Electrically tunable two-dimensional liquid crystals gratings induced by polarization holography

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Abstract: Two-dimensional (2D) gratings made up of an array of differently twisted nematic structures are obtained by crossed assembling of 1D polarization holograms recorded at the photoaligning substrates. The rotating linear polarization pattern, produced by the interference of two opposite circularly polarized beams, is recorded on the azo-dye doped polyimide aligning layers. The 2D gratings diffract light in different directions with different polarization states, that can be optically controlled. Orthogonal circularly and linearly polarized diffraction orders are simultaneously obtained irradiating the grating with a linearly polarized beam. An external ac voltage allows to completely control the diffracted energy distribution.

OCIS codes: (050.1950) Diffraction gratings; (090.2890) Holographic optical elements; (160.3710) Liquid crystals; (230.5440) Polarization-sensitive devices.

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1. Introduction

Liquid crystal (LC) based diffraction gratings have attracted great interest due to their promising applications in displays technology, photonics and optical communications [1, 2]. The high birefringence, the high sensitivity to external fields and the influence of the surface anchoring forces allow to develop highly functional optical devices for information technologies. Switchable LC gratings with spatially periodic modulation of the refractive index have been investigated in different configurations, and several techniques and materials have been used: the phase separation of LC in polymer matrix [3,4], and the spatial patterning of LC alignment [1,5-10] have been extensively exploited.

The need to manipulate the optical signal has stimulated the development of multibeam optical devices. Among these, the 2D gratings represent an efficient way to distribute an optical signal into an array of receivers. Several approaches have been proposed for 2D switchable diffraction LC gratings as for example, ordered liquid crystal droplets structures, layer modulations in cholesteric LC and holographic patterning of the aligning substrates, polymeric and dye-doped LCs [10-12].

The control over the surface anchoring is an important issue in LC based electro optical devices and several approaches have been proposed to obtain multidomain LC films with periodic orientation of the nematic director: photo-lithography [1], laser scanning [6], mask photo-polymerization [8], atomic force microscope patterning [9], holographic recording [7, 10, 12, 13]. Among these methods, the polarization holography is a versatile single step technique that exploiting polarization holograms recorded on the photosensitive aligning layers [10, 13] has demonstrated spatial modulation of the optical axis direction in the LC bulk. Making use of interfering beams of equal intensity and orthogonal linear or circular polarizations, a periodic modulation of the light polarization state occurs in the interference region, where the intensity is almost uniform, allowing a fine and local control of the LC anchoring direction on the polarization-sensitive aligning materials. Exploiting this method, 1D and 2D LC based gratings have been obtained [10, 13, 14]. In the case of 1D grating, the switching of the total incident energy into the first order diffracted beams with ~100% diffraction efficiency has been reported. Moreover, a complete control of the diffraction efficiency from 0 to 100% by means of a low applied voltage has been demonstrated [13].

In this paper we propose electrically tunable 2D gratings consisting of a bidimensional array of supramolecular chiral structures. The crossed assembling of the polarization holograms, recorded on the photosensitive aligning substrates by means of the interference of two laser beams with opposite circular (OC) polarizations, allows to obtain a liquid crystal cell consisting of a 2D array of twisted nematic structures with different twist and handness.

The resulting 2D gratings not only influence the spatial energy distribution but also convert the polarization state of the incident beam, as usual for polarization holograms. In fact, they diffract the incident beam in several orders with various polarization states: orthogonal linear and circular polarized beams simultaneously occur. Very efficient gratings are obtained with a total diffracted intensity higher than 50%. The spatial energy distribution can be controlled by means of the polarization state of the incident beam, i.e. linear, circular or elliptical. Moreover exploiting the high sensitivity of the liquid crystal based devices to the external fields, the intensity distribution on the diffracted beams can be completely controlled by means of a low applied voltage, that modifies the director configuration. Even if this

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particular geometry has been already investigated by other authors [10], no polarization analysis of the diffracted waves has been shown. Moreover the published results do not agree with the findings reported in the present paper. In our opinion, this discrepancy, also observed for the 1D gratings [10, 13], could be due to some relevant differences in the experimental conditions, such as the anchoring strength at the aligning substrates and/or the geometrical parameters of the system (i.e., thickness of the LC cell and spatial periodicity of the holograms recorded on the surfaces).

2. Experimental results and discussion

In the experiment, the ~20nm thick polarization sensitive layers of azo-dye doped polyimide (1:1 by weight), whose chemical formula and absorption spectra are reported in Ref. 15, were prepared from its polyamic acid solution (2% by weight) in dimethyl formamide by spin coating (FR10KPA, CaLCTec S.r.l.) on indium-tin oxide coated glasses, followed by solvent evaporation and imidization. These substrates were individually exposed to the periodic spatially rotating linear polarization pattern obtained by the interference of two OC polarized beams of an Ar^+ laser (wavelength, λ = 458nm) with equal intensity of 100mW/cm^2 and for an exposure time of 60s (see Fig. 1). The spatial periodicity of the polarization pattern Λ is 20µm.

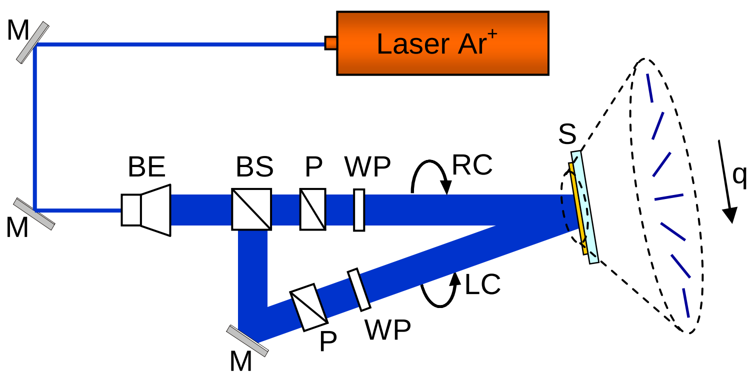

Fig. 1. Experimental setup for the recording of polarization holograms on the photosensitive substrates. M – mirror, BE – beam splitter, P – polarizer, WP – quarter wave plates, S – photosensitive substrate, q – grating vector, RC – right circular polarization, LC – left circular polarization. The dashed region denotes the rotating linear polarization pattern.

Cells of 3, 5, 7 and 10µm thicknesses were subsequently assembled orienting the patterned substrates with the wave vectors of the polarization grating orthogonal with each other [see Fig. 2(a)]. The cells were filled by capillary action with the LC mixture E7 (BL001, of Merck) above the clearing temperature (~70°C) and slowly cooled down in the nematic phase to room temperature. Following the anchoring configuration imposed by the aligning substrates, the expected cell configuration is a 2D continuous array of differently twisted nematic, where the easy axes at the two aligning substrates assume all the possible orientations in the x-y plane. Therefore, the twist angles vary from 0° (planar alignment) to 90° (complete twist). In Fig. 2(b) we report the scheme of the 2D array where the red and black arrows represent the easy axes at the front and back substrate, respectively.

A He-Ne laser at λ_p=633nm was used as probe beam to investigate the diffraction properties of the LC gratings. No detectable diffraction of the probe beam has been observed by the assembled polarization holograms (empty cells). Bidimensional diffraction occurred

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only when the LC was infiltrated in the cell. A polarimeter [16] was used to investigate the polarization state of the diffracted beams.

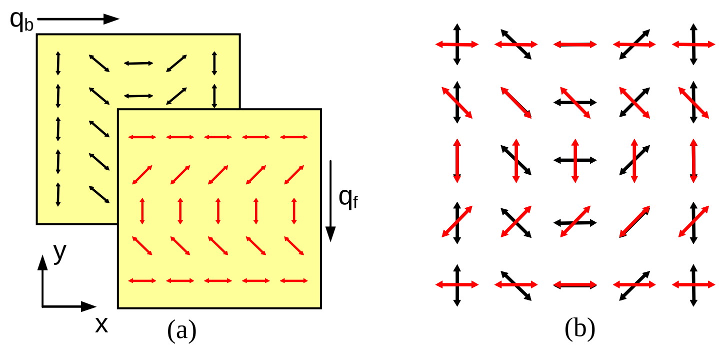

Fig. 2. Assembling of the polarization patterned substrates of the liquid crystal cell with orthogonal grating vectors q_f and q_b for the front and back substrates, respectively (a). Scheme of the 2D array (b): easy axes at the front (red arrows) and back (black arrows) substrates.

In Fig. 3(a) the typical far field diffraction pattern created by these LC gratings is shown, which is characterized by an unusually low scattering and high efficiency. The grating vectors are slanted with 0°, 90° and 135° with respect to the x axis, while the grating wave vector at 45° is absent. Moreover the grating vector at 135° corresponds to a spatial periodicity equal to $\sqrt{2}\Lambda$. Diffraction efficiency (DE) of ~20% has been obtained for the beams diffracted with grating vectors at 0° and 90°, while the DE is ~5% at 135°. In Fig. 3 we report the diffraction patterns and the polarization states of the beams diffracted by the 2D LC grating in the 3μm thick cell, for linear (b), right circular (c) and left circular (d) polarization of the probe beam. The (-1,0), (1,0), (0,-1) and (0,1) orders of diffraction always exhibit OC polarization states [see Fig. 3(b)], while the zero order (0,0) has the same polarization state of the incident beam, which is linear in Fig. 3(b) and circular in Figs. 3(c) and 3(d). For linear polarization of the probe beam the (-1, 1) and (1,-1) orders exhibit linear polarization which is perpendicular with respect to the incident and the (0,0) beams, as shown in Fig. 3(b). For circularly polarized probe beam only the (1,0) and (0,1) or (-1,0) and (0,-1) orders appear, depending on the helicity (RC or LC) of the incident beam, while the (-1,1) and (1,-1) orders are always present, see Figs. 3(c) and 3(d). Moreover, all the transmitted and diffracted beams are circularly polarized with opposite helicity.

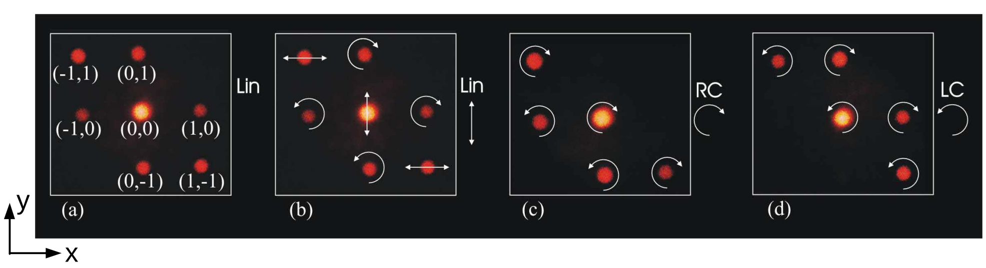

Fig. 3. Photos of the far field diffraction pattern produced by 2D grating in 3μm thick cell. Diffraction pattern for linear probe beam with the actual order names (a) and polarization state (b). Diffraction patterns and polarization states for circular right handed (c) and left handed (d) polarization of the probe beam.

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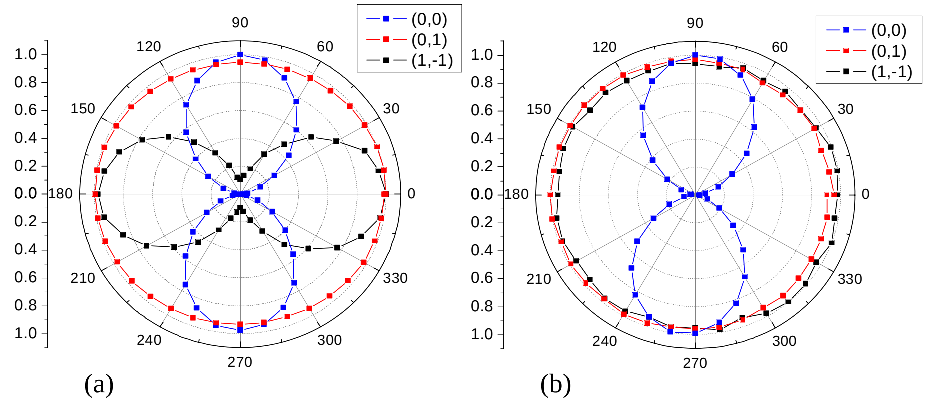

Fig. 4. Polarization states of the (0,0) beam (blue), of the (0,1) beam (red), and of the (1,-1) beam (black), for 3µm thick cell (a) and 5µm thick cell (b).

In Fig. 4(a) we report the polar plots of the (0, 0), (0,1) and (1,-1) orders for a linearly polarized probe beam. The intensities after a rotating linear polarizer have been measured versus the angle of the polarizer axis with respect to the x axis. The graphs prove the good quality of the linear or circular polarization of the diffracted beams.

These results show that the spatial energy distribution in the diffracted orders can be optically controlled by means of the ellipticity of the probe beam.

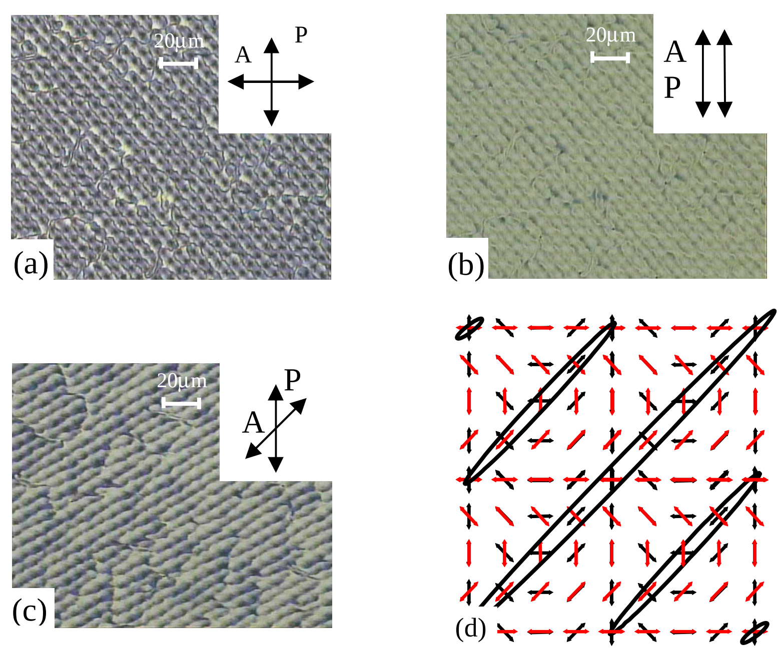

Fig. 5. Optical microscopy images of the 2D structure between crossed polarizer and analyzer (a), parallel polarizer and analyzer (b) and with the analyzer at 45° with respect to the polarizer (c). Scheme of the 2D array with highlighted oblique homogeneous regions (d).

In Fig. 5 we report the optical microscope images of the 3µm thick cell between crossed polarizers [Fig. 5(a)], parallel polarizers (Fig. 5(b)) and with the analyzer at 135° with respect

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to the polarizer [Fig. 5(c)]. These investigations allow to gain insight about the LC configuration in the bulk. 2D LC structures with crossed defect lines are observed. In Fig. 5(a), the dark areas correspond to the planar nematic regions whose director is parallel or perpendicular with respect to the polarizer, while the bright areas correspond to the completely twisted regions where the nematic optical axis at the exit surface is parallel to the analyzer. Between parallel polarizers [Fig. 5(b)] the contrast is reversed. The 90° twisted regions with the anchoring axes perpendicular to the polarizers correspond to the dark regions. Other local configurations of the nematic director originate different grey scale depending on the relative orientations between the optical axes at the entrance and exit surfaces and the optical axes orientation of the polarizers. The image with the analyzer at 135° reveals a periodic optical structure with the grating vector at 135° [Fig. 5(c)]. This evidence could be explained looking at the scheme in Fig. 5(d) where homogeneous regions characterized by an equal angle of twist exist along the direction at 135°.

The investigation performed on thicker cells made evidence of some differences in the diffraction properties with respect to the results obtained for the 3μm cell. In these cases, the (-1,1) and (1,-1) diffracted beams are always circularly polarized with opposite helicity for both linear and circular polarization of the probe beam. For circularly polarized probe beam only one order for each grating vector appears. In Fig. 4(b) we report the polar plots of the diffracted beams for the 5μm thick cell, showing that the (1,-1) order exhibits a good circular polarization state, differently from the 3 μm thick cell [Fig. 4(a)].

To account for these two distinct behaviors, we suggest that different actual configurations of the nematic director are achieved in the bulk, depending on geometrical cell parameters like thickness (d) and spatial periodicity of the polarization holograms (Λ). Indeed, a similar geometrical stability condition for the bulk nematic configuration has been recently proposed [2] and experimentally proved for the 1D polarization gratings LC replica [13]. In that case, in fact, for d/Λ higher than a certain threshold value the nematic configuration in the bulk deviates from the uniform rotation of the director imposed by the patterned substrates because of the elasticity of the LC. We believe that the ideal 2D twisted configuration of the nematic director [as depicted in Fig. 2(b)] is only attained in thin cells, i.e., for d/Λ lower than a certain threshold. On the other hand, we can think of the nematic film in the thicker cells like a three layers system: the two outer layers, confining with the aligning substrates, in which the liquid crystal director follows the directions imposed by the nearest surface, and the inner optically isotropic layer where the nematic distortion relaxes due to the competition between the anchoring and the elastic energies. This hypothesis is supported by the theoretical analysis of the diffracted fields by means of the Jones matrix formalism, whose details will appear elsewhere.

The polarization investigations make evidence of some interesting features of this diffractive LC device related to the control of both the beams propagation directions and the polarization states by means of the polarization state of the incident light beam. Similar features have been obtained exploiting more complex procedures as, for example, multiple recording of crossed polarization gratings in thin film of polarization sensitive materials [17] or multibeam holography [12]. These procedures generally produce permanent recording in the bulk of photosensitive materials. In the present case, on the contrary, the permanent bulk configuration of the nematic director is achieved through the surface anchoring conditions and, as usual for LC devices, it can be modified by an external field. This peculiarity of the 2D LC grating adds interesting features which are useful for beam steering, optical switching, polarizing and multibeam devices. In fact, the energy distribution in the diffracted beams can be modulated by applying an external voltage to the LC cell.

Low external voltage [2, 10, 13], uniformly applied to the 2D LC grating, provides control of the effective birefringence Δn and allows to properly adjust the DE of the diffraction orders. The electro-optical behavior of the LC gratings has been investigated measuring the intensities of the diffracted beams versus the ac voltage (f = 5kHz) ramped from V_{RMS} = 0 to 7 V. In Fig. 6(a) we report the DE values of the orders (0,0), (0,1), (1,-1), (-1,0) of the 3 μm

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thick cell versus V_{RMS}, for right circularly polarized probe beam . Starting from a value of 5 % for the (0,1) and 3% for the (1,-1) orders when V_{RMS} = 0V, the (0,1) order DE first increases to ~18% at $V_{RMS} \cong 2V$ (simultaneously the same occurs for the (1,0) beam, not shown in the figure), then decreases towards zero, whereas the (1,-1) DE decreases to 0 at $V_{RMS} \cong 3V$. The transmitted beam (0, 0) vanish when the (0,1) and (1,0) orders reach the maximum value. This behavior is similarly reproduced in the 5μm thick cell where a larger number of oscillations of the intensity of the beams is observed versus the voltage [Fig. 6(b)], due to the larger thickness [13]. These results show that a low external voltage allows to easily switch ON and OFF the diffracted and transmitted beams.

It is worth noting that while the threshold voltage for the 3μm thick cell is nearly the Freedericks value (~1.0 V for E7), for the thicker cell the director reorientation occurs at lower voltage. The observed behavior, according to which the threshold voltage of the 2D LC gratings diminishes versus the cell thickness *d* for fixed Λ, is analogous to what has been recently predicted for 1D gratings [18], for which a lowering of the threshold is expected when d/Λ increases. Even if the bulk director configuration for the 1D LC gratings is simpler, we suggest that the reason of the threshold reduction for the 2D LC gratings is similar. In particular, because of the rotation of the anchoring direction at the patterned substrates, the nematic distribution in the bulk tend to deviate from the configuration imposed by the surfaces (due to the elasticity). This elastic contribution towards the equilibrium configuration in the bulk enhances the effect of the electric field, resulting in a lowering of the threshold voltage.

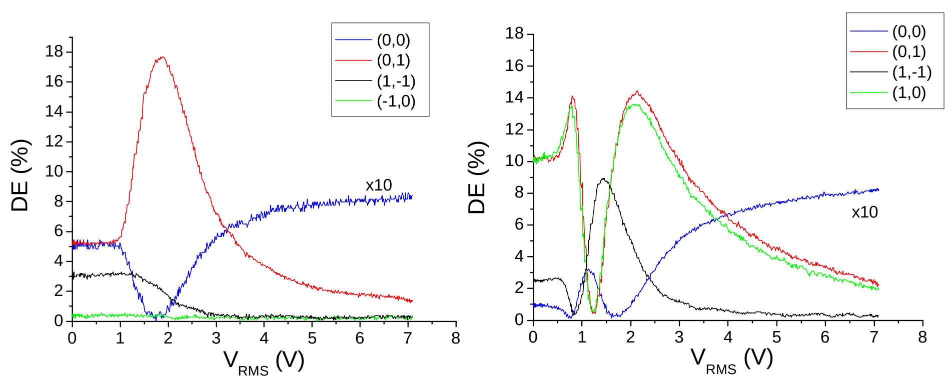

Fig. 6. Diffraction efficiencies versus the ac voltage (f = 5kHz) of the 3μm (a), and 5μm (b) thick cell, for circularly polarized probe beam.

3. Conclusion

In the present paper we demonstrate the possibility to obtain a highly functional multibeam optical element exploiting the large sensitivity and flexibility of LC devices and the polarization holography. The 2D diffraction gratings are obtained in a LC cell by the crossed assembling of the polarization holograms recorded on photosensitive aligning substrates. Low scattering and high efficiency have been reported. The gratings diffract in different directions with different polarization states, that can be optically controlled through the polarization state of the incident light beam. Additionally, a complete control of the diffracted energy distribution between all orders of diffraction has been obtained applying a low external voltage. Two regimes for the energy distribution and the polarization states of the diffracted orders have been observed depending on geometrical parameters of the LC cell.

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