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Polarization independent liquid crystal gratings based on orthogonal photoalignments

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The polarization independence of liquid crystal gratings with alternate orthogonal aligned regions is theoritically studied and demonstrated by means of photoalignment technique. The different alignments in adjecent regions are achieved by two-step photo exposure to guide orientations of sulfonic azo dye layers and further align the liquid crystal molecules. Both one-dimensional and two-dimensional switchable phase gratings have been demonstrated. Such polarizer-free gratings show very high transmittance (∼92%), diffraction efficiency (over 31%), and optical contrast (over 150) including low power consumption. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3694921]

Liquid crystal (LC) technologies have played important roles in tunable passive components[1–4] for the advantages of light weight, low cost, no moving parts, and low power consumption. Switchable phase grating is one kind of such components that have been studied extensively. To construct a grating profile, periodical refractive index change of LC is necessary that can be generated by two basic approaches. First, by exploiting striped electrodes to generate periodic electrical field distribution and locally control the directors of uniformly aligned LCs.[5,6] The other is to directly guide the initial LC directors to realize periodic refractive index profile through patterned alignment layers[7–9] or holographic recording in polymer dispersed liquid crystals.[10,11]

Linearly polarized light is needed for LC components which limits the optical efficiency, thus, introduction of approaches for polarization independent design is considerably important. There are mainly two different strategies. One solution is utilizing an optically isotropic blue phase LC driven by vertical electric field,[12,13] but it demands high driving voltage; therefore the research on traditional nematic LC components is still in high demand. By deploying orthogonal LC alignments together in one cell, with either double perpendicular rubbing[7] or optically generated alignment layers,[8] polarization independent nematic LC components could be demonstrated as well. However, previous fabrication techniques based on the strategy are complicated that limits the output efficiency and performance; moreover, the mechanism has not been thoroughly revealed.

Herein, we theoritically analyse the polarization independence of LC gratings with orthogonal aligned regions and propose a practical method for its fabrication by means of photoalignment. The presented technique would be a promising approach for several advantages. First, it simplifies both the electrical driving and the fabrication process, avoiding any undesired diffraction effects resulting from initial periodical probes and fringe field, and making the process industrial compatible. Second, the photoalignment employed here has been proved to enable the creation of high quality LC alignment with resolution up to 1 μm,[14,15] without any mechanical damage, electrostatic charge, or dust contamination[16] compared to usual rubbed PI, which could ensure high performance and wide application in polarization independent LC devices.

In the present work, the adjacent regions of the LC gratings are with orthogonally parallel alignments (PAs), as schematically illustrated in Fig. 1(a). Thanks to the orthogonal PA structure, incident light could be decomposed into two components, polarized along the two alignment directions (defined as x and y axes shown in Fig. 1(a)), respectively. Light in each polarization direction experiences a refractive index change (Δn_x or Δn_y) between two adjacent

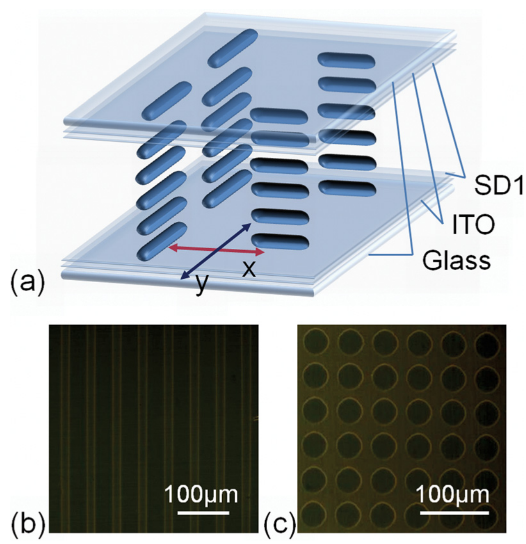

FIG. 1. (Color online) (a) Schematic cell structure of an orthogonal-PA cell, micrographs of (b) 1D and (c) 2D LC gratings.

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regions, thus induces phase retardation, defined as $\Delta\varphi_x$ or $\Delta\varphi_y$, respectively. As Δn_x and Δn_y have the same absolute value of $\Delta n_{eff} = n_{eff} - n_o$ (n_{eff} changes from n_e to n_o when applying voltages), $\Delta\varphi_x$ and $\Delta\varphi_y$ could be calculated as

$$|\Delta\varphi_x| = |\Delta\varphi_y| = \frac{2\pi\Delta n_{eff} d}{\lambda}. \quad (1)$$

Here d is the cell gap and λ is the incident wavelength. Thus the design is a phase grating with its modulation depth tunable by applying external fields.

For this phase grating, the intensity of nth diffraction order I_n can also be divided into two orthogonal components along x and y axes

$$I_n = |E_{x,n}|^2 + |E_{y,n}|^2 = \eta_{x,n}|E_x|^2 + \eta_{y,n}|E_y|^2. \quad (2)$$

Here E_x and E_y are the total electric fields of incident light in x and y directions separately, while $E_{x,n}$ and $E_{y,n}$ are those of nth order. $\eta_{x,n}$ and $\eta_{y,n}$ are the diffraction efficiencies in x and y directions of nth order, respectively, which can be expressed as follows:[17]

$$\eta_{x,n} = \frac{1}{\Lambda^2}\left|\int_0^l e^{i(\Delta\varphi_x + \frac{2\pi n}{\Lambda}x)}dx + \int_l^\Lambda e^{i\frac{2\pi n}{\Lambda}x}dx\right|^2, \quad (3)$$

$$\eta_{y,n} = \frac{1}{\Lambda^2}\left|\int_0^l e^{i(\Delta\varphi_y + \frac{2\pi n}{\Lambda}x)}dx + \int_l^\Lambda e^{i\frac{2\pi n}{\Lambda}x}dx\right|^2, \quad (4)$$

where Λ represents the period of the gratings while l means the width of one region. At the condition of Eq. (1), after integration of Eqs. (3) and (4), we found that the diffraction efficiencies in two directions are equal to each other

$$\eta_{x,n} = \eta_{y,n} = \frac{1}{n^2\pi^2}(1 - \cos\Delta\varphi)\left(1 - \cos\frac{2\pi nl}{\Lambda}\right). \quad (5)$$

Thus, I_n can be written as

$$I_n = \eta_n E^2(\cos^2\theta + \sin^2\theta) = \eta_n E^2, \quad (6)$$

θ is the angle between incident polarization direction and x direction. Therefore in such a design, the diffraction efficiency is independent of incident polarization directions. From the above derivation, we can see that the condition for realizing polarization independence is $|\Delta\varphi_x| = |\Delta\varphi_y|$, which requires the LC direction of two adjacent regions to be strictly perpendicular to each other.

In our work, the adjacent orthogonal PA regions are achieved by two-step photo exposure on sulfonic azo dye (SD1, Dai-Nippon Ink and Chemicals, Japan) layers. SD1 molecules tend to align their absorption oscillators perpendicular to the polarization of the incident UV light. They exhibit not only considerably high anchoring energy comparable to that of rubbed PI,[16,18] but also good alignment rewritability,[19] that makes the multi-domain alignment approach more practical. The detailed fabrication process is presented below. Just after coating SD1 (0.5 wt. % in N, N-dimethylformamide) layers, two glass substrates with ITO films are assembled to form a cell with 6.0 μm in thickness. The cell is exposed with linearly polarized light of $\lambda = 405 \pm 10$ nm for a dose of 5 J/cm^2. Afterwards, the same cell is turned 90° and exposed again through an amplitude mask. The exposed window areas were realigned to be orthogonal to the original orientation of mask shadow regions. Thus the cell with alternate orthogonal PA alignments has been constructed. Thereafter, a LC RDP-41063 (Dai-Nippon Ink and Chemicals) is injected into the cell by the capillary action. The voltage-dependent diffraction properties of LC gratings were studied by illuminating the cells, normally, by a He–Ne laser (632.8 nm at room temperature) and then after, light was collected by a photo detector.

Based on above design, both one-dimensional (1D) and two-dimensional (2D) LC gratings were fabricated. Figs. 1(b) and 1(c) present the optical micro photographs of the cells under crossed polarizer. The transmittance differences in alternate regions obviously show replicas of photo mask patterns. The slight transmittance difference is due to the small angle deviation in manually angle turning and can be much depressed by utilizing precise adjusting equipments. The cell fabrication process is considerably easier and cheaper than the previous techniques and thus is more compatible for the mass industrial production.

The voltage-dependent diffraction properties of 1D gratings copied from a photo mask with 20 μm stripes separated by 30 μm spaces have been studied. High total transmittance up to 92% is achieved in the whole applying voltage range. As the gratings is Raman–Nath type, energy of normally incident light will be distributed to diffraction orders symmetrically on both sides of order 0th. Applying voltage changes the diffracted intensity of different orders due to the Δn_{eff} changing. Figure 2(a) reveals two voltage dependent

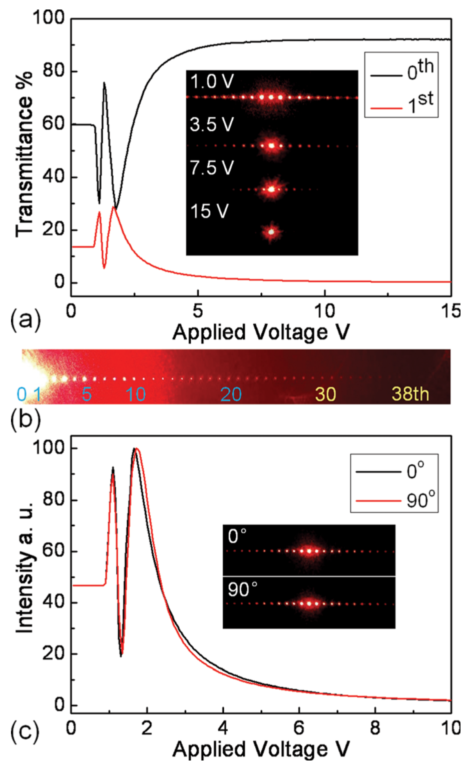

FIG. 2. (Color online) (a) V-T curves of 0th and 1st orders, insets (Media 1) show the diffraction patterns at different voltages, (b) diffraction patterns of 1st order at on state, (c) diffraction intensities of 1st order under different polarized incident light, insets (Media 2) show corresponding diffraction patterns at voltage off state (enhanced online). [URL: http://dx.doi.org/10.1063/1.3694921.1] [URL: http://dx.doi.org/10.1063/1.3694921.2]

transmittance (V-T) curves of 0th and 1st orders, respectively, which are calculated with respect to the total incident light intensity. The transmission peak and valleys in the zero order curve correspond to a $\Delta\varphi_x$ and $\Delta\varphi_y$ of 2π (η_{min}), η and 3π (η_{max}), respectively. While it is reverse for first order. As expected, the transmittance variations of 0th order and 1st order, as a function of applied voltage at fixed frequency of 1 kHz square wave, are mirror replica to each other. The measured diffraction efficiency of 1st order (η_1) reaches 31.4% at 1.75 V (all given voltages are root mean square values), while the theoretical efficiency is calculated to be 36.6% according to Eq. (5). The measured value approaching the theoretical maximum confirms the good alignment and high performance of the LC gratings. Due to the high efficiency, 38 diffraction orders could be distinguished by naked eyes at on state (Fig. 2(b)). Optical contrast for 1st order is more than 150 in a voltage range from 0 to 15 V. Insets in Fig. 2(a) provide some diffraction patterns at different voltages. The patterns follow the curves very well and directly prove the tunability of the gratings. In our experiment, a sheet of paper was placed as a screen and diffraction patterns were recorded from the back side, which causes some small light scattering. Besides, the disclination of LC molecules at the domain boundaries also facilitates the scattering, especially during rapid voltage changing.[9]

The polarization independence of proposed gratings is tested by changing the incident light polarization from 0° to 90°. Fig. 2(c) illustrates the voltage dependent behavior of the first order (n = 1) for two input polarizations, one parallel to x axis and the other perpendicular. The result indicates that the test gratings have very good polarization independence of diffraction. The inset shows two diffraction pattern at V = 0 for the two cases which are in high accordance with each other.

Herein, both substrates of LC cell are patterned, which induce a rectangular phase profile with higher diffraction efficiency than sinusoidal ones. Moreover, the simultaneous patterning avoids any mismatch and makes the fabrication simple and more accurate. The diffraction efficiency η could be further improved by the optimization of cell and material parameters. As we can summarize from Eq. (5) that below parameters: l/Λ, n, and $\Delta\varphi$, would affect the diffraction efficiencies. For instance theoretically η_1 could be further improved to 40.6% by changing the l/Λ to be 0.5.

A 2D diffraction grating, which is especially meaningful for beam multiplexing that distributes an optical signal into an array of receivers,[20] has also been demonstrated using a photo mask with $25 \times 25\ \mu m^2$ square-hole-arrays in metal grids (Fig. 1(c)). The pattern looks like circular disks because of the beam size expansion and LC disclinations. Fig. 3 shows voltage dependent intensities of both 0th and 1st orders. A lower transmittance of 87% is attributed to more domain boundaries and stronger scattering. The diffraction efficiency and optical contrast of 1st order are ~14% and over 140, respectively. The insets exhibit the diffraction patterns at different applied voltages and directly prove the tunability of the 2D gratings, which follow the curves very well.

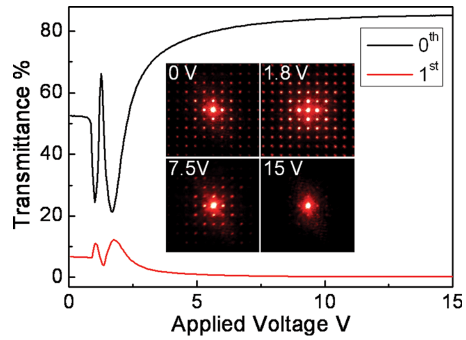

FIG. 3. (Color online) V-T curves of 0th and 1st orders of a 2D grating; insets show the diffraction patterns at different voltages.

Since the initial spatial distribution of LC directors is determined only by photo patterning, arbitrary patterns could be accomplished by predesigned photo masks. It permits the technique to be applied for a wide field of tunable optical elements and devices viz. optical interconnects, beam steering devices, and optically addressed spatial light modulators.

In this letter, a LC grating based on photoalignment technique has been proposed and its polarization independence is theoretically proved. Both 1D and 2D LC gratings are demonstrated by using different amplitude masks with orthogonal PAs executed on both inner sides of the cell. The gratings' switchability and tenability is based on phase modulation by uniform external electrical field. Besides polarization independence, advantages of proposed gratings include simple fabrication process, high resolution, low operation voltage, high transmittance with high efficiency, and optical contrast.

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[1] Y. H. Lin, H. W. Ren, Y. H. Wu, Y. Zhao, J. Y. Fang, Z. B. Ge, and S. T. Wu, Opt. Express **13**(22), 8746 (2005).
[2] H. W. Ren, D. Fox, P. A. Anderson, B. Wu, and S. T. Wu, Opt. Express **14**(18), 8031 (2006).
[3] J. Feng, Y. Zhao, S. S. Li, X. W. Lin, F. Xu, and Y. Q. Lu, IEEE Photon. J. **2**(5), 292 (2010).
[4] X. W. Lin, J. B. Wu, W. Hu, Z. G. Zheng, Z. J. Wu, G. Zhu, F. Xu, B. B. Jin, and Y. Q. Lu, AIP Adv. **1**(3), 032133 (2011).
[5] R. G. Lindquist, J. H. Kulick, G. P. Nordin, J. M. Jarem, S. T. Kowel, M. Friends, and T. M. Leslie, Opt. Lett. **19**(9), 670 (1994).
[6] L. L. Gu, X. N. Chen, W. Jiang, B. Howley, and R. T. Chen, Appl. Phys. Lett. **87**(20), 201106 (2005).
[7] J. Chen, P. J. Bos, H. Vithana, and D. L. Johnson, Appl. Phys. Lett. **67**(18), 2588 (1995).
[8] W. M. Gibbons and S. T. Sun, Appl. Phys. Lett. **65**(20), 2542 (1994).
[9] W. Hu, A. Srivastava, F. Xu, J. T. Sun, X. W. Lin, H. Q. Cui, V. Chigrinov, and Y. Q. Lu, Opt. Express **20**(5), 5384 (2012).
[10] R. L. Sutherland, L. V. Natarajan, V. P. Tondiglia, and T. J. Bunning, Chem. Mater. **5**(10), 1533 (1993).
[11] Y. Q. Lu, F. Du, and S. T. Wu, J. Appl. Phys. **95**(3), 810 (2004).

[12]Y. H. Lin, H. S. Chen, H. C. Lin, Y. S. Tsou, H. K. Hsu, and W. Y. Li, Appl. Phys. Lett. **96**(11), 113505 (2010).
[13]Y. Li and S. T. Wu, Opt. Express **19**(9), 8045 (2011).
[14]V. Kapoustine, A. Kazakevitch, V. So, and R. Tam, Opt. Commun. **266**(1), 1 (2006).
[15]X. Zhao, A. Bermak, F. Boussaid, T. Du, and V. G. Chigrinov, Opt. Lett. **34**(23), 3619 (2009).
[16]H. Akiyama, T. Kawara, H. Takada, H. Takatsu, V. Chigrinov, E. Prudnikova, V. Kozenkov, and H. Kwok, Liq. Cryst. **29**(10), 1321 (2002).
[17]R. Magnusson and T. K. Gaylord, J. Opt. Soc. Am. **68**(6), 806 (1978).
[18]V. Chigrinov, A. Muravski, and H. S. Kwok, Phys. Rev. E **68**, 061702 (2003).
[19]V. G. Chigrinov, V. M. Kozenkov, and H. S. Kwok, *Photoalignment of Liquid Crystalline Materials: Physics and Applications*. (Wiley, England, 2008).
[20]B. I. Senyuk, Smalyukh II, and O. D. Lavrentovich, Opt. Lett. **30**(4), 349 (2005).