template by etching a periodic liquid crystalline composite material called POLICRYPS (POlymer LIquid CRYstal Polimer Slices), a microcomposite holographic grating made of slices of almost pure polymer alternated to films of well aligned NLC [11–13]. In these structures, the NLC can be conveniently removed by using a microfluidic etching process and the obtained polymeric template can be filled, in a second step, with self-organizing materials. Here, we propose a review of some all-optical devices [14–16] realized by combining the high quality morphology of the polymeric template with the high performance properties of a PLC of the CPND series. In particular, we show that it is possible to exploit the light sensitive microstructure as all-optical diffraction grating and as an optical controlled beam splitter as well.

All-Optical Diffraction Gratings

We have realized a light responsive LC by doping a common NLC (E7, by Merck) with a 15% (in weight) of a PLC named "CPND-57" (a mixture of the piperazine-based push-pull LC azo dyes CPND 5 and CPND 7) [17]. To induce a long range order in the material, we have exploited the universal characteristics of a POLICRYPS-like polymeric microstructure realized according to the technique described in Ref. [10]. By capillary flow, we injected the PLC into the micro-channels of the polymeric template; during the whole filling process the sample was kept at a fixed high temperature (70°C); this ensured a complete transition to the isotropic state of the LCs. After the filling process had come to the end, by slowly (0.5 deg/min) cooling down the sample to room temperature, a self-organization process occurred, which gave rise to a uniform and permanent alignment of the PLC within the micro-channels; the excellent optical quality of the sample is evident in the POM view of Fig. 1(c), while Fig. 1(a), and b, shows a schematic representation of the all optical control of the grating index contrast. By using a low power red beam as a probe, it is possible to monitor the time behaviour of the diffraction efficiency of the structure. If only the probe impinges on the POLICRYPS, this exhibits a high diffraction due to the high index contrast between the NLC phase and the polymer (Fig. 1(a)). By irradiating with a green pump laser over the spot of the red light, it is possible to induce the trans-cis isomerization of the azo-dye which affects the NLC order (Fig. 1(b)); in this case, the structure shows an almost vanishing index contrast and becomes transparent to the impinging probe light. However, when the green pump beam is turned off, the red probe light itself is able to induce a reverse (*cis*→*trans*) isomerization process and the NLC order is restored. In order to investigate this effect, we have realized the all-optical setup reported in Ref. [18] which exploits a green diode pump laser emitting at $\lambda = 532$ nm and a He-Ne laser probe beam at $\lambda = 633$ nm. The wavelength of the pump beam has been selected by taking into account the absorption range of the PLC, while the wavelength of the probe beam is a compromise between the need of a high diffraction efficiency of the structure and previously obtained indications related to the absorption of the *cis* isomers. Indeed, by positioning the wavelength of the probe beam (with a suitable power) in the absorption range of the *cis* isomers, we can lower the relaxation time of the *cis*→*trans* back transition, as already reported in Ref. [19]. Preliminary attempts had shown that the best performances are exhibited by a grating of

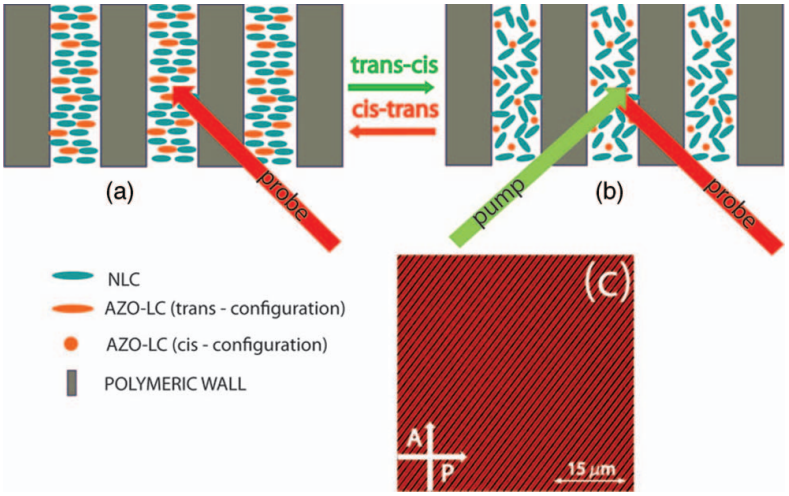

Figure 1. (color online): Schematic representation of the photo-isomerization process inside the POLICRYPS structure (**a**, **b**). POM view of the microstructure filled with PLC (**c**).

$L = 7.8\ \mu$m thickness, with a grating pitch $\Lambda = 1.48\ \mu$m, this value being such that a very high diffraction efficiency is obtained with the utilized cell [20].

Figure 2 shows a sharp variation of the diffracted beam intensity (the diffraction efficiency varies from 89% to 4%) driven by a sequence of On-Off irradiance with a pump green light ($\lambda = 532$ nm). When the structure is excited by the pump beam, NLC molecules become disordered, due to the trans-cis photoisomerization process induced by the green light in the CPND-57 component. In these conditions, the probe light ($\lambda = 633$ nm) experiences an average refractive index, of the NLC, whose value is very close to the value of the refractive index of polymeric slices; this causes a noticeable decrease of the diffraction efficiency. When the pump green light is switched Off, a *cis*→*trans* photoisomerization of the CPND-57 molecules takes place; this process, which is favoured by the probe red light, induces the re-orientation of the NLC director. In these conditions, a high modulation of the refractive index is restored and a high diffraction efficiency of the grating is thus

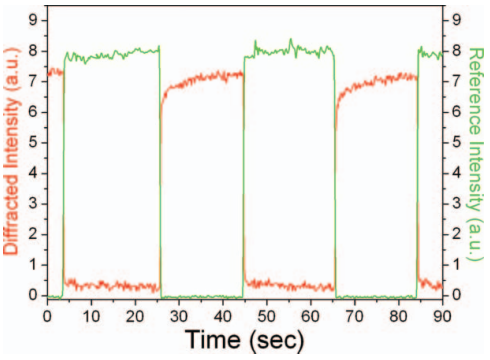

Figure 2. (color online): Optical response of the sample (red curve) triggered with a sequence of On-Off pump beam irradiance (green curve).

re-established. Response times are perfectly in phase (within the experimental error of $+/-10^{-4}$s) with the On-Off sequence of pump light irradiance.

All-Optical Beam Splitter

In order to characterize and exploit the light sensitive diffraction grating as an Optical Beam Splitter (OBS), we have exploited the interferometer setup reported in Fig. 3. The interference pattern (reported in the dark insets of Fig. 3) produced by overlapping the transmitted and first diffracted beams is monitored by the detector PD, which is provided with a small aperture (500 μm) on top of the active area. The pattern periodicity is set by varying the orientation of the Semi- Reflecting Mirror, thus the angle θ_{int}. In our experiment, θ_{int} was relatively small ($\sim 0.04^\circ$, scale is reported in the same dark inset of Fig. 3).

The fringe visibility, defined as $V = (I_{max} - I_{min})/(I_{max} + I_{min})$, (where I_{max} and I_{min} are the measured maximum and minimum intensity values of the interference pattern) strongly depends on the ratio $R = I_{1T}/I_{0T}$ of the intensities of the first diffracted and the transmitted beams. It is related to the diffraction efficiency (η) of the structure trough the equation:

$$\eta = I_{1T}/(I_{0T} + I_{1T}) = R/(1 + R) \tag{1}$$

The polarization of the probe beam and its incident angle have been adjusted to obtain, a maximum diffraction efficiency value $\eta_{max} = 50\%$ that is to say $R_{max} = 1$, when the pump beam is off. For our geometry, it is easy to see that:

$$V = [2(I_{0T}I_{1T})^{1/2}/(I_{0T} + I_{1T})]|\gamma| = [2(R)^{1/2}/(1 + R)]|\gamma| \tag{2}$$

Here, γ (the degree of coherence of the two beams) is related to the difference Δl of the optical path lengths of the two beams and to the coherence length l_c of the probe laser beam, which in our case is of the order of 10cm [HRP050 Thorlabs]. We can assume that Δl does not exceed few μm even when the piezo mirror PM is shifted back and forward (of few μm), therefore $|\gamma| = (1 - \Delta l/l_c) \sim 1$ [21]. Relating η to R by the equation (1) and

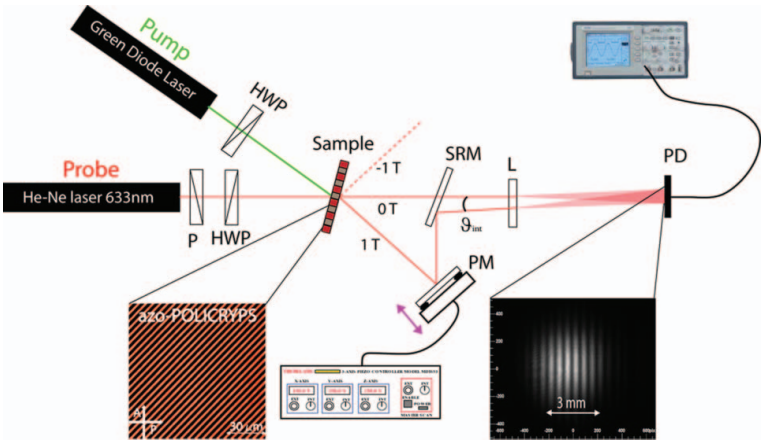

Figure 3. (color online): All-optical OBS and interferometer setup: P, polarizer; HWP, half-wave plate; SRM, semi-reflective mirror; θ_{int}, interference angle; PM, piezo-mirror; PD, photo-detector; L, lens.

substituting it into equation (2) we obtain:

$$V = 2[\eta(1-\eta)]^{1/2} \tag{3}$$

Since in our case η varies with the impinging pump power P_{pump}, we have investigated the behaviour of our tuneable OBS by detecting the fringe visibility V versus P_{pump}. Measurements have been performed by applying a linear voltage to the piezo mirror PM included in the interferometric part of the setup of Fig. 3. In this way, we were able to modify the optical path length of one of the two arms, thus allowing a scrolling of the fringe pattern on the PD and a measurement of I_{max} and I_{min} values, without moving the PD from the top of the impinging Gaussian beams. Indeed, a linear movement of the piezo mirror in the direction perpendicular to the mirror plane corresponds to a shift of the fringe pattern along a direction parallel to the PD surface. Therefore, the output signal from the PD exhibits the sinusoidal behaviour shown in Fig. 4(a) (blue curve).

The amplitude of the observed sinusoidal modulation is strongly attenuated (red curve) when irradiating with the green pump laser ($P_{pump} = 48$ mW/cm^2) over the spot of the red light. The behaviour of V versus P_{pump} is reported in Fig. 4(b). Curves can be explained by considering that the rate of the trans-cis isomerization process depends on the number of excited molecules; therefore, the rate of concentration of photoisomerized azo-LC molecules is proportional to the pump power density. This phenomenon directly affects R and therefore V, which varies from 0.94 to 0.2. As for the measured V values, following equation (2), V should vary between 1 (when $R = 1$) and 0 (when $R = 0$). The observed discrepancy (0.92 instead of 1 and 0.2 instead of 0) can be explained by taking into account that, due to the birefringence of the grating, the transmitted beam is, in fact, elliptically polarized, with an ellipticity of the order of $a/b \sim 10/1$ where a and b are the major and minor axes of the polarization ellipse, respectively. The weak component, which is polarized perpendicularly to the diffracted field is responsible for the small discrepancy between measured and predicted V values.

In conclusion, we have reported on the fabrication and characterization of a light sensitive diffractive grating for realizing all-optical devices. The diffractive structure has been exploited as light controllable diffraction grating and as Optical Beam Splitter as well. Devices exhibiting such features are of great interest in the field of optical engineering and can enable fabrication of a new generation of components with low-power and high-contrast optical switching capability, at telecommunication wavelengths.

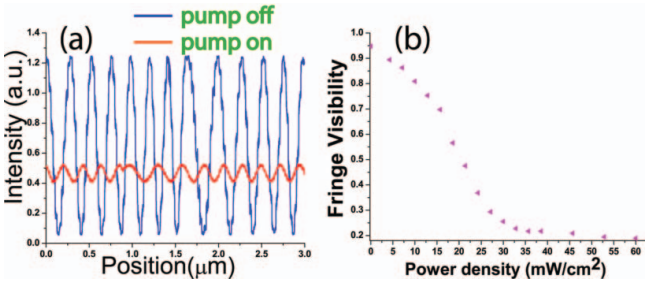

Figure 4. (color online): Intensity profile of the interference pattern versus the piezo mirror position (**a**). Fringe visibility versus the pump power density (**b**).

Acknowledgments

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