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Experimental characterization of a switchable wedge-shaped holographic grating involved as a tunable phase retarder is reported. The structure is made of polymer slices alternated to films of well aligned Liquid Crystals (POLICRYPS). The sample shows a birefringence that depends on the anisotropy of the composite liquid crystalline material and on the geometrical cell parameters. The phase retardation introduced by the structure on the impinging probe light can be finely tuned by varying the amplitude of the externally applied electric field or by spatially shifting the probed area on the sample. The quarter wave plate condition for a He-Ne laser probe has been obtained confirming the possible application of the structure as an achromatic phase retarder.

Keywords Liquid crystals; diffraction gratings; polarization selective devices

Introduction

Fundamental and applied research on polymer composite materials is very fascinating for the large amount of available possibilities. The introduction of a novel structure called POLICRYPS, fabricated by exploiting a holographic technique and showing a sharp and precise morphology (POLICRYPS acronym stands for Polymer Liquid Crystal Polymer Slices), represents an interesting contribution in this direction[1]. In the last 10 years, we performed several characterizations of this system and reported a number of possible applications.[2–8] Probably, the main advantage of POLICRYPS is the possibility to tune its optical properties and behavior by applying external fields (electric or temperature). These fields operate a change in the orientation of the Liquid Crystal (LC) component within the structure. One of the most recent implementation of POLICRYPS sees the structure involved as a phase retarder.[9] Indeed, the good confinement and stabilization, that polymer slices impose to the LC component, make the POLICRYPS a good candidate for that particular application. This structure does not suffer of typical drawbacks, like sensitivity to temperature variations or elevated probe powers, shown by other tunable systems which have been employed for the same aim.[10–14] The phase retardation mechanism is quite simple: the probe light impinging on a POLICRYPS structure is decomposed into ordinary and extraordinary components, which travel within the medium with different velocities.[15] In a perfectly aligned Nematic Liquid Crystal (NLC) film, we expect a relative phase

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difference, introduced between these two components, which can be calculated as:

$$\delta_{LC} = 2\pi L \Delta n_{LC}/\lambda$$

where Δn_{LC} is the birefringence exhibited by the LC film, L is the sample thickness and λ is the light wavelength. In a POLICRYPS, due to the presence of polymer slices which confine the LC component, we have an average birefringence value $\Delta n_{avg} \leq \Delta n_{LC}$, so that the light shone on it will experience a phase difference $\delta = 2\pi L \Delta n_{avg}/\lambda$.

Wedge-Shaped Policryps Grating

The key-factor of an optoelectronic device consists in its tunability: how fine and how large is the tuning interval can make the difference with industrial applications. In order to test our POLICRYPS as a device, we decided to fabricate a wedge shaped cell. This choice allows a very fine tunability of the introduced phase retardation because its value can be modified in, at least, two ways: a) by applying an external electric field $\boldsymbol{E}$ perpendicular to the glass slabs of the POLICRYPS; in this case, the NLC director reorients along the direction of $\boldsymbol{E}$, thus affecting the birefringence value Δn_{avg} of the structure, and hence the effective phase retardation between the ordinary and extraordinary components of the propagating beam. b) By varying the thickness L of the structure; in this case, we expect that Δn_{avg} remains fixed but the variation of L enables a tuning action on δ. The realized wedge-shaped structure has a thickness varying in the interval ($3.00 \div 5.00\ \mu$m) and has been experimentally characterized by means of the setup shown in Fig. 1. The laser beam from an He-Ne laser source ($\lambda = 632.8$ nm) is linearly polarized by the polarizer P; the polarization direction forms an angle $\alpha = \pi/4$ with the x axis of the reference system sketched in Fig. 1. The sample structure is put with its optical axis along the x axis while the polarization axis of the analyzer A can be oriented at a generic angle β (the condition $\beta = \pi/4$ corresponds to the analyzer parallel to the polarizer).

An easy way to measure both the phase retardation δ introduced by the structure and its birefringence is given by the use of the Jones Matrix formalism. As reported in [16], every component of the optical setup of Fig. 1 can be represented with a Jones matrix. Some

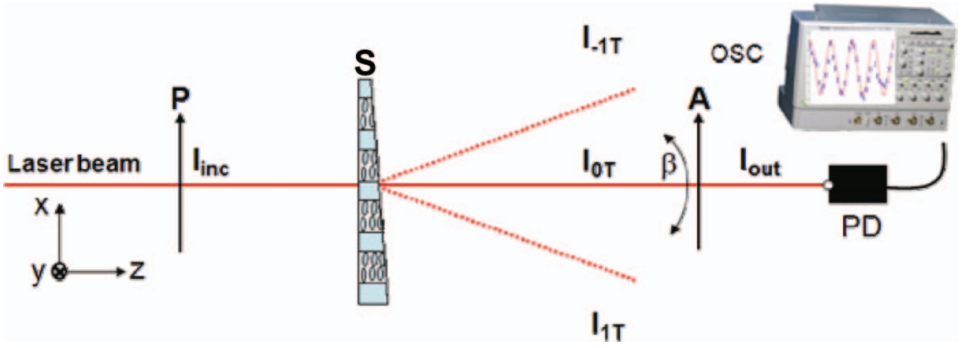

Figure 1. Experimental geometry utilized to measure the intensity transmitted by the system composed of a birefringent/dichroic sample S (POLICRYPS) put between two polarizers. P, polarizer; A, analyzer; I_{inc}, total incident intensity; I_{out}, output intensity; I_{0T} and $I_{\pm 1T}$, zeroth and first order transmitted intensities, respectively; PD, Photo-detector; OSC, oscilloscope. The probe beam is from a He-Ne laser at the wavelength $\lambda = 632.8$ nm.

attention is necessary for the Jones representation of the POLICRYPS itself. It has been observed in the past [2] that, in a POLICRYPS diffraction grating, very well aligned NLC films are confined by polymer slices, the molecular director being oriented, in average, perpendicularly to the polymeric material. This orientation of the birefringent material has an influence on the grating diffraction efficiency η, which strongly depends on the angle θ between the light electric field $\boldsymbol{E}$ and the average orientation of the NLC director (optical axis of the grating). If we roughly define the refractive index modulation along the grating structure as $\Delta n_{gr} = n_{eff} - n_p$ (where n_{eff} is the effective refractive index of the liquid crystal experienced by a light beam of given polarization, and n_p is the polymer refractive index), light polarized along the nematic director will experience a high value of Δn_{gr} (since $n_{eff} \approx n_e$ where n_e is the extraordinary refractive index of the NLC); therefore, according to Kogelnik's theory, the grating will exhibit a high value of diffraction efficiency $\eta \propto \Delta n_{gr}$. In the opposite case (light polarized perpendicularly to the NLC director), the value of Δn_{gr} is low (zero if the liquid crystal is perfectly aligned and $n_p \approx n_o$ where n_o is the ordinary refractive index of the NLC) and the grating will exhibit a very low diffraction efficiency. It is worth noting that high η values correspond to low intensity I_t of the transmitted (zero order diffracted) beam and vice versa; the grating exhibits, therefore, a dichroic effect in the transmission of light in a way which is very similar to the behavior of a linear polarizer. In Fig. 2, the experimentally measured behavior of the diffraction efficiency of a POLICRYPS structure, probed with a linearly polarized beam impinging on the sample at the Bragg angle, is plotted as a function of the angle θ between the field $\boldsymbol{E}$ of the probe light and the optical axis of the grating.

All above considerations brought us to introduce for the POLICRYPS, considered as a dichroic phase retarder, the matrix D given by:

$$D = \begin{pmatrix} He^{i\frac{\delta}{2}} & 0 \\ 0 & Ve^{-i\frac{\delta}{2}} \end{pmatrix} \tag{1}$$

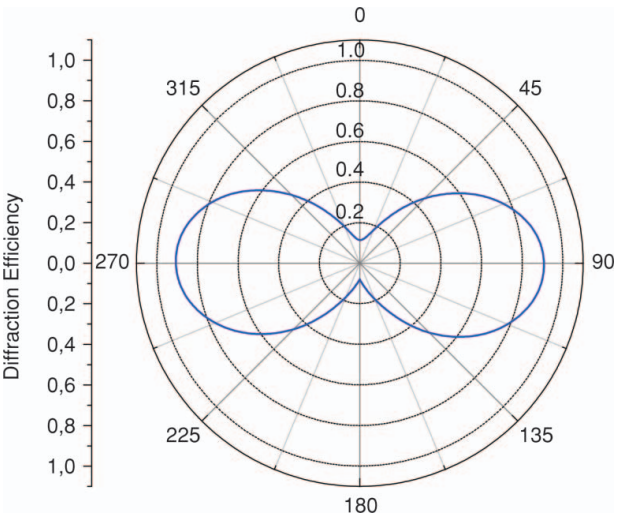

Figure 2. Experimental behavior of the diffraction efficiency of a POLICRYPS grating as a function of the angle between the NLC director and the electric field direction in the linearly polarized wave impinging on the sample at the Bragg angle.

where H and V are suitable parameters that take into account the behaviour of the structure in transmission when probed with different linear polarizations. The remaining elements of the setup in Fig. 1 can be expressed in terms of Jones matrices as follows: the complex amplitude of the electric field associated to the incident wave can be written as

$$\tilde{E}_{inc} = \frac{\sqrt{2}}{2}\sqrt{I_{inc}}\begin{pmatrix}1\\1\end{pmatrix}$$

where I_{inc} indicates the light intensity while the matrix of the analyzer, rotated of a generic angle β, is

$$A(\beta) = \begin{pmatrix}\sin^2\beta & \sin\beta\cos\beta\\ \sin\beta\cos\beta & \cos^2\beta\end{pmatrix}$$

At this point, we can calculate the electric field of the radiation coming out from the analyzer in the experimental geometry of Fig. 1 as:

$$\tilde{E}_{out} = \begin{pmatrix}\sin^2\beta & \sin\beta\cos\beta\\ \sin\beta\cos\beta & \cos^2\beta\end{pmatrix}\begin{pmatrix}He^{i\frac{\delta}{2}} & 0\\ 0 & Ve^{i\frac{\delta}{2}}\end{pmatrix}\frac{\sqrt{2}}{2}\sqrt{I_{inc}}\begin{pmatrix}1\\1\end{pmatrix}$$

which gives:

$$\tilde{E}_{out} = \frac{\sqrt{2}}{2}\sqrt{I_{inc}}\begin{pmatrix}He^{i\frac{\delta}{2}}\sin^2\beta + Ve^{-i\frac{\delta}{2}}\sin\beta\cos\beta\\ He^{i\frac{\delta}{2}}\sin\beta\cos\beta + Ve^{-i\frac{\delta}{2}}\cos^2\beta\end{pmatrix} \tag{2}$$

From eq. (2) we derive the intensity of the light transmitted by the analyzer:

$$I_{out}(\beta) = \tilde{E}_{out}(\beta)\cdot\tilde{E}^*_{out}(\beta) = \frac{I_{inc}}{2}\left[H^2\sin^2\beta + V^2\cos^2\beta + HV\sin 2\beta\cos\delta\right] \tag{3}$$

which depends on the angle β. In order to evaluate H, V and δ appearing in eq. (3), we notice that, when the axis of the analyzer is parallel ($\beta = 0$) or perpendicular ($\beta = \pi/2$) to the axis of the sample, the output intensity holds:

$$I_{out}(\beta = 0) = I_{inc}V^2/2 \quad \text{or} \quad I_{out}\left(\beta = \pi/2\right) = I_{inc}H^2/2$$

respectively, which yield:

$$V = \sqrt{\frac{2I_{out}(\beta = 0)}{I_{inc}}} \quad \text{and} \quad H = \sqrt{\frac{2I_{out}\left(\beta = \pi/2\right)}{I_{inc}}} \tag{4}$$

Knowledge of H and V values for the system under investigation, allows the calculation of the phase retardation δ :

$$\cos\delta = \frac{1}{HV}\left[\frac{2I_{out}\left(\beta = \pi/4\right)}{I_{inc}} - \frac{H^2+V^2}{2}\right] \tag{5}$$

Experimental Results

The check of the electro-optical tunability of the sample birefringence, has been performed by probing the fabricated sample in the area corresponding to a thickness $L = 4.35\mu$m. This and other thickness values have been measured before filling the cell by means of an Agilent spectrophotometer and considering the cell as a Fabry-Perot etalon. The applied electric field is a bipolar square wave with frequency $\nu = 1$ kHz and a peak-to-peak amplitude varying in the interval ($0 \div 9$ Volts/μm). Measurements of the intensity $I_{out}(\beta)$ of light transmitted by the analyzer A have been performed by changing β in the interval $0 \leq \beta \leq 2\pi$, for different values of the applied electric field. Obtained results show that the application of an electric field with amplitude varying in the interval ($0 \div 10$ Volts/μm) produces a tuning action of the phase retardation from 1.64 rad to 1.07 rad. By substituting in eq. 3 values for H, V and δ, calculated by means of eqs. 4 and 5, it is possible to compare experimental results with the predicted behavior of our structure. In each curve of Fig. 3, dots represent experimental values whereas solid lines indicate theoretical predictions; it is evident that the agreement is very good. The plot of both the birefringence value Δn_{avg} (red dots) and the phase retardation δ (blue dots) of the structure, calculated considering a thickness $L = 4.35$ μm, are reported in Fig. 4 as a function of the applied electric field. Phase retardation variations yield, in this case ($\lambda = 632.8$ nm), to a birefringence value varying in the interval ($0.024 \div 0.038$).

The phase retardation/birefringence properties of our POLICRYPS structure can be also varied by shifting the probed area of the sample along the wedge direction. Several positions have been probed; for each L value, we have measured the intensity $I_{out}(\beta)$ for values of β in the interval $0 \leq \beta \leq 2\pi$. Experimental results and corresponding theoretical curves are shown in Fig. 4. Also in this case, results confirm the possibility of tuning the

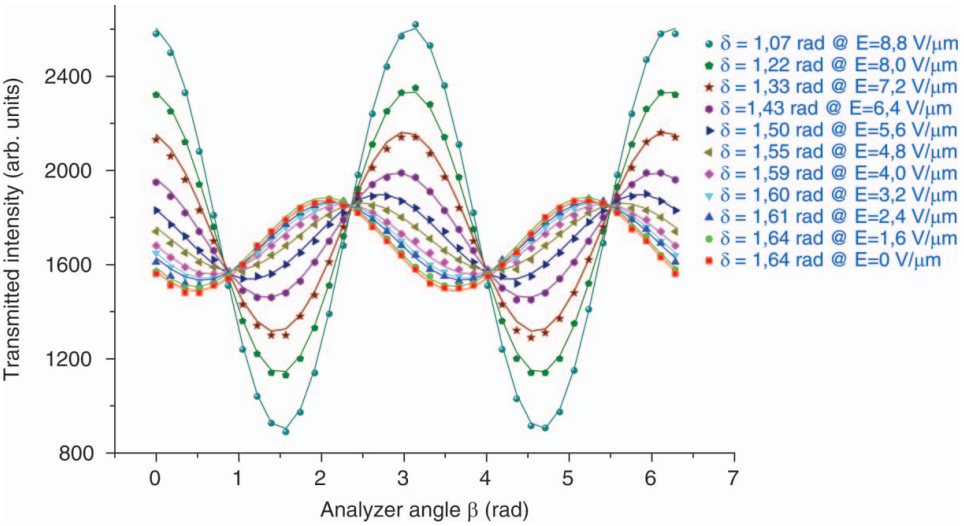

Figure 3. Behavior of the intensity transmitted by the analyzer put after the POLICRYPS grating obtained by changing the amplitude of the applied electric field. For each amplitude, the output intensity has been measured by varying β between 0 and 2π. Solid lines are theoretical fits while dots represent experimental data. Experimental errors are of the order of the dot size.

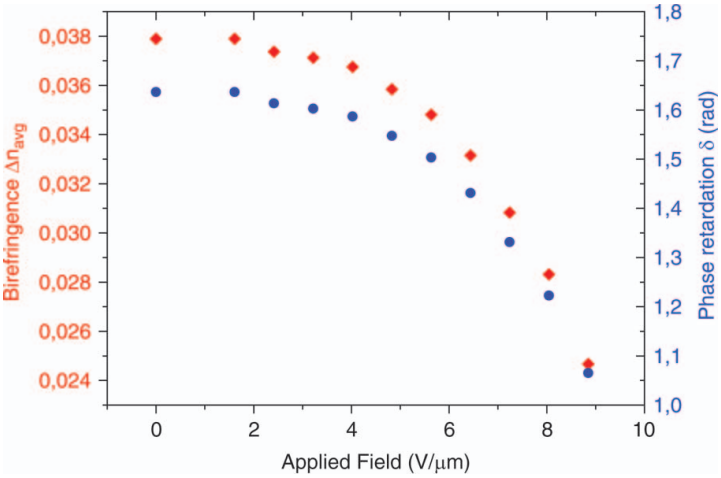

Figure 4. Plot of birefringence Δn_{avg} (red dots) and phase retardation δ (blue dots) of the POLICRYPS structure versus the amplitude of the applied electric field.

phase retardation at will by just probing the sample in the position where it has the right thickness.

The thickness value L = 4.10 μm corresponds to a phase retardation $\delta = 1.55$ rad (orange curve in Fig. 5) which is close to the condition of quarter wave plate for the He-Ne laser wavelength. This curve is almost constant for every β angle, as expected

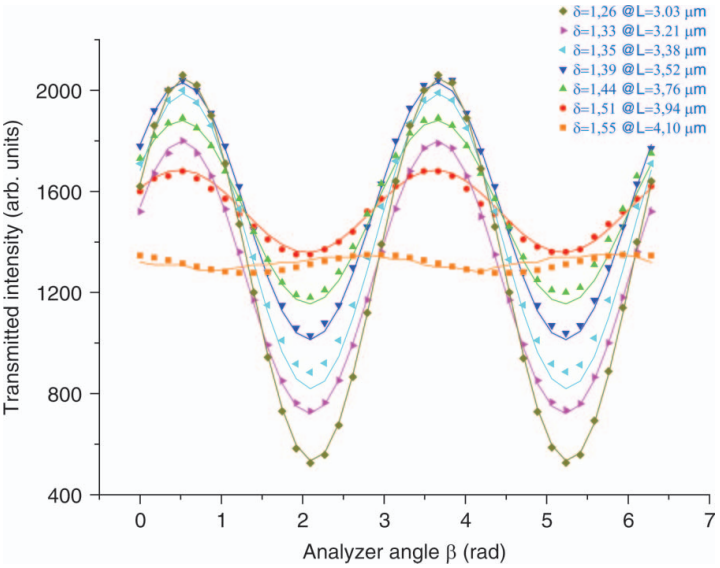

Figure 5. Behavior of the intensity transmitted by the analyzer put after a POLICRYPS grating obtained by shifting the sample along the wedge direction and probing it in areas with different thickness. For each thickness, the output intensity has been measured by varying β between 0 and 2π. Solid lines are theoretical fits while dots represent experimental data. Experimental errors are of the order of the dot size.

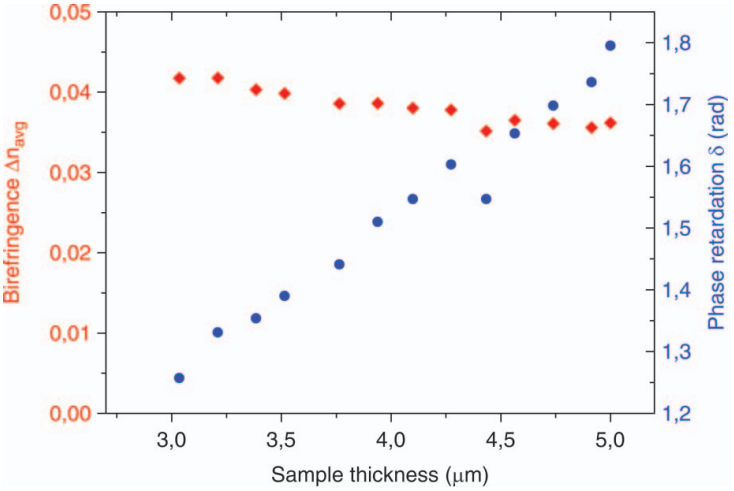

Figure 6. Plot of birefringence Δn_{avg} (red dots) and phase retardation δ (blue dots) of the POLICRYPS structure measured by shifting the sample along the wedge direction and probing it in areas of different cell thickness.

for this particular value of the phase retardation. This result confirms the possibility of finely tuning the phase retardation introduced by the structure by playing both with the amplitude of the applied electric field and the position of the sample for finding the area corresponding to the optimal thickness. Birefringence and corresponding phase retardation values, measured by shifting the sample along the wedge direction, are reported in Fig. 6. We can notice that, by increasing the thickness L in the interval ($3.0 \div 5.0$ μm), Δn_{avg} remains almost constant, as expected if we consider that the POLICRYPS grating exhibits a quite homogeneous morphology. On the contrary, the phase retardation δ shows a linear increase with values varying in the interval ($1.25 \div 1.80$ rad).

Conclusions

In this paper, we reported the application of a POLICRYPS structure as a tunable phase retarder. Experimental results have shown that the use of a wedge shaped POLICRYPS allows a double phase retardation tunability. In one case, the use of an electric field externally applied to the sample induces a reorientation of the liquid crystal component (confined between polymer slices in the structure) and hence a change of the phase retardation because of a modification of the birefringence of the overall structure. Due to the wedge shape, the phase retardation can be tuned as well by probing the structure in positions corresponding to different cell thicknesses. In this case, the birefringence remains fixed and it is the phase retardation to vary. Phase retardation/birefringence values have been measured by describing our experimental setup through a simple model based on the Jones matrix formalism. A fine tuning of the phase retardation, allowed to exactly obtain the quarter wave plate condition for a He-Ne laser. This suggests a possible use of the POLICRYPS as an achromatic phase retarder, compatibly with the achievable tunability of the phase retardation.

Acknowledgements

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