## Holographically generated twisted nematic liquid crystal gratings

Cite as: Appl. Phys. Lett. **88**, 021905 (2006); https://doi.org/10.1063/1.2162672 Submitted: 18 July 2005 . Accepted: 16 November 2005 . Published Online: 10 January 2006

Hyunhee Choi, J. W. Wu, Hye Jeong Chang, and Byoungchoo Park



Liquid-crystal diffraction gratings using polarization holography alignment techniques Journal of Applied Physics **98**, 123102 (2005); https://doi.org/10.1063/1.2146075

Highly stable polarization gratings in photocrosslinkable polymer liquid crystals Journal of Applied Physics **94**, 1298 (2003); https://doi.org/10.1063/1.1587269

Three-dimensionally modulated anisotropic structure for diffractive optical elements created by one-step three-beam polarization holographic photoalignment Journal of Applied Physics **119**, 123102 (2016); https://doi.org/10.1063/1.4944810



Applied Physics Reviews Now accepting original research

Appl. Phys. Lett. **88**, 021905 (2006); https://doi.org/10.1063/1.2162672 © 2006 American Institute of Physics. View Online

2017 Journal Impact Factor:

## Holographically generated twisted nematic liquid crystal gratings

Hyunhee Choi and J. W. Wu<sup>a)</sup> Department of Physics, Ewha Womans University, Seoul 120-750, Korea

Hye Jeong Chang

The Institute of Optics, University of Rochester, Rochester, New York 14627

Byoungchoo Park

Department of Electrophysics, Kwangwoon University, Seoul 139-701, Korea

(Received 18 July 2005; accepted 16 November 2005; published online 10 January 2006)

A reflection holographic method is introduced to fabricate an electro-optically tunable twisted nematic (TN) liquid crystal (LC) grating, forgoing the geometrical drawing. The photoisomerization process occurring on the LC alignment layers of an LC cell in the reflection holographic configuration gives a control over the twist angle, and the grating spacing is determined by the slant angle of reflection holographic configuration. The resulting diffraction grating is in a structure of a reverse TN LC, permitting a polarization-independent diffraction efficiency. The electro-optic tunability of the diffraction efficiency is also demonstrated. © 2006 American Institute of Physics. [DOI: 10.1063/1.2162672]

Liquid crystals (LCs) are widely employed in optical devices having functions such as beam steering and beam shaping as well as LC diffraction grating. In particular, the ability to control the diffraction efficiency electrically renders an LC grating very important optical component. Previous works to fabricate an LC grating adopt contact treatments of the LC alignment layer by a double rubbing technique<sup>1,2</sup> and a microrubbing employing atomic force microscope tips<sup>3</sup> or metallic balls.<sup>4,5</sup> While a noncontact optical treatment of the LC alignment layer has been introduced<sup>6</sup> and is also employed in fabricating a LC grating,<sup>7</sup> the grating is generated directly by a microcontrol of a single writing beam. In both the contact and noncontact treatments, it is necessary to have a high-precision control of positioning in a micron scale, since the fabrication of the LC grating is based on the simple geometrical drawing of one-dimensional lines on the LC alignment layer.

When an azobenzene-containing polymer is employed as an LC alignment layer, the *trans-cis* photoisomerization process is known to be an effective means to achieve a surface alignment in an LC cell.<sup>6</sup> In an LC cell fabricated with photoaligned alignment layers, due to the dichroic absorption property, an asymmetric attenuation takes place when two orthogonally linearly polarized beams are counterpropagating inside the LC cell. The polarization interference pattern formed inside the LC cell gives rise to a formation of microsized polarization domains, which corresponds to a reflection holographic inscription of interference patterns. In this letter, we employ the reflection holographic method to fabricate a twisted nematic (TN) LC diffraction grating.

The photopolymer is commercially available from Sigma-Aldrich, which is an azobenzene side-chain polymer, poly[(methylmethacrylate)-co-(disperse red 1 methacrylate)](PDR1-MMA). PDR1-MMA was dissolved in tetrahydrofurane by 3-4 wt. %. A photoalignment layer of 300 nm thick polymer film was readily obtained by spin coating onto indium tin oxide (ITO) substrate and subsequent drying for 1 h at 100 °C. The UV-visible spectrum of the

Now we examine what kind of the polarization modulation results when two counterpropagating beams interfere. In the S/P-polarization reflection hologram, the polarization modulation is given as

$$E_{s}^{+} + E_{p}^{-} = E_{os} \cos(\omega t - kz + \rho)\hat{\mathbf{y}} + E_{op} \cos(\omega t + kz)\hat{\mathbf{x}}$$
$$\approx E_{op} \{\cos kz \cos \omega t [E_{os}/E_{op}\hat{\mathbf{y}} + \hat{\mathbf{x}}] + \sin kz \sin \omega t [E_{os}/E_{op}\hat{\mathbf{y}} - \hat{\mathbf{x}}]\}, \tag{1}$$

where  $E_s^+$  and  $E_p^-$  denote *S*- and *P*-polarization electric fields propagating along the +*z* and -*z* axes, respectively, and  $\rho$  is the phase difference between the two. When  $E_{os}=E_{op}$ , Eq. (1) describes two standing waves with wave planes of  $(\hat{x} + \hat{y})/\sqrt{2} + \hat{z}$  and  $(-\hat{x} + \hat{y})/\sqrt{2} + \hat{z}$ , and a polarization modulation results from the optical interference, as shown in the middle row of Fig. 1(b). We find that the polarization state goes

0003-6951/2006/88(2)/021905/3/\$23.00

PDR1-MMA film showed the absorption peak at 490 nm, and the optical density at 514.5 nm, the wavelength of writing beams, was about 0.8. An empty cell, separated by 9.2  $\mu$ m spacers, is fabricated by gluing two PDR1-MMA spin-coated ITO substrates with a UV-curable epoxy. Filtered mixtures of a nematic LC (ZLI-2293,  $\Delta n$ =0.1322, Merck) and 0.3 wt. % DR1 are introduced into the empty cell by a capillary action at the temperature of 55 °C. The resulting LC cell at room temperature did not exhibit any optical birefringence, since no alignment process has been performed on the surface of the photoalignment layers. As a priming to induce an optical birefringence, a photoalignment of the filled LC cell was carried out by a normal-incident illumination of the 514.5 nm line of an Ar<sup>+</sup> laser with the linear polarization along the y axis, called S polarization, the intensity of which is 100 mW/cm<sup>2</sup> on the film with a typical illumination time of 30 min [see Fig. 1(a)]. The photoisomerization process occurring in the azobenzene moiety inside the two photoalignment layers of PL1 and PL2 resulted in an optical birefringence in the nematic LC cell with the optic axis along the x axis. We note that the birefringent nematic LC cell also exhibits a dichroic absorption, namely, a polarization-dependent absorption, at a wavelength of 514.5 nm.

<sup>&</sup>lt;sup>a)</sup>Electronic mail: jwwu@ewha.ac.kr



FIG. 1. (Color online) (a) Reflection holographic configuration to inscribe the *S*- and *P*-polarization modulation in a nematic LC cell with the inset showing a magnified view of the polarization modulation formed on the surface of the azo photoalignment layer. (*PL*1 and *PL*2: azo photoalignment layers 1 and 2,  $\theta_s$ : the slant grating angle). (b) The polarization modulation from the interference of *S*- and *P*-polarized writing beams for three different intensity ratios.

through a periodic modulation from right-circular to linear to left-circular to linear polarizations along the z axis, which corresponds to the sample depth direction. However, when  $E_{os} \neq E_{op}$ , the wave planes of two standing waves deviate from the planes of  $(\hat{x}+\hat{y})/\sqrt{2+\hat{z}}$  and  $(-\hat{x}+\hat{y})/\sqrt{2+\hat{z}}$ , and at the same time a polarization modulation from right-elliptical to linear to left-elliptical to linear polarizations is produced along the z axis, as described in the top and bottom rows  $(E_{os} > E_{op} \text{ or } E_{os} < E_{op})$  of Fig. 1(b). When the birefringent nematic LC cell is positioned inside the polarization modulation produced, S-polarized light (polarization along the y axis) goes through an optical attenuation less than *P*-polarized light (polarization along the x axis) does, owing to the dichroic absorption of the LC cell. When counterpropagating through the dichroically absorptive LC cell, two S- and P-polarized lights with initial equal intensities,  $E_{os}^{(1)}$  $=E_{op}^{(2)}$ , get attenuated by a different amount, resulting in  $E_{os}^{(1)} > E_{op}^{(1)}$  on *PL*1 layer and  $E_{os}^{(2)} < E_{op}^{(2)}$  on *PL*2 layer, which was made possible by the presence of low-level 0.3 wt. % doping of DR1 in the LC. The resulting polarization phase modulation inscribed on PL1 and PL2 layers will be the top and bottom ones shown in Fig. 1(b), respectively.

In order to inscribe the polarization grating inside the birefringent nematic LC cell, two counterpropagating beams with orthogonal S and P linear polarizations from the 514.5 nm line of an Ar<sup>+</sup> laser are prepared as writing beams by use of a beam splitter and half-wave plates. The light intensity was 200–300 mW/cm<sup>2</sup> and the illumination time was 10–20 s. In the case of a normal incidence  $\theta_s = 0$ , the polarization state, corresponding to one of the polarization states described in the top or bottom rows of Fig. 1(b), is uniform on the entire x-y plane of *PL*1 and *PL*2 layers, which is the photoalignment polymeric surface. However, when the birefringent nematic LC cell is slightly slanted with a slant grating angle  $\theta_s$  of 0.1°-2.0° in a reflection holographic configuration, as shown in Fig. 1(a), a periodic modulation of polarization state emerges along the x axis on the photoalignment polymeric surface with the period  $\Lambda$ 



FIG. 2. (Color online) Schematic illustration of the LC grating formed by the polarization modulation and microtextures. (a) The front view ( $\theta_t$ : the twist angle of TN domain,  $\theta_{off}$ : the offset angle of the polarization direction with respect to *x* axis). (b) A reverse twisted nematic LC cell. (c) The microscopic texture of TN domains taken with an optical polarizing microscope (upper left:  $\phi=0^\circ$ , upper right:  $\phi=-45^\circ$ , lower left:  $\phi=+45^\circ$ , lower right:  $\phi=90^\circ$ ).

 $=\lambda/4 \sin \theta_s$ , determined by the slant grating angle  $\theta_s$  and the wavelength of writing beam  $\lambda$ , as shown magnified inside the circle of Fig. 1(a). In the current experimental configuration,  $E_{os} > E_{op}$  on the PL1 layer,  $E_{os} < E_{op}$  on the PL2 layer, and  $\theta_s \neq 0$ ; hence, the major axes of the two modulated elliptical polarizations on the PL1 and PL2 layers do not coincide. Now, on each PL1 and PL2 layer the presence of a modulated polarization state gives rise to a modulated orientation of azo moieties along x axis on the surface of the LC alignment layer via photoisomerization process, and the relative orientational direction of azo moieties inside two facing alignment layers *PL*1 and *PL*2 are determined by the values of the ratio  $E_{os}/E_{op}$  at each layer. A nonparallel orientation of azo moieties inside two photoalignments gives rise to a TN structure inside the birefringent LC cell, twisted in x-y plane with the twist axis along the z axis. Furthermore, at the surface of each alignment layer, the alignment of LCs is achieved by an orthogonal photoalignment following the zigzag-shaped polarization modulation pattern along the x axis with a nonzero offset angle  $\theta_{off}$  with respect to the x axis, and the offset angles are different in PL1 and PL2 [see Fig. 2(a)]. This leads to a formation of two different kinds of TN domains: one twisted in the clockwise sense and the other twisted in the counterclockwise sense. The resulting LC grating is in the structure of a reverse TN LC grating<sup>2</sup> [see Fig. 2(b)].

From the measurement of the dichroic absorption of the fabricated birefringent cell, the ratios  $E_{os}/E_{op}$  at *PL*1 and *PL*2 are determined as 3.0 and 1.0, respectively. From the relation of the offset angle  $\theta_{off}$  with the ratio  $E_{os}/E_{op}$ , i.e.,  $\tan(\theta_{off})=E_{os}/E_{op}$ , we find that the axes of the linear polar-



FIG. 3. (Color online) (a) A CCD picture of diffraction orders, (b) the polar plot of the polarization state of diffracted orders, (c) the diffraction efficiency as a function of the polarization angle, and (d) the diffraction efficiency as a function of the applied voltage.

ization state appearing in the polarization modulation are rotated by  $+75^{\circ}$  at the *PL*1 layer and  $+35^{\circ}$  at the *PL*2 layer relative to the +*x* axis.

The reverse TN LC grating structure is examined by observing the textures of the LC cell in a polarizing optical microscope. The light path is from the polarizer to *PL1* to *PL2* to the analyzer, with the polarization axis of the polarizer along the *y* axis. As seen in Fig. 2(c), the microscopic textures, characteristic of a phase grating, confirm the presence of a TN array. The upper left, the upper right, the lower left, and the lower right ones correspond to the textures for the sample rotation angles of  $\phi=0^\circ$ ,  $-45^\circ$ ,  $+45^\circ$ , and  $90^\circ$  of the grating vector relative to the polarization axis (*x* axis fixed in the laboratory) of the polarizer, respectively. We determine that the offset angles are  $\sim 20^\circ$  and  $\sim 60^\circ$  at the *PL1* and *PL2* layers, respectively, which gives the twist angle  $\theta_t = 40^\circ$ . We found that  $\theta_t$  depends on the LC cell thickness and that it can be increased up to  $90^\circ$  for a thick cell.

Next, the diffraction property of the fabricated LC grating is investigated with the 632.8 nm line of a less than 1 mW He–Ne laser. In Fig. 3(a) is shown a CCD picture of the diffraction pattern. The polarization state of the outcoming diffracted order is examined and is plotted in Fig. 3(b). The polarization direction of the light propagating from *PL*1 to *PL*2 is y polarized, perpendicular to the grating vector, with the angle 0° corresponding to the y axis. The ±1 orders go through a 90° rotation in the polarization state, while there is no change for the 0th order.<sup>8</sup> Figure 3(c) shows the polarization independence of the diffraction efficiency  $\eta$  for the 0th and ±1st orders, which is the characteristic feature of a reverse TN LC grating. We then looked into the electrooptic tunability of the diffraction efficiency by measuring the diffraction efficiency of the –1st order as a function of the applied voltage. As shown in Fig. 3(d), below the Freedericksz transition,  $\eta$  is constant and polarization independent, while there appear different changes in  $\eta$  depending on the polarization when undergoing the Freedericksz transition. Above ~3 V beyond the Freedericksz transition,  $\eta$ is again polarization independent and exhibits a smooth electrotunability.

In summary, a liquid crystal grating is fabricated in a slanted reflection holographic configuration by inscribing an *S*- and *P*-polarization interference via a photoisomerization process. The resulting grating is in a structure of a reverse twisted nematic LC, which permits the polarization-independent diffraction efficiency. The electro-optic tunability of the diffraction efficiency is also demonstrated. The novel LC grating proposed here should find a wide application in optical devices employing LCs as electro-optic materials.

This work is supported by ABRL program at Ewha Womans University as well as by Korea Research Foundations (Grant No. 2004-C00057).

- <sup>1</sup>J. Chen, P. J. Bos, H. Vithana, and D. L. Johnson, Appl. Phys. Lett. **67**, 2558 (1995).
- <sup>2</sup>C. M. Titus and P. J. Bos, Appl. Phys. Lett. **71**, 2239 (1997).
- <sup>3</sup>J.-H. Kim, M. Yoneya, and H. Yokoyama, Nature (London) **420**, 159 (2002).
- <sup>4</sup>M. Honma and T. Nose, Jpn. J. Appl. Phys., Part 2 **42**, 6992 (2003).
- <sup>5</sup>S. Varghese, G. P. Crawford, C. W. M. Bastiaansen, D. K. G. de Boer, and D. J. Broer, Appl. Phys. Lett. 85, 230 (2004).
- <sup>6</sup>P. J. Shannon, W. M. Gibbons, and S. T. Sun, Nature (London) **368**, 532 (1994).
- <sup>7</sup>W. M. Gibbons and S.-T. Sun, Appl. Phys. Lett. **65**, 2542 (1994).
- <sup>8</sup>Z. He and S. Sato, Appl. Opt. **37**, 6755 (1998).