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High efficiency reflective liquid crystal polarization gratings

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We experimentally demonstrate a reflective-mode liquid crystal polarization grating with high reflectance, small grating period, and subms switching times. This switchable optical element can diffract ~100% into a single order, have highly polarization-sensitive first orders, and have a polarization-insensitive zero order. Here we introduce an absorbing layer that overcomes the reflection of the (ultraviolet) holographic beams, which otherwise prevents high quality fabrication. At a grating period of 2.1 μm, we report 98% diffraction efficiency, 90% reflectance, ~600:1 contrast-ratio, and ~3000:1 polarization contrast. These elements can therefore be configured as polarization-independent modulators or switchable polarizing beam splitters, for use in telecommunications, displays, spatial-light modulators, and polarimetry. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3197011]

Switchable reflective diffraction gratings are important for applications such as displays, beam steering, tunable filters, and telecommunication components. Conventional reflective diffractive optical switches consist of microelectromechanical systems (MEMS),[1] cholesteric liquid crystals (LCs),[2–4] and holographic polymer dispersed LCs (H-PDLCs).[5–7] Drawbacks which limit these technologies include an expensive fabrication process in the case of MEMS, poor reflectance of only 40%–50% in the case of cholesteric LCs, scattering losses and high driving voltages (>100 V) in H-PDLCs. In this work, we present a versatile reflective diffractive switch based on LC polarization gratings (PGs)[8,9] that can modulate light regardless of incident polarization, preserves nearly 100% maximum reflectance, provides fast dynamic response times, offers reasonable contrast at low operating voltages, and is in essence fabricated via a one-step process. While we primarily focus here on applications in the visible wavelength range, this element can be tailored for operation in the infrared regime.

Recently, a variety of switchable nematic LC diffraction gratings,[6,10–12] have been explored on transmissive substrates. Several of these belong to the general category of PGs, and possess anisotropic structures resulting in unique diffractive properties. Various types of PGs have been fabricated using conventional patterning techniques,[9–11,13–15] and tested with a view toward potential application in microdisplays, beam steering, etc. Only some of these approaches have been applied to reflective substrates,[13] and only with less than ideal results due to their discrete PG profile, and fabrication challenges. The continuous profile shown in Fig. 1(a) ,[9,11,14,16,17] which offers several unique properties, has so far not been fabricated in reflective mode. However, high-quality transmissive LCPGs with >99% diffraction efficiency[18] and 5000:1 polarization extinction-ratio in the first orders have been fabricated, and applications involving projections displays[19] and tunable filters[20] have been demonstrated.

Reflective LC modulators in general offer faster electrical switching times than their transmissive counterparts due to the reduced cell thickness. In the case of LCPGs,[21] the cell thickness d strongly influences the minimum optical grating period $\Lambda_{\min} \geq d\sqrt{0.4+0.6(2K_{33}-K_{22})/K_{11}}$ where K_{ii}, ($i=1,2,3$) are the LC elastic constants. Since the reflective-mode LCPG is optimally formed with half the cell thickness of the transmissive-mode (i.e., a quarterwave retardation, as discussed below), the minimum possible grating period Λ can also be reduced by half,[21,22] enabling larger diffraction angles for the same materials. Moreover, reflective spatial light modulators (SLMs) and LC on silicon (LCoS) microdisplays offer higher pixel resolution and fill-factor than transmissive modes. However, reflective LCPG fabrication faces a fundamental challenge: The periodic LCPG profile[22] is recorded by polarization holography, which involves two coherent, circularly polarized, orthogonal, nearly parallel beams; and as such, the recording beams are reflected back into the photo-sensitive material (thin photoalignment polymers[23]). This corrupts the polarization and the intensity of the hologram itself, and leads to a deformed LC director

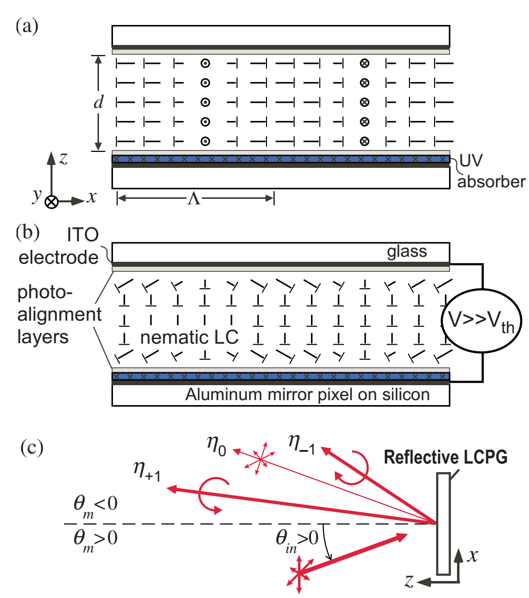

FIG. 1. (Color online) Cross-sectional view of the reflective LCPG (a) under no external field and, (b) when a voltage much larger than the threshold voltage is applied. (c) Geometry and diffraction notation for incident monochromatic light.

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profile, scattering from LC defects, and extra diffracted orders. Furthermore, diffraction from a pixel array (as in reflective SLMs and LCoS) further degrades the recording hologram. To avoid reflections entirely, we employ a thin layer to absorb the recording wavelength, arranged between the reflective substrate and the photo-alignment material, as shown in Fig. 1. In this way, we have been able to fabricate reflective LCPGs with small period (2.1 μm), high efficiency, and nearly ideal polarization properties.

Fabrication involved the following: We used glass (Delta Technologies) coated only with indium tin oxide (ITO) and aluminum mirrors (Edmund Industrial Optics) as substrates. A solution of 90% (wt/wt) of WiDE™-15B (Brewer Science) and 10% of 2-2′ dihydroxybenzophenone,[24] was spin coated onto the mirrors at 6000 RPM for 1 min, and then dried at 130 °C for 5 min. This processing produced ~1 μm thick films that reduce the reflectance of the mirrors at 325 nm (the recording wavelength in our process) to only about 10%, but maintain a high reflectance over the entire visible range from 450 to 750 nm. The photo-alignment material, ROP-103/2CP (Rolic) was then spin-coated onto both the substrates at 3000 rpm for 45 s and subsequently cured at 135 °C for about 10 min. A sandwich was then made with these two substrates to create a cell gap of $d=1.2$ μm, and exposed to an interference pattern formed between two orthogonally circularly polarized UV laser beams at $\lambda=325$ nm. These cells were then filled (without vacuum) with the LC MDA-06–177 (Merck, $\Delta n=0.143$, $T_{NI}=100$ °C) in the isotropic state at 135 °C. Note that the resulting cell has quarter-wave retardation for red light, as described in further detail below.

Ideally, when this polarization hologram is captured by the alignment layer, only three diffraction orders are produced, and the two first orders are circularly polarized with opposite handedness as shown in Fig. 1(c). We define the diffraction efficiency of the mth order as $\eta_m=I_m/\Sigma I_m$, which is a normalized measure of the grating apart from the losses in the substrate. However, the net reflectance defined by $R_m=I_m/I_{in}$ does include these losses. Here I_m is the intensity of mth order while I_{in} is the input intensity. In Fig. 2(a), we show the measured diffraction efficiency and reflectance for various voltages (4 kHz square wave, zero dc bias). Linearly polarized light from a He–Ne laser incident at 5° was used for measurement [as shown in Fig. 1(c)]. Note that the zero-order diffraction efficiency η_0 (i.e., the specular reflection) is low (3%) at low voltages, while the sum of the first-order diffraction efficiencies $\Sigma\eta_{\pm 1}$ (diffracted reflection) is high (95%). The total first-order reflectance was 90% at 0 V, and is limited mainly by Fresnel losses at the interfaces (air/glass/ITO) and mirror absorption, which can be improved if anti-reflection coatings and higher quality mirrors are used. As the voltage is increased, a Freedericksz transition[11,21] is observed at a threshold voltage of $V_{th}=1.8$ V. At higher voltages, the LC molecules in Fig. 1(a) reorient perpendicular to the substrates which effectively erases the PG profile, as shown in Fig. 1(b). As a result, most of the light is directed into the zero-order and at 10 V, η_0 increases to about 90%. As we anticipated, the smaller LC layer thickness led to fast switching times (submicrosecond total). We show in Fig. 2(b) the rise and fall times[21] for various voltages. Despite the LCPG profile, the general trend of the dynamic response is clearly reminiscent of most nematic LC modes.

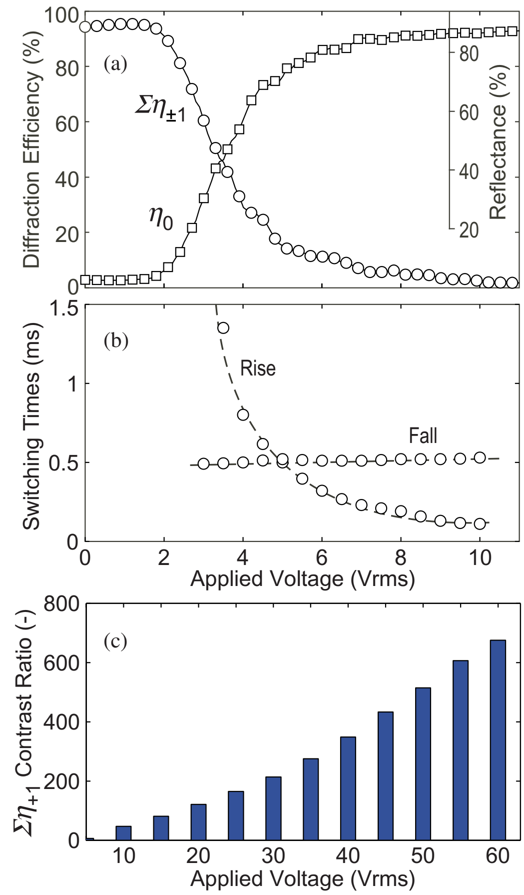

FIG. 2. (Color online) (a) Diffraction efficiencies and Reflectance for the ±1 and 0 orders. (b) Electrical switching times. (c) First-order contrast-ratio measured at different voltages. Incident angle was fixed at 5° and probe was a He–Ne laser at 633 nm.

Note that the total switching time was ~600 μs, composed of ~100 μs rise time and ~500 μs fall time, even at a modest voltage of 10 V. The electrical contrast-ratios of the first-orders, defined by $\max(\Sigma\eta_{\pm 1})/\min(\Sigma\eta_{\pm 1})$, are shown in Fig. 2(c), which range from 200:1 at 20 V to 650:1 at 60 V. In contrast, control samples prepared with the same exact processing as above but without the UV absorbing layer had poor LC alignment, produced severe scattering larger than 20%, and had poor contrast ratios of <50:1 even at large voltages.

The optical properties of reflective LCPGs can also be approximately derived using the Jones Matrix method.[25] Following the notation in Fig. 1 and assuming a paraxial case, the diffraction efficiencies are given by

$$\eta_0=\cos^2\left(\frac{2\pi\Delta n d}{\lambda}\right), \tag{1}$$

$$\eta_{\pm 1}=\frac{1\pm S_3'}{2}\sin^2\left(\frac{2\pi\Delta n d}{\lambda}\right), \tag{2}$$

which are an extension of the transmissive case.[11,15,26] Here, λ is the wavelength, d is the grating thickness while Δn is the birefringence of the LC material. The normalized Stokes' parameter $S_3'=S_3/S_0$ is a measure of the amount of circular polarization in the incident light. $S_3'=\pm 1$ when the polarization of the incident light is right circular and left circular respectively. A number of things are apparent from the above expressions. The individual efficiencies of the first orders are

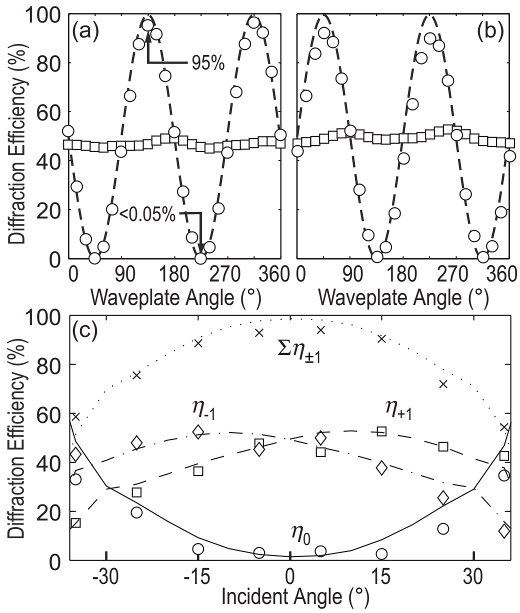

FIG. 3. Diffraction efficiencies of the (a) +1 and (b) −1 reflected orders for different input polarization, as set by the rotation of a QWP (circles) and HWP (squares) respectively. Angle of incidence was fixed at 5°. (c) Comparison of measured (markers) and simulated (lines) diffraction efficiencies of reflective LCPGs at various incident angles for linearly polarized light input. A He–Ne laser (λ=633 nm) was used for all the measurements.

highly sensitive with respect to S_3', and thus $\eta_{\pm 1}$ can be varied between 0 and 100% by modulating the polarization state of the incident light, when $d=\lambda/4\Delta n$. However, both η_0 and $\Sigma\eta_{\pm 1}$ are independent of S_3', even at oblique incident angles. So, both highly polarization sensitive as well as polarization independent diffraction can be achieved using reflective LCPGs. This behavior is similar to the transmissive case discussed elsewhere.[26] The polarization sensitive first-order diffraction from these reflective samples is illustrated in Fig. 3(a). The first plot is for the +1 order while the second one is the response for the −1 order according to the convention noted earlier. Here the sample is probed with a linearly polarized (vertical) He–Ne laser after it is passed through a corresponding waveplate. Rotation of a quarter-waveplate (QWP) causes S_3' to vary from 0 to 1, that corresponds to modulating the first order efficiency from 0 to 100%, when $d=\lambda/(4\Delta n)$ from Eqs. (2). A similar experimental sensitivity can be noted (from ~0% to ~95%) from this data, even at a small incident angle of 5°. The polarization contrast in response to a QWP is measured to be about 4000:1 in the +1 order and 3000:1 for the −1 order, with the small oblique incidence being the reason for the asymmetry. These values already exceed those achieved by most conventional approaches[27] to polarizing beam splitters. A half-waveplate (HWP) has no effect on S_3' and thus on the diffraction, which can also be observed. Note that regardless of the orientation of the waveplates, the zero-order efficiency remained constant within our measurement error (±0.25%). Therefore, the zero-order modulation is polarization insensitive.

The angular behavior [shown in Fig. 3(c)] of these gratings is somewhat complex, and was measured using the setup illustrated in Fig. 1(c) where the plane of incidence contained the grating vector. The general trend is that the first-order efficiency is reduced (and zero-order efficiency increases) as the angle of incidence increases. In Fig. 3(b) we compare simulated results and measurements of diffraction efficiencies from the reflective LCPGs for various incident angles. Simulations were carried out using WOLFSIM,[26] a simulation tool for analyzing periodic anisotropic media developed based on the finite difference time domain[26,28] method. There is a good correlation between the measured values and the simulated results at all the angles considered. This correlation strongly suggests that this angular response is fundamental to the reflective LCPG structure, and not a measurement artifact.

In conclusion, we have demonstrated a reflective diffractive LC switch containing the LCPG profile that can modulate light with high efficiency and subms switching times at a 2.1 μm grating period. Moreover, we show that reflective LCPGs have highly polarization-sensitive first-orders and a polarization-insensitive zero-order, similar to the transmissive mode.[26] These nearly-ideal properties indicate that reflective LCPGs are excellent candidates for polarization-insensitive modulation, and should be considered for applications including telecommunication light control elements, beam-steering, displays, and spatial-light-modulators.

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[1] M. C. Wu, Proc. IEEE **85**, 1833 (1997).
[2] D. K. Yang, J. L. West, L. C. Chien, and J. W. Doane, J. Appl. Phys. **76**, 1331 (1994).
[3] M. H. Lu, J. Appl. Phys. **81**, 1063 (1997).
[4] C. H. Lin, A. Y. G. Fuh, T. S. Mo, and C. Y. Huang, Jpn. J. Appl. Phys., Part 1 **41**, 7441 (2002).
[5] T. J. Bunning, L. V. Natarajan, V. P. Tondiglia, and R. L. Sutherland, Annu. Rev. Mater. Sci. **30**, 83 (2000).
[6] C. C. Bowley and G. P. Crawford, J. Opt. Technol. **67**, 717 (2000).
[7] V. K. S. Hsiao, T. C. Lin, G. S. He, A. N. Cartwright, P. N. Prasad, L. V. Natarajan, V. P. Tondiglia, and T. J. Bunning, Appl. Phys. Lett. **86**, 131113 (2005).
[8] F. Gori, Opt. Lett. **24**, 584 (1999).
[9] S. R. Nersisyan, N. V. Tabiryan, D. M. Steeves, and B. R. Kimball, J. Nonlinear Opt. Phys. Mater. **18**, 1 (2009).
[10] J. Chen, P. J. Bos, H. Vithana, and D. L. Johnson, Appl. Phys. Lett. **67**, 2588 (1995).
[11] J. Eakin, Y. Xie, R. A. Pelcovits, M. D. Radcliffe, and G. P. Crawford, Appl. Phys. Lett. **85**, 1671 (2004).
[12] M. Honma and T. Nose, Jpn. J. Appl. Phys., Part 2 **43**, 8151 (2004).
[13] C. M. Titus and P. J. Bos, Appl. Phys. Lett. **71**, 2239 (1997).
[14] J. Tervo and J. Turunen, Opt. Lett. **25**, 785 (2000).
[15] M. J. Escuti and W. M. Jones, SID Int. Symp. Digest Tech. Papers **37**, 1443 (2006).
[16] C. Provenzano, P. Pagliusi, and G. Cipparrone, Appl. Phys. Lett. **89**, 121105 (2006).
[17] H. Sarkissian, S. V. Serak, N. V. Tabiryan, L. B. Glebov, V. Rotar, and B. Y. Zeldovich, Opt. Lett. **31**, 2248 (2006).
[18] M. J. Escuti and W. M. Jones, Proc. SPIE **6332**, 63320M (2006).
[19] R. K. Komanduri, C. Oh, M. J. Escuti, and D. J. Kekas, SID Int. Symp. Digest Tech. Papers **39**, 236 (2008).
[20] E. Nicolescu and M. J. Escuti, Proc. SPIE **6654**, 665405 (2007).
[21] R. K. Komanduri and M. J. Escuti, Phys. Rev. E **76**, 021701 (2007).
[22] R. K. Komanduri, W. M. Jones, C. Oh, and M. J. Escuti, J. Soc. Inf. Disp. **15**, 589 (2007).
[23] M. Schadt, H. Seiberle, and A. Schuster, Nature (London) **381**, 212 (1996).
[24] M. Zayat, P. Garcia-Parejo, and D. Levy, Chem. Soc. Rev. **36**, 1270 (2007).
[25] P. Yeh and C. Gu, *Optics of Liquid Crystal Displays* (Wiley, New York, 1999).
[26] C. Oh and M. J. Escuti, Phys. Rev. A **76**, 043815 (2007).
[27] R. C. Tyan, P. C. Sun, A. Scherer, and Y. Fainman, Opt. Lett. **21**, 761 (1996).
[28] C. Oh and M. J. Escuti, Opt. Express **14**, 11870 (2006).