The principles of laser beam control with polarization gratings introduced as diffractive waveplates

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ABSTRACT

The development history of polarization gratings (PGs), with origins in holography and Bragg gratings, accentuated and reinforced their perception as gratings. We highlight their nature as waveplates – diffractive waveplates (DWs) – and stress their family connection to vector vortex waveplates. This approach provides a straightforward understanding of the unusual properties of PGs, such as nearly 100% diffraction in thin material layers, the presence of only one diffraction order for a circularly polarized beam, wide diffraction bandwidth and the possibility of achromatic behavior. With technology being ripe for applications such as beam steering, and optical switching, we characterize the resistance of DWs to optical radiation, the effects of temperature and deformations. We also show that the boundary effects in the manufacturing process make it necessary to use substrates larger than the desired aperture of the DW. The multi-component systems are discussed for developing normally transmissive switchable imaging systems, beam scanning, and achromatic diffraction.

Keywords: Polarization gratings, Diffractive waveplates, Holography, Imaging, Liquid crystals, Optical switching, Beam steering, Electro-optics.

1. INTRODUCTION

Waveplates and diffraction gratings are two important classes of optical components. The functions performed by gratings are hard if not impossible to accomplish with waveplates and vice versa. For example, can a waveplate diffract a beam like a Bragg grating? Or could a grating be used for reversing the sign of circular polarization of a light beam? The updated answer to both questions is… yes, but only if the grating is also a waveplate. Such grating-waveplates have been known for some time now as "polarization gratings (PGs)"[1,2,3,4]. PGs are apparently the shorter version of polarization holography gratings - the term meant to describe a grating of optical axis orientation of a birefringent material recorded in the process of polarization holography, where the light intensity is constant and only the state of polarization is modulated in space. The name conceals the nature of those components, thus making it difficult to understand their ability to produce nearly 100% diffraction in thin layers (defined by the half-wave plate condition), and its spectrally and angularly broadband nature. Moreover, it further conceals the familiar relationship of "polarization gratings" with vector vortex waveplates (known also as q-plates and spiral phase plates)[1,5,6], Figure 1.

In this paper, we highlight the waveplate nature of seemingly the most prominent representative of polarization holography gratings, "Cycloidal Diffractive Waveplates," Figure 1(a). Like vector vortex waveplates, or q-plates, Figure 1(b), they are Pancharatnam-Berry Phase Optical Elements (PBOE). One main purpose of this paper is to encourage looking at them as waveplates; diffractive waveplates in particular. The term "Diffractive Waveplate," compared to "grating-waveplates" has the advantage of encompassing the widest variety of optical axis modulation patterns, one-

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dimensional, two-dimensional, Figure 1(c), or with axial symmetry, that could be produced in a waveplate resulting in the widest variety of diffractive elements. One such remarkable optical component not yet demonstrated experimentally is the DW lens produced by two-dimensional optical modulation of optical axis orientation in polar coordinates[5].

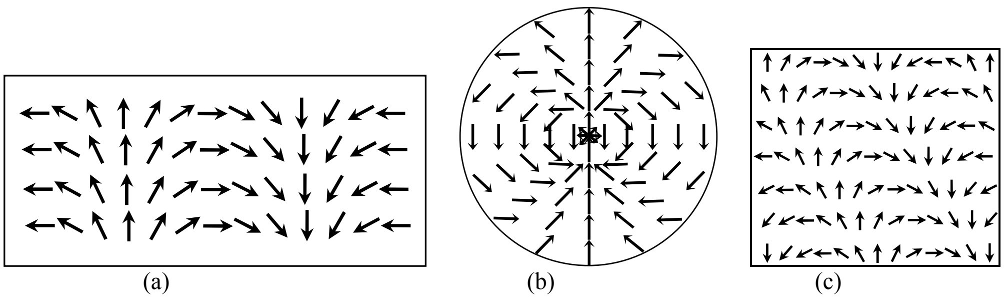


Figure 1. The optical axis orientation in various Diffractive Waveplates (DWs): (a) Cycloidal; (b) Axial (vector vortex plate, q-plate); and (c) 2-D Cycloidal.

2. CYCLOIDAL DIFFRACTIVE WAVEPLATE (CDW) EXPLAINED

Figure 2(a) shows a series of half-wave plates, arranged side-by-side, with their optical axis rotating in space. A linearly polarized beam exits a half-wave plate with the polarization rotated at an angle which is double the angle made between the input beam polarization and the optical axis of the waveplate. For most half-wave plate applications, the optical axis makes a 45 degree angle with respect to the polarization of the input beam in order to rotate it by 90 degrees. In the case corresponding to Figure 2(a), the linear polarized input light beam emerges from the series of waveplates with the polarization angle changing from one plate to the other. This rotation pattern, in the case of continuously rotating optical axis orientation, is also continuous and, if the optical axis modulation period Λ is comparable to the wavelength of a light beam λ, the polarization modulation pattern, Figure 2(c), can be the same as in the overlap region of two orthogonal circularly polarized beams propagating at an angle $\alpha = \pm\lambda/\Lambda$ with respect to each other, Figure 2(b).

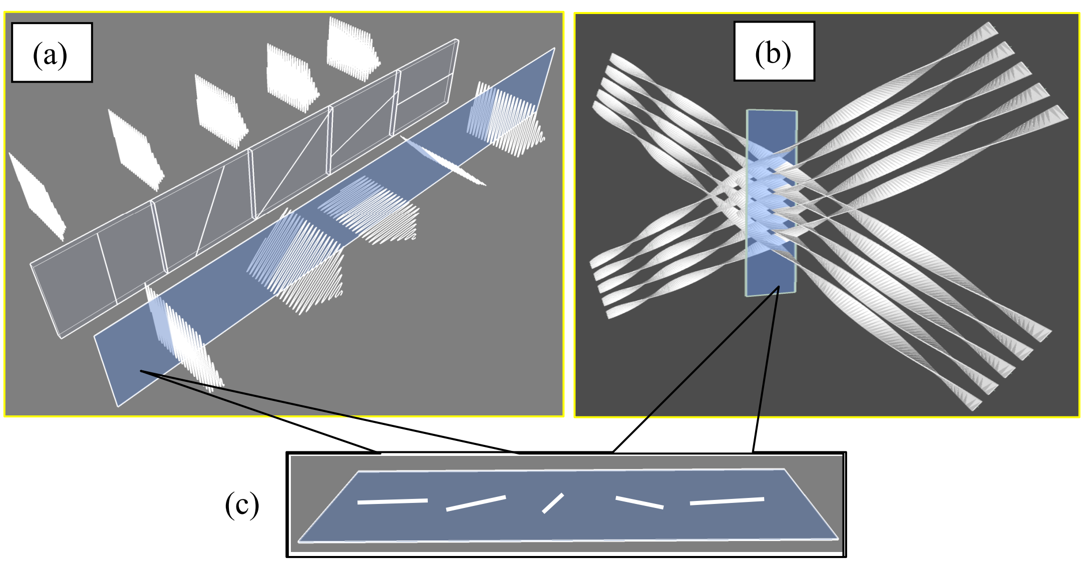


Figure 2. (a) Half-wave plate with continuous rotation of optical axis orientation; (b) Overlapping beams with orthogonal circular polarization; (c) Same polarization modulation pattern at the cross-section.

This explains the splitting of a linear polarized beam into right- and left-circular polarizations at the output of such a cycloidal waveplate with the diffraction angle $\alpha = \pm\lambda/\Lambda$. There would be one diffraction order only for a circularly polarized input beam, and the sign of the circular polarization of the diffracted beam will be orthogonal to that of the input beam (as one would expect from a half-wave plate). If the wavelength of the beam deviates from the half-wave plate condition, the diffraction efficiency for a circularly polarized beam, determined by the conversion efficiency of the input polarization into the orthogonal one by the waveplate, will change correspondingly, following the familiar law

$$\eta = \sin^2 \frac{\pi L(n_e - n_o)}{\lambda} \tag{1}$$

By that, the transmission coefficient for the input beam, independent of polarization, is equal to

$$T = \cos^2 \frac{\pi L(n_e - n_o)}{\lambda} \tag{2}$$

Thus, the "magic" of PGs is easily unraveled when approaching them as half-wave plates. The unique capabilities of these components are intensely studied these days. For many applications, especially involving laser beams, it is important to characterize the effect of radiation on stability and properties of DWs themselves.

3. THE EFFECTS OF RADIATION ON CDW

Historically, it may not have been so, but the first applications that should come to mind, with the realization of a micrometer thin optical element with 100% diffraction efficiency, are high energy/high power laser systems. Small absorption of thin and transparent CDW layers in visible and near IR spectral ranges allows one the freedom of choosing a substrate that is most transparent for the wavelength of interest, thus maximizing the laser beam energy/power range for functionality of the optical components[7].

3.1. Resistance to radiation

We performed some preliminary research to characterize the effect of radiation on CDWs based on liquid crystal (LC) material systems. No damage of a LC polymer CDW was observed in a continuous wave (CW) beam and, for short laser pulses, up to the energy density levels that cause damage to the glass substrates (microscope slides in these tests). The results are summarized below in Table 1.

Table 1: Characterization of radiation damage of LCP CDWs

Beam type	Wavelength, μm	Exp. Condition (beam size)	Max energy/power/ Intensity	Result
CW	1.06	Unfocused (2.5 mm)	22 W 100 W/cm^2	No damage observed.
CW	1.06	Focused (4 μm)	22 W 30 kW/cm^2	No damage observed.
Single Pulses (4 ns)	0.532	Unfocused (2.6 mm)	230 mJ 0.2 GW	No damage observed.
Pulse train (4 ns, 10 Hz)	0.532	Unfocused (2.6 mm)	230 mJ 0.2 GW	No damage observed.
Single Pulses (4 ns)	0.532	Focused (6.5 μm)	6 mJ 0.9 GW	Substrate damage.
Pulse train (4 ns, 10 Hz)	0.532	Focused (6.5 μm)	5 kW/cm^2	Substrate damage.

3.2. Heating

Even if the CDW layer is too thin and transparent and does not absorb the beam in any appreciable way, heating of substrates in a high power laser beam inevitably leads to a temperature increase, and is another key factor to take into account, particularly when dealing with LCs. The temperature affects the characteristics of the CDW by changing the optical anisotropy of the material $\Delta n = n_e - n_o$. The wavelength corresponding to peak diffraction efficiency, the Bragg wavelength λ_B, changes according to

$$\frac{d\lambda_B}{dT} = 2L\frac{d\Delta n}{dT} \tag{3}$$

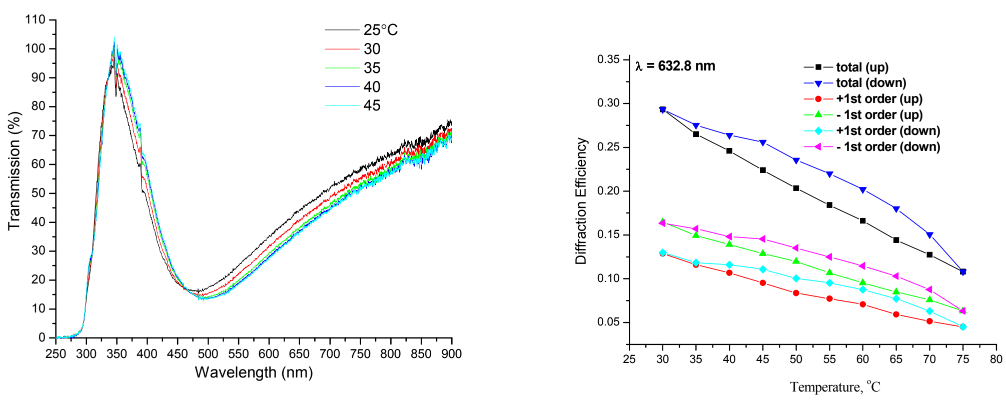
Thus, assuming $d\Delta n/dT \sim 10^{-3}K^{-1}$, and $L \sim 1$ μm, we get $d\lambda_B/dT \sim 2$ nm/K. The temperature dependence of the optical anisotropy of a LC is strongest far from the critical temperature for phase transition into the isotropic state. The effect of temperature can be reduced by using a LC with a wide temperature range for its mesophase, but it also can be increased by using LCs near their clearing point for other applications such as sensing. Note here also, that the relative change in the Bragg wavelength is equal to the relative change of the optical anisotropy of the material, $(d\lambda_B/dT)/\lambda_B = (d\Delta n/dT)/\Delta n$, and it does not depend on the CDW layer thickness.

Variation of the Bragg wavelength results in changing diffraction efficiency for the beam of a given wavelength:

$$\frac{d\eta}{dT} = \frac{d\Delta n}{dT}\sin\frac{2\pi L\Delta n}{\lambda} = \frac{d\Delta n}{dT}\sin\frac{\pi\lambda_B}{\lambda} \tag{4}$$

The change is at the minimum for the Bragg wavelength ($d\eta/dT = 0$ at λ_B) and at the maximum at $\lambda = 2\lambda_B$.

Figure 3 shows the effect of temperature on a LC-based CDW. The wavelength corresponding to the peak diffraction efficiency is shifted by nearly 10 nm with a 20°C temperature increase. The diffraction efficiency of the CDW with λ_B = 488 nm is decreased from ~16% to ~6%, for a red wavelength λ_B = 633 nm when the temperature is increased from 30°C to 75°C.



(a) (b)

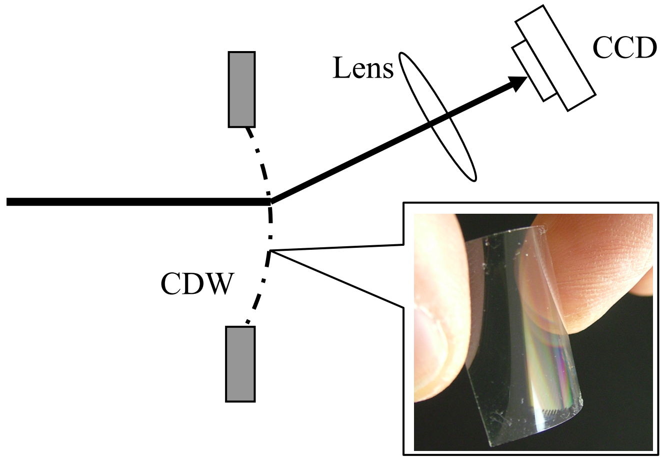
Figure 3. (a) Temperature dependence of the transmission spectrum of a LC CDW measured with a fiber-optic spectrometer – low transmission corresponds to high diffraction efficiency. (b) Temperature dependence of the diffraction efficiency of a LC CDW.

Note again, that the wide variety of LC and LC polymer materials provides a means for increasing or decreasing the effect of temperature on the optical characteristics of a CDW over a wide range.

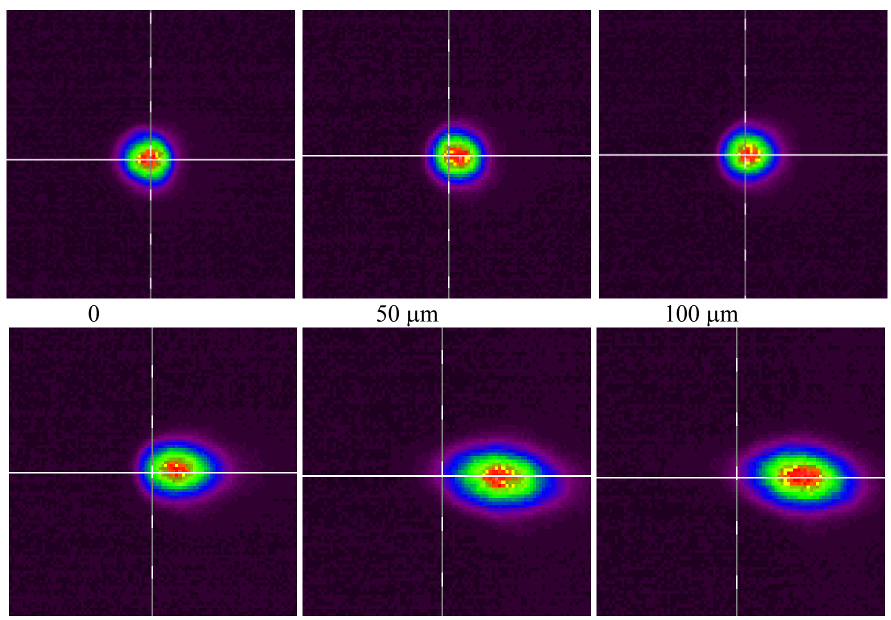
3.3. The effect of deformations

Thermal stresses may result in CDW deformations. To study the effect of deformations we measured the change in the beam profile as a function of bend and twist deformations for a CDW deposited on a polymer film. The flexibility of the polymer allowed the introduction of very large deformations. Bending was obtained by pressing the polymer from its sides, Figure 4(a), in a horizontal plane. A diffracted He-Ne laser beam expanded to 5 mm was registered by a CCD beam profiler. A lens (600 mm focal length) was required for projecting the beam into the CCD. At large bending size, ~

100 μm, the beam profile exhibited elongation in the horizontal direction, Figure 4(b). The diffraction angle was also changed, resulting in a shift of the position of the beam at the CCD. Both, the magnitude of the shift and the change in the beam width are shown in Figure 5. The sensitivity of the CCD had to be adjusted for each deformation in order to maintain the peak intensity value.

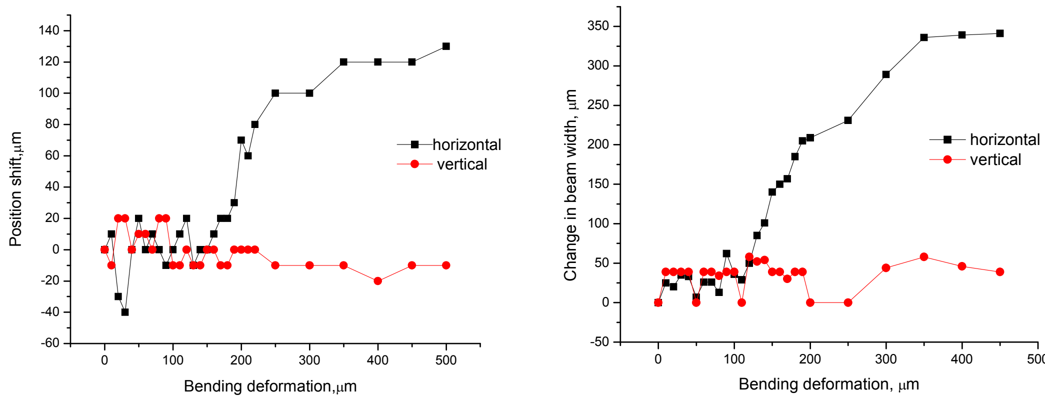


(a)



(b)

Figure 4. (a) The experimental setup. (b) The test beam profile at different bending sizes.



(a) (b)

Figure 5. The change in the position (a) and in the width (b) of the test beam as a function of bending deformation size.

In the case of twist deformation, induced by rotating the upper edge of the CDW with respect to the bottom, the beam profile was elongated and also tilted without shift, Figure 6. The photos in Figure 6 were taken in the regime of auto positioning. As in the case of bending deformation, the sensitivity of the CCD had to be adjusted for each deformation in order to maintain the peak intensity value.

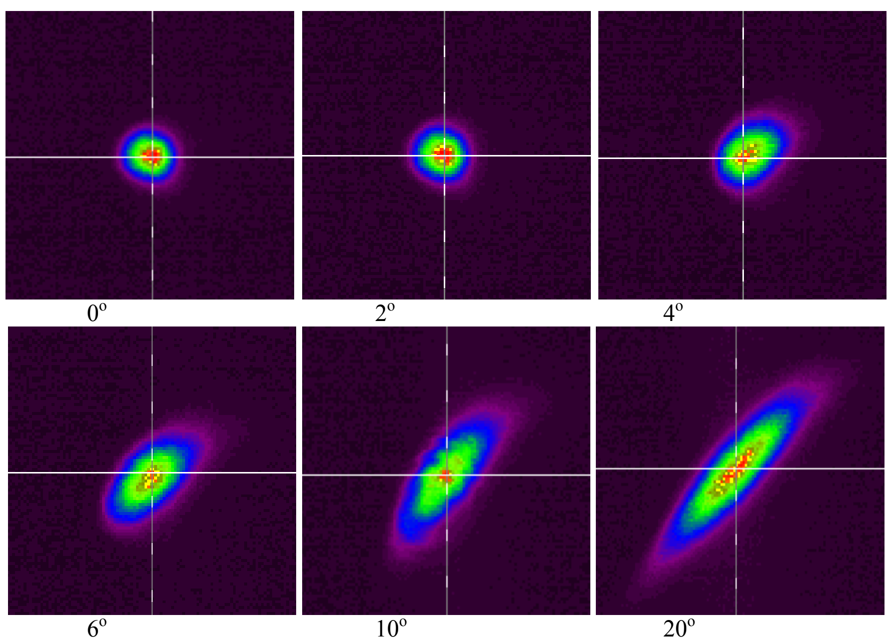


Figure 6. Beam deformation as a function of twist angle.

3.4. Optical homogeneity

Due to its waveplate nature, thickness plays a critical role in the optical characteristics of CDW. The spin coating technique allows for high precision control of LC polymer CDW layer thickness; however, we show below that the boundary effects could be significant. Therefore, to obtain a CDW of a given aperture size, it should be fabricated on a larger substrate. To determine the boundary effects, a LC polymer CDW was fabricated on a square glass substrate of 25 mm size. It was then scanned in a laser beam of 1.5 mm size while registering the intensity of a diffracted beam. Figure 7 shows that the diffraction efficiency is perfectly constant in the central part of the CDW while it starts varying at about 5 mm from the edges.

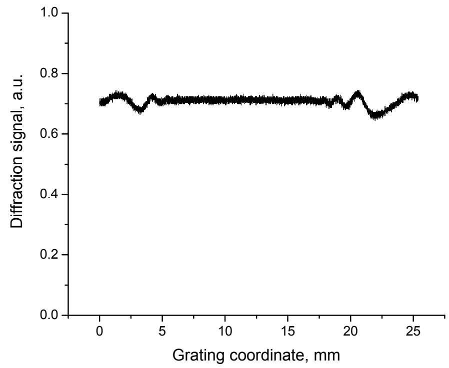
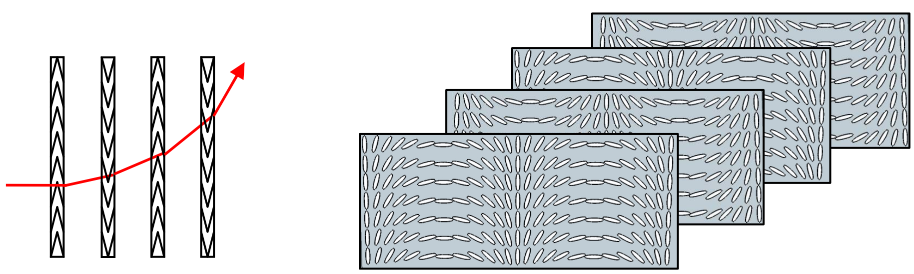


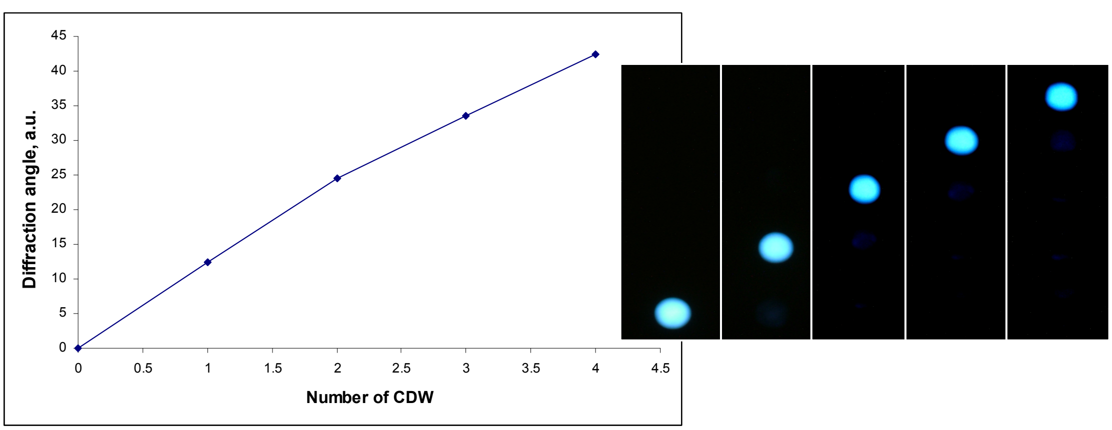
Figure 7. Diffraction efficiency of a LC polymer CDW across the CDW area.

4. MULTILAYER SYSTEMS

Due to high diffraction efficiency over a wide range of angles, the deflection angle of a light beam can be changed by arranging CDWs in a series, Figure 8. The increase in the deflection angle in Figure 8, however, takes place only when each subsequent CDW is rotated by 180 degrees around the axis in the plane of the CDW. This is shown in Figure 8(a) by up and down arrowheads.



(a)



(b)

Figure 8. Changing diffraction angle with a sequence of CDWs with alternating parallel/anti-parallel alignment patterns: (a) schematic; (b) experimental.

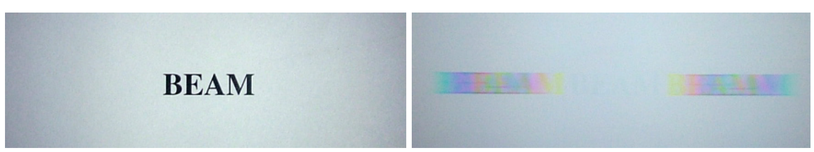
The diffraction is cancelled for a pair of CDWs arranged in parallel patterns[8]. Thus, as shown in [8] a pair of CDWs can be used for steering a laser beam similar to a pair of Riesley's prisms or a pair of Bragg gratings[9]. Due to their high damage threshold and the opportunity to obtain large area components without increasing their thickness and weight, a compact and low power mechanical system can be used for fast steering of high power beams over large angles. Moreover, since there is no need for special high-index substrates, the spectral range of functionality is also highly straightforward to expand. The speed and diffraction angle range of rotating CDWs can be considerably extended, as discussed above, by increasing the number of CDWs (which is practically impossible in the case of prisms) and by incorporating electrically controlled retarders into the system that could switch the sign of circular polarization of the beam. Such a hybrid, electronic and mechanical system, could allow considerably faster beam steering than a mechanical system.

A more fundamental difference of a CDW pair from a pair of prisms is that maximum deflection with a pair of prisms is achieved when they are arranged parallel, and the deflection is compensated when one of the prisms is rotated by 180 degrees to complement the first prism into a rectangle. In the case of CDWs, as we discussed above, the deflection is absent when they are arranged in parallel, and it is maximum when one of them is rotated by 180 degrees. In this sense, the situation is more in line with a pair of polarizers: light propagates through the pair when they are parallel, and is blocked (deflected) when they are crossed (anti-parallel). It is also more in line with a pair of diffractive waveplates: two half-wave plates together make a full-wave plate that does not affect the polarization state, hence does not diffract. And the two of them arranged anti-parallel double the spatial frequency of optical axis modulation, hence the diffraction angle. The need to distinguish between the two states of the CDWs (PGs) was appreciated earlier[4,10], particularly as polarizers when arranged parallel and anti-parallel[11]. "The implications for pure beam steering of this arrangement" were realized and discussed recently in[12,13].

The opportunity for cancelling the diffraction with parallel pairs of CDWs has highly practical implications. Having one optically (electrically, thermally, mechanically) switchable CDW in the pair allows one to switch the state of the CDW from a high-transmission (non-diffractive) to a low-transmission (diffractive) state. In its normal state, a single CDW is indeed diffractive, and application of the optical (electrical) field is required for obtaining the high-transmission state.

A sequence of switchable CDWs with varying pitch can be used for practically continuous beam steering with no mechanical moving parts. Indeed, a sequence of fixed CDWs combined with spatial light modulators can be used as well for this purpose, due to the dependence of the diffraction order (angle) on the polarization state of light[14.15].

Producing achromatic diffraction in multilayer CDW systems is an ultimate demonstration of the waveplate nature of PGs. An interesting technique that allowed making an achromatic CDW with the aid of two layers was described in[16]. Following the routine described in[16], we were not able to produce such CDWs. Even using the same materials, it took us at least 4 layers. Below, in Figure 9, we show imaging and doubled diffraction with two achromatic CDW pairs arranged parallel and anti-parallel.



(a) (b)

Figure 9. The BEAM Co. sign viewed through a pair of achromatic CDWs in (a) parallel/diffraction compensation configuration; and (b) in anti-parallel/diffraction angle doubling configuration.

5. THE DEVELOPMENT MILESTONES OF "POLARIZATION GRATINGS"

Polarization holography and development of polarization gratings/optical axis gratings/cycloidal diffractive waveplates in liquid crystal material systems has a long history reviewed in detail in monographs[2,17] and review papers[1,3,4]. With no pretence to be complete regarding citations, below we outline the timeline of achievements that, in our opinion, set milestones in those developments.

1972. Polarization holography is born [Sh.D. Kakichashvili, "On polarization recording of holograms", Optics and Spectroscopy, 32, 324, 1972].

1983: The feasibility of 100% diffraction efficiency in thin gratings recorded by two circularly polarized coherent waves is suggested [T. Todorov, N. Tomova, L. Nikolova, "High-sensitivity material with reversible photo-induced anisotropy," Opt. Commun., 47, 123, 1983; "Anisotropic gratings recorded from", M. Attia, J.M.C. Jonathan, Opt. Commun., 47, 85, 1983].
1984: Instead of photoanisotropic materials with low birefringence, the use of "light-sensitive material, possessing birefringence, which is not influenced by light" is suggested [L. Nikolova and T.Todorov, Diffraction efficiency and selectivity of polarization holographic recording, Optica Acta 31, 579, 1984].
1987: Demonstration of 100% efficiency [I.D. Shatalin, V.I. Kakichashvili, Sh.D. Kakichashvili, "Polarization hologram of 100% diffraction efficiency (polarization kinoform)," Sov. Tech. Phys. Lett. 13, 1051, 1987].
1991: Laying the basics of photoalignment technology for fabricating LC polarization gratings [W.M. Gibbons, P.J. Shannon, S.-T., Sun, & B.J. Swetlin, "Surface-mediated alignment of nematic liquid crystals with polarized laser light," Nature 351, 49, 1991].
1994: Demonstrated that "…liquid crystal can be photoaligned with high spatial and angular resolution (potentially, submicron)…" W.M. Gibbons and S.-T. Sun, "Optically generated liquid crystal gratings," Appl. Phys. Lett. 20, 2542, 1994.
2000: The concept of polarizer-free LCDs based on achromatic polarization gratings is disclosed [B.Ya. Zeldovich, N.V. Tabirian, "Devices for displaying visual information," Patent Disclosure, School of Optics / CREOL, 2000].
2003: The concept is being widely advertised and the key in fabricating cycloidal LC polarization gratings is revealed [H. Sarkissian, J.B. Park, N.V. Tabirian, B.Ya. Zeldovich, "Periodically aligned liquid crystal: potential application for projection displays and stability of LC configuration," Optics in the Southeast 2003 (PSE 02), Orlando, FL];
2003: Development of "Highly stable polarization gratings in photocrosslinkable polymer liquid crystals," H. Ono, A. Emoto, F. Takahashi, N. Kawatsuki, T. Hasegawa, J. Appl. Phys., 94, 1298, 2003.
2006: Demonstration of electrically switchable "Highly efficient liquid crystal based diffraction grating induced by polarization holograms at the aligning surfaces," [C. Provenzano, P. Pagliusi, and G. Cipparrone. Appl. Phys. Lett. 89, 121105, 2006; "A polarization-independent liquid crystal spatial-light-modulator," M.J. Escuti and W.M. Jones, Proc. SPIE 6332, 63320M, 2006].
2006: The beam propagation is switched using a fixed CDW and an electrically controlled phase retarder [H. Sarkissian, S. V. Serak, N. Tabiryan, L. B. Glebov, V. Rotar, and B. Y. Zeldovich, "Polarization-controlled switching between diffraction orders in transverse-periodically aligned nematic liquid crystals," Opt. Lett. 31, 2248, 2006].
2007: CDWs are suggested as uniquely promising components for controlling high energy laser beams due to their small thickness and absorption [S. Serak, N. Tabiryan, and B. Zeldovich, "High-efficiency 1.5 μm thick optical axis grating and its use for laser beam combining," Opt. Lett. 32, 169, 2007].
2007: Demonstrating commercial quality large area 100% efficiency LC polymer polarization gratings [Invited presentation: U. Hrozhyk, S.V. Serak, N.V. Tabiryan, T.J. Bunning, "Phototunable cholesterics, cycloidal nematics, and other optical axis gratings," New Optical Materials and Applications, NOMA 07, Cetraro, Italy, June 03-09, 2007].
2008: Achromatic polarizationgratings demonstrated [C. Oh and M.J. Escuti, "Achromatic diffraction from polarization grating with high efficiency," Opt. Lett. 33, 2287, 2008].
2009: The key to fabrication of high quality LC polymer polarization gratings is revealed [S.R. Nersisyan, N.V. Tabiryan, D.M. Steeves, B.R. Kimball, "Optical Axis Gratings in Liquid Crystals and their use for Polarization insensitive optical switching," J. Nonlin. Opt. Phys. & Mat., 18, 1–47, 2009].
2009: The concept of sequencing polarization gratings for designing normally transmissive switchable systems and beam steering is advanced and demonstrated [S.R. Nersisyan, N.V. Tabiryan, L. Hoke, D.M. Steeves, B. Kimball, "Polarization insensitive imaging through polarization gratings,"Opt. Express, 17, 1817, 2009].
2009: Inexpensive, robust, and versatile technology for commercial printing of polarization gratings is developed [S.R. Nersisyan, N.V. Tabiryan, D.M. Steeves, and B.R. Kimball, "Characterization of optically imprinted polarization gratings," Appl. Optics 48, 4062, 2009].
2010: The technology is applied to increasing the degree of axial diffractive waveplates to the highest reported level (64!), and is used for printing their arrays [N.V. Tabiryan, S.R. Nersisyan, D.M. Steeves, B.R. Kimball, The Promise of Diffractive Waveplates, Optics and Photonics News, 21, 41, 2010].

The "defective" member of the family of liquid crystalline diffractive waveplates, axial DWs/q-plates/vector vortex waveplates evolved largely on its own, see, e.g. [5,6,18,] until recently when the technology for fabricating CDWs was applied to their fabrication[1,19].

ACKNOWLEDGMENTS

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