Research Article | Vol. 7, No. 1 | 1 Jan 2017 | OPTICAL MATERIALS EXPRESS 8

Optical Materials EXPRESS

Switchable Fresnel lens based on hybrid photo-aligned dual frequency nematic liquid crystal

XIAO-QIAN WANG,[1,2,4] WEI-QIANG YANG,[1] ZHEN LIU,[1] WEI DUAN,[2] WEI HU[2], ZHI-GANG ZHENG,[1,*] DONG SHEN,[1] VLADIMIR G. CHIGRINOV,[3] AND HOI-SING KWOK[3]

[1]*Physics Department, East China University of Science and Technology, Shanghai 200237, China*
[2]*National Laboratory of Solid State Microstructures, Collaborative Innovation Center of Advanced Microstructures and College of Engineering and Applied Sciences, Nanjing University, Nanjing 210093, China*
[3]*Department of Electronic and Computer Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
[4]*xqwang@ecust.edu.cn*
**zgzheng@ecust.edu.cn*

Abstract: In this article we disclose a method to fabricate a polarization independent dual frequency liquid crystal (DFLC) Fresnel lens (FL) with relatively high efficiency. The switchable FL is based on a patterned hybrid photo-aligned nematic (HPAN) DFLC cell assembled by one substrate providing the homeotropic anchoring and the other one providing the in-plane patterned alignment, with mutually orthogonal easy axis in the neighboring alignment domains, which has been prepared by means of two-step photo-alignment technique. Due to the electro-optical properties of dual frequency LC, the proposed HPAN DFLC FL, which manifests relatively high diffraction efficiency of 38.5% and low driving voltage, has the possibility of achieving a fast response by alternatively switching between high frequency and low frequency electric fields. Thus, with an excellent rewritable performance leading to the alternative focus/defocus switch, the HPAN DFLC FL would definitely be practical and promising in many modern devices.

OCIS codes: (160.3710) Liquid crystals; (160.5335) Photosensitive materials; (220.0220) Optical design and fabrication; (230.0230) Optical devices; (250.6715) Switching; (260.5430) Polarization.

References and links

1. J. G. Lu, X. F. Sun, Y. Song, and H. P. D. Shieh, "2-D/3-D Switchable Display by Fresnel-Type LC Lens," Disp. Technol. **7**(4), 215–219 (2011).
2. C. Dorrer, S. K. H. Wei, P. Leung, M. Vargas, K. Wegman, J. Boulé, Z. Zhao, K. L. Marshall, and S. H. Chen, "High-damage-threshold static laser beam shaping using optically patterned liquid-crystal devices," Opt. Lett. **36**(20), 4035–4037 (2011).
3. S. J. Hwang, T. A. Chen, K. R. Lin, and S. C. Jeng, "Ultraviolet-light-treated polyimide alignment layers for polarization-independent liquid crystal Fresnel lenses," Appl. Phys. B **107**(1), 151–155 (2012).
4. X. Q. Wang, F. Fan, T. Du, A. M. W. Tam, Y. Ma, A. K. Srivastava, V. G. Chigrinov, and H. S. Kwok, "Liquid crystal Fresnel zone lens based on single-side-patterned photoalignment layer," Appl. Opt. **53**(10), 2026–2029 (2014).
5. X. Q. Wang, A. K. Srivastava, V. G. Chigrinov, and H. S. Kwok, "Switchable Fresnel lens based on micropatterned alignment," Opt. Lett. **38**(11), 1775–1777 (2013).
6. A. K. Srivastava, X. Wang, S. Q. Gong, D. Shen, Y. Q. Lu, V. G. Chigrinov, and H. S. Kwok, "Micro-patterned photo-aligned ferroelectric liquid crystal Fresnel zone lens," Opt. Lett. **40**(8), 1643–1646 (2015).
7. C. R. Lee, K. C. Lo, and T. S. Mo, "Electrically Switchable Fresnel Lens Based on a Liquid Crystal Film with a Polymer Relief Pattern," Jpn. J. Appl. Phys. **46**(7A), 4144–4147 (2007).
8. Y. Lou, Q. Liu, H. Wang, Y. Shi, and S. He, "Rapid fabrication of an electrically switchable liquid crystal Fresnel zone lens," Appl. Opt. **49**(26), 4995–5000 (2010).
9. H. Jashnsaz, N. H. Nataj, E. Mohajerani, and A. Khabbazi, "All-optical switchable holographic Fresnel lens based on azo-dye-doped polymer-dispersed liquid crystals," Appl. Opt. **50**(22), 4295–4301 (2011).

#279712 http://dx.doi.org/10.1364/OME.7.000008
Journal © 2017 Received 28 Oct 2016; revised 29 Nov 2016; accepted 29 Nov 2016; published 2 Dec 2016

Optical Materials EXPRESS

10. H. Ren, Y. H. Fan, and S. T. Wu, "Tunable Fresnel lens using nanoscale polymer-dispersed liquid crystals," Appl. Phys. Lett. **83**(8), 1515 (2003).
11. Y. H. Fan, H. Ren, and S. T. Wu, "Switchable Fresnel lens using polymer-stabilized liquid crystals," Opt. Express **11**(23), 3080–3086 (2003).
12. H. Nemati, E. Mohajerani, A. Moheghi, M. B. Rad, and N. H. Nataj, "A simple holographic technic for fabricating a LC/polymer switchable Fresnel lens," Europhys. Lett. **87**(6), 64001 (2009).
13. L. C. Lin, H. C. Jau, T. H. Lin, and A. Y. Fuh, "Highly efficient and polarization-independent Fresnel lens based on dye-doped liquid crystal," Opt. Express **15**(6), 2900–2906 (2007).
14. L. C. Lin, K. T. Cheng, C. K. Liu, C. L. Ting, H. C. Jau, T. H. Lin, and A. Y. G. Fuh, "Fresnel lenses based on dye-doped liquid crystals," Proc. SPIE **6911**, 69110 (2008).
15. K. T. Cheng, C. K. Liu, C. L. Ting, and A. Y. G. Fuh, "Electrically switchable and optically rewritable reflective Fresnel zone plate in dye-doped cholesteric liquid crystals," Opt. Express **15**(21), 14078–14085 (2007).
16. Y. Li, Y. S. Yu, L. Guo, S. Z. Wu, C. Chen, L. G. Niu, A. W. Li, and H. Yang, "High efficiency multilevel phase-type Fresnel zone plates produced by two-photon polymerization of SU-8," J. Opt. **12**(3), 035203 (2010).
17. C. H. Lin, Y. Y. Wang, and C. W. Hsieh, "Polarization-independent and high-diffraction-efficiency Fresnel lenses based on blue phase liquid crystals," Opt. Lett. **36**(4), 502–504 (2011).
18. C. H. Lin, H. Y. Huang, and J. Y. Wang, "Polarization-Independent Liquid-Crystal Fresnel Lenses Based on Surface-Mode Switching of 90°Twisted-Nematic Liquid Crystals," IEEE Photonics Technol. Lett. **22**(3), 137–139 (2010).
19. S. H. Lin, C. Y. Li, C. T. Kuo, and H. C. Yeh, "Fresnel Lenses in 90° Twisted-Nematic Liquid Crystals With Optical and Electrical Controllability," IEEE Photonics Technol. Lett. **28**(13), 1462–1464 (2016).
20. S. H. Lin, B. Y. Huang, C. Y. Li, K. Y. Yu, J. L. Chen, and C. T. Kuo, "Electrically and optically tunable Fresnel lens in a liquid crystal cell with a rewritable photoconductive layer," Opt. Mater. Express **6**(7), 2229 (2016).
21. S. Suyama, M. Date, and H. Takada, "Three-Dimensional Display System with Dual-Frequency Liquid-Crystal Varifocal Lens," Jpn. J. Appl. Phys. **39**(Part 1, No. 2A), 480–484 (2000).
22. P. Kumar, S. W. Kang, and S. H. Lee, "Advanced bistable cholesteric light shutter with dual frequency nematic liquid crystal," Opt. Mater. Express **2**(8), 1121 (2012).
23. W. Duan, P. Chen, B. Y. Wei, S. J. Ge, X. Liang, W. Hu, and Y. Q. Lu, "Fast-response and high-efficiency optical switch based on dual-frequency liquid crystal polarization grating," Opt. Mater. Express **6**(2), 597 (2016).
24. Y. Li and D. Luo, "Fabrication and application of 1D micro-cavity film made by cholesteric liquid crystal and reactive mesogen," Opt. Mater. Express **6**(2), 691 (2016).
25. Y. C. Hsiao, I. V. Timofeev, V. Y. Zyryanov, and W. Lee, "Hybrid anchoring for a color-reflective dual-frequency cholesteric liquid crystal device switched by low voltages," Opt. Mater. Express **5**(11), 2715 (2015).
26. S. Yabu, H. Yoshida, G. Lim, K. Kaneko, Y. Okumura, N. Uehara, H. Kikuchi, and M. Ozaki, "Dual frequency operation of a blue phase liquid crystal," Opt. Mater. Express **1**(8), 1577 (2011).
27. Q. Song, H. Q. Xianyu, S. Gauza, and S. T. Wu, "High Birefringence and Low Crossover Frequency Dual-Frequency Liquid Crystals," Mol. Cryst. Liq. Cryst. (Phila. Pa.) **488**(1), 179–189 (2008).
28. H. Q. Xianyu, S.-T. Wu, and C.-L. Lin, "Dual frequency liquid crystals: a review," Liq. Cryst. **36**(6–7), 717–726 (2009).
29. H. Q. Xianyu, X. Liang, J. Suna, and S. T. Wu, "High performance dual frequency liquid crystal compounds and mixture for operation at elevated temperature," Liq. Cryst. **37**(12), 1493–1499 (2010).
30. O. Pishnyak, S. Sato, and O. D. Lavrentovich, "Electrically tunable lens based on a dual-frequency nematic liquid crystal," Appl. Opt. **45**(19), 4576–4582 (2006).
31. X. W. Lin, W. Hu, X. K. Hu, X. Liang, Y. Chen, H. Q. Cui, G. Zhu, J. N. Li, V. Chigrinov, and Y. Q. Lu, "Fast response dual-frequency liquid crystal switch with photo-patterned alignments," Opt. Lett. **37**(17), 3627–3629 (2012).
32. S. A. Jewell, T. S. Taphouse, and J. R. Sambles, "Rapid switching in a dual-frequency hybrid aligned nematic liquid crystal cell," Appl. Phys. Lett. **87**(2), 021106 (2005).
33. Y. Q. Lu, X. Liang, Y. H. Wu, F. Du, and S. T. Wu, "Dual-frequency addressed hybrid-aligned nematic liquid crystal," Appl. Phys. Lett. **85**(16), 3354 (2004).
34. V. Chigrinov, V. Kozenkov, and H. S. Kwok, *Photoalignment of Liquid Crystalline Materials: Physics and Applications* (Wiley, 2008).
35. J. Sun, A. K. Srivastava, L. Wang, V. G. Chigrinov, and H. S. Kwok, "Optically tunable and rewritable diffraction grating with photoaligned liquid crystals," Opt. Lett. **38**(13), 2342–2344 (2013).
36. J. T. Sun and V. G. Chigrinov, "Effect of Azo Dye Layer on Rewriting Speed of Optical Rewritable E-paper," Mol. Cryst. Liq. Cryst. (Phila. Pa.) **561**(1), 1–7 (2012).
37. L. C. Lin, H. C. Jau, T. H. Lin, and A. Y. Fuh, "Highly efficient and polarization-independent Fresnel lens based on dye-doped liquid crystal," Opt. Express **15**(6), 2900–2906 (2007).

1. Introduction

The fast switchable lens with high efficiency is broadly desirable for variety of applications. Liquid crystal (LC) lenses have attracted lots of attentions extensively under the circumstance. An LC Fresnel lens (FL), as a diffractive optical element (DOE), is one of the promising LC lenses, due to its outstanding electro-optical performances. Many works on

Optical Materials EXPRESS

improving its efficiency as well as its switching speed have been well documented [1–6]. Generally, there are two common ways of fabricating LC FL. The first one makes use of the patterned electrodes to generate the designed electric field distribution and locally guide the LC directors in the Fresnel zones [1]. The second one involves initially aligning the LC directors to realize non-periodic refractive index profile by means of ultra violet (UV) modified alignment layer [4–6], patterned polymer relief [7, 8], polymer participated liquid crystal [9–12], and dye-doped liquid crystals [13–16], *etc*. Apart from the diffraction efficiency of such DOE, the polarization independence is also significant for the optical systems, considering from the perspective of effective utilization of light energy.

Among all the existing LC FL, the fastest responding FL was based on ferroelectric liquid crystal (FLC), whose total switching time was about 120μs, however, a pair of polarizers must be employed otherwise its diffraction pattern could not be switched [6]. Due to the unique electro-optical property of blue phase liquid crystal (BPLC), the polarization-independent Fresnel lens with the fast response time of ~1ms was demonstrated by Lin *et al*., however, the operating voltage U>120V had to be applied [17]. In another approach, Lin *et al*. proposed a polarization-independent LC FL by deploying the patterned electrode [18], of which the total response time was 9ms and the diffraction efficiency was less than 25%. Furthermore, the fabrication process to obtain the patterned electrode was complicated, which means that once the LC FL was produced, its focal length was also permanently fixed. Lin *et al*. reported an optically and electrically controlled LC FL in 90°-twisted-nematic LC which provided a possibility for varying the focal length. An interference method was used to generate the Fresnel zone profile during the fabrication. The diffraction efficiency reached up to 28%, and the total switching time was 1.7s [19]. Recently, an LC FL with a relatively high diffraction efficiency of 34.5% was proposed. A rewritable photoconductive layer was employed, enabling an erasing and rewriting of the Fresnel pattern [20].

Most of these works were based on complicated fabrications and were characterized by low efficiency, polarization dependent, high operating voltage or long switching time. Therefore, an LC FL with high diffraction efficiency, fast responsiveness and easy fabrication is contemporarily in high demand. Dual-frequency LCs (DFLCs) offer the possibility to accelerate both rise and decay processes, therefore some electro-optical devices based on DFLCs [21–26], *e.g.*, the DFLC FL with the total response time of ~10ms [21] and the DFLC polarization grating [23], were proposed to achieve fast switching. Usually, a DFLC mixture consists of LC compounds of both positive and negative dielectric anisotropy ($\Delta\varepsilon$), wherein the positive compound exhibits $\Delta\varepsilon>0$ at low frequency, but $\Delta\varepsilon$ decreases with the increase of driving frequency, and the negative compound exhibits $\Delta\varepsilon<0$ and $\Delta\varepsilon$ remains almost constant at driving frequency below ~MHz. A low crossover frequency (<10kHz) of the DFLC mixture, whose value is mainly determined by the relaxation frequency of the positive compound, would minimize the dielectric heating and reduce the energy consumption for driving [27–29]. Thus, the electro-optical devices based on the DFLCs with low crossover frequencies are highly desired. Hitherto, it is well known that the hybrid aligned nematic (HAN) LC cell has no Freedericks transition threshold, but only half of the LC phase retardation could be realized due to the continuous transition of the LC directors from homeotropic orientation on one substrate to homogeneous planar orientation on the other. However, with the aid of the DFLC in proper condition, the HAN cell can achieve the identical phase retardation to that of the planar aligned (PA) one [30]. In addition, the HAN LC cell has the advantage of the shorter response time over the PA one. Hence, a DFLC is preferred in HAN cell [23, 31–33].

Thanks to the photo-alignment technology which provides us an opportunity to facilely control LC alignment, therefore exhibiting a phase profile as Fresnel zones, a polarization independent DFLC FL with high diffraction efficiency and fast responsiveness behavior was achieved by confining the DFLC with a low crossover frequency in a patterned hybrid photo-aligned nematic (HPAN) cell, whose rising and decay time were controlled by the external

Optical Materials EXPRESS

field with alternate high frequency and low frequency voltage signals. In this work, the diffraction efficiency of our proposed HPAN DFLC FL almost reached the theoretical limit, and simultaneously the response time was only 2.6ms, which was much faster than the existing fastest responding DFLC FL [21] and was shortened two to three orders of magnitude as compared with those of prior reported [1, 19]. Moreover, the diffraction efficiency of HPAN DFLC FL can be tuned by external electric-field and can be rewritten as another FL with different focal length, owing to the excellent property of the optically active photo-alignment material.

2. Principles and experiments

Two substrates of LC cell were judiciously designed on two indium-tin-oxide (ITO) glass slices, one of which was treated to provide homeotropic anchoring, and the other substrate was handled to provide the in-plane patterned alignment with mutually orthogonal easy axis in the adjacent alignment domains. Figure 1(a) represents the schematic configuration of liquid crystal in the cross section. The LC molecules under both white regions (odd zones) and black regions (even zones) are in two distinct HAN domains, where the LC molecules in odd zones orient in the y-o-z plane and those in even zones orient in the x-o-z plane. Note that the x-o-z and y-o-z planes are mutually orthogonal to each other. Such an HPAN DFLC FL can be electrically switched between diffractive and non-diffractive states, and its focal length can be optically tuned as well, due to the photo-rewritability of the optically active alignment layer. Furthermore, the proposed HPAN DFLC FL is polarization independent, thereby enabling a double optical efficiency in case of an unpolarized light incidence.

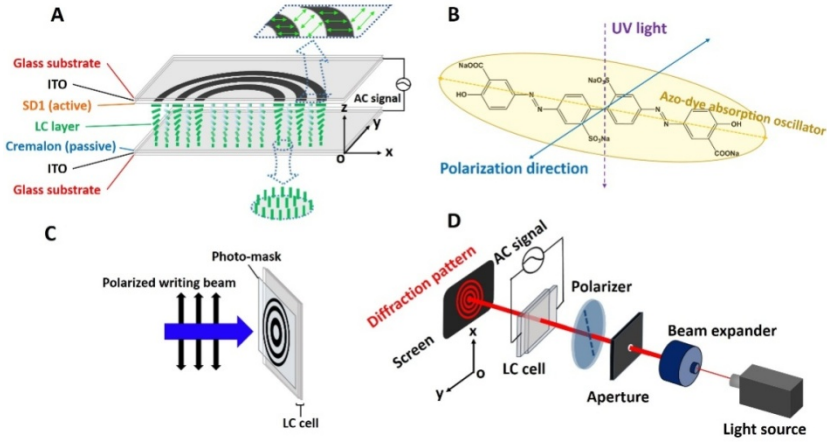

Fig. 1. Configuration, fabrication and testing setup of the proposed HPAN DFLC FL. (A) Configuration of HPAN DFLC FL cell. The molecules under the white regions (odd zones) and the black regions (even zones) orient in the y-o-z plane and the x-o-z plane, respectively. The zoomed area in the blue dotted square shows the easy axis distribution in two different alignment domains and that in the blue dotted circle shows the homeotropic alignment of the LC molecules. (B) Mechanism of the photo-alignment of SD1. The yellow dashed double arrow along the long molecular axis represents the absorption oscillator of the SD1 molecule, and the molecule tends to reorient so as to make the azimuthal angle θ between the polarization plane of the UV light and the absorption oscillator approach 90° under the exposing energy dose of 5J/cm^2. (C) Patterned photo-alignment process with a photo-mask and a polarized writing beam. (D) The experimental setup for measuring the electro-optical properties of the HPAN DFLC FL cell. The wavelength of the probe beam is 632.8nm.

In this experiment, a chromium salt (Cremalon, 0.9wt% in iso-propanol) layer, which was insensitive to the light exposure, was coated on one substrate as an optically passive alignment layer to provide fixed homeotropic alignment as shown in the blue dotted circle of Fig. 1(a). Whereas, the other alignment layer was optically active and could change its

Optical Materials EXPRESS

alignment direction after being exposed under polarized light. A sulfonic azo dye SD1 (Dai-Nippon Ink and Chemicals, Japan (DIC)) (0.5wt% in N, N-dimethylformamide) was coated on the other substrate as an optically active alignment layer to provide planar alignment, which was sensitive to a polarized light within a specific wavelength range. Afterwards, two developed ITO substrates were assembled to form an LC cell with 1.8μm in thickness which met the half-wave condition corresponded to the wavelength of 632.8nm. The LC cell was initially exposed with linearly polarized light of the wavelength, λ = 450 ± 10nm, for a dose of 5J/cm^2. Assuming that the polarization plane of the light made an arbitrary azimuthal angle of θ with respect to the orientation of the azo-dye molecules as shown in Fig. 1(b), the energy absorbed by SD1 molecules was proportional to $\cos^2\theta$, indicating that the probability distribution was angularly dependent [34]. Therefore, those SD1 molecules with their transition dipole moments parallel to the polarization plane of the exposure light got excessive energy, leading to their reorientation from the initial position. This process would not terminate until the absorption oscillator of SD1 was perpendicular to the polarization plane of the writing beam, *i.e.*, $\cos^2\theta$ equals to 0 [34]. In other words, the SD1 molecules on the substrate were aligned perpendicular to the polarization plane of the impinging light. Moreover, these molecules provided the alignment with almost zero pre-tilt angle and high anchoring energy. Then after, the same cell was turned 90° and exposed again through a Fresnel-zone-patterned photo-mask (the pattern follows the equation $R_k = \sqrt{k\lambda f}, k = 1, 2, 3\ldots$, where R_k is the radius of the k^{th} ring, λ is the wavelength of the incident light, f is the designed focal length) which was in close contact with the LC cell as shown in Fig. 1(c). The SD1 molecules in the exposed areas (white regions) were realigned to be orthogonal to the original orientation of those in mask shadow regions (black regions), and the resultant patterned alignment is illustrated in the blue dotted square of Fig. 1(a). Thus, the fabricated cell showed Fresnel zones profile and thereafter, a homemade dual frequency LC with birefringence $\Delta n \approx 0.174$ at λ = 632.8nm was injected into the cell by the capillary action. The absorption of the SD1 molecules mainly occurred in the spectral region from UV to the waveband of blue light (*i.e.*, <450nm), thereby the unpolarized probe beam (see Fig. 1(d)) with the wavelength of 632.8nm could pass through the LC cell without destroying the photo-aligned pattern on the substrate. Moreover, the Fresnel zones pattern with a certain focal length of the proposed HPAN DFLC FL can be erased and rewritten for another one with different focal length by using a polarized laser (λ = 450 ± 10nm) [35].The response time of the erasing and rewriting depends on the elastic parameters of the LC and the anchoring energy of the alignment layer which can be tuned by doses of the exposing energy [36]. Therefore, selecting the LC with proper elastic parameter and using laser with high power can shorten the response time to less than 100ms [35].

The DFLC mixture contains the ester-linking-group-based positive dielectric anisotropic compound with low relaxation frequency [28, 29] which results in the low crossover frequency, f_c, ~4.5kHz of our homemade DFLC. Our experimental results show that $\Delta\varepsilon = -0.984 < 0$ at 40kHz *(i.e.*, high frequency), while $\Delta\varepsilon = 1.834 > 0$ at 1kHz (*i.e.*, low frequency) for the homemade DFLC. Therefore, under the saturated voltage with signal frequency, $f > f_c$, the light passes through the HPAN DFLC FL cell, and thus the two different alignment domains, results in the far-field diffraction pattern showing dozens of concentric rings. Whereas, under the saturated voltage with signal frequency, $f > f_c$, all LC molecules in both domains are switched to orient perpendicular to the substrates and hence the Fresnel zones profile vanishes. Thus, the HPAN DFLC FL can be switched by alternating high frequency and low frequency electric field.

Figure 2(a) shows the micrograph of the HPAN DFLC FL with a designed focal length of 4.4cm under polarizing optical microscopy (POM) with crossed polarizers. The odd zones and even zones present black region since that the photo-aligned easy axis is respectively parallel and perpendicular to the transmission axis of the polarizer. The bright rings represent

Optical Materials EXPRESS

the boundaries between two different alignment domains. The radius of the innermost ring is ~167μm. The photo-aligned pattern of such an HPAN DFLC FL was then erased and rewritten as another HPAN DFLC FL with different designed focal length of 13.2cm, as shown in Fig. 2(b). The corresponding radius of innermost ring is ~289μm.

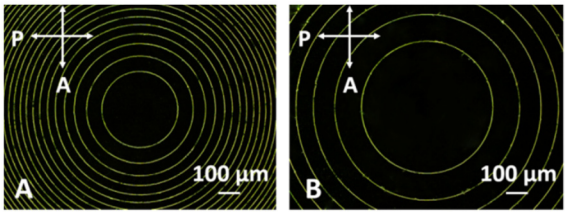

Fig. 2. Micrographs of the HPAN DFLC FLs under the POM. (A) The micrograph of the HPAN DFLC FL with the designed focal length of 4.4cm and (B) the micrograph of the rewritten one with the designed focal length of 13.2cm.

For the theoretical elaboration, we assume that the polarization of the incident light has an arbitrary angle α to the x-axis. The electric field of the incident light E_{in} is denoted as $E_{in} = \begin{bmatrix} E_0 \cos\alpha \\ E_0 \sin\alpha \end{bmatrix}$. When a high frequency ($f > f_c$) electric field much stronger than threshold voltage is applied, the LC in odd zones (*i.e.*, white regions in Fig. 1(a)) and even zones (*i.e.*, black regions in Fig. 1(a)) exhibits different optical states. The outgoing fields E_{out} through the odd zones and even zones are expressed respectively by $E_{out|odd} = \begin{bmatrix} E_0 \cos\alpha \cdot e^{in_o \frac{2\pi}{\lambda} d} \\ E_0 \sin\alpha \cdot e^{in_e \frac{2\pi}{\lambda} d} \end{bmatrix}$ and $E_{out|even} = \begin{bmatrix} E_0 \cos\alpha \cdot e^{in_e \frac{2\pi}{\lambda} d} \\ E_0 \sin\alpha \cdot e^{in_o \frac{2\pi}{\lambda} d} \end{bmatrix}$, where n_e and n_o are extraordinary and ordinary refractive index of LC, respectively, d is the thickness of the LC cell and λ is the wavelength of the probe beam. Thus, the LC molecules in every two adjacent regions are orthogonal to each other, undergoing a π phase shift. When a strong low-frequency ($f > f_c$) electric field is applied, LC molecules tend to be vertically aligned. Therefore, the outgoing fields E_{out} through the white regions and black regions are given by $E_{out|even} = \begin{bmatrix} E_0 \cos\alpha \cdot e^{in_e \frac{2\pi}{\lambda} d} \\ E_0 \sin\alpha \cdot e^{in_o \frac{2\pi}{\lambda} d} \end{bmatrix}$ and $E_{out|odd} = \begin{bmatrix} E_0 \cos\alpha \cdot e^{in_o \frac{2\pi}{\lambda} d} \\ E_0 \sin\alpha \cdot e^{in_e \frac{2\pi}{\lambda} d} \end{bmatrix}$, therefore the far-field diffraction pattern disappears. The first-order diffracted light field E_1 is given by $E_1 = \frac{e^{in_o \frac{2\pi}{\lambda} d}(e^{i\frac{2\pi\Delta nd}{\lambda}} - 1)}{i\pi} \begin{bmatrix} -E_0 \cos\alpha \\ E_0 \sin\alpha \end{bmatrix}$. Therefore, the theoretical diffraction efficiency is defined as $\eta_1 = \frac{|E_1|^2}{|E_{in}|^2} = \frac{4}{\pi^2}$, when the HPAN DFLC FL meets the half-wave condition [37].

3. Results and discussion

Like most of the LC FL, our proposed HPAN DFLC FL was designed for monochromatic light, thus a He-Ne laser with the wavelength of 632.8nm was employed in our experiment. The probe He-Ne laser was expanded and impinged on the sample by passing through an aperture and a polarizer (Fig. 1(d)). The first-order diffraction efficiency of ~38.5% was obtained, which was close to the theoretical limit. The voltage dependent light intensities at 1kHz (low frequency) and 40kHz (high frequency) were obtained respectively by detecting

Optical Materials EXPRESS

the light intensity at the focal point of the HPAN DFLC FL cell. The HPAN DFLC FL initially exhibits an inadequate focusing effect and manifests the light intensity of $I(0)$ in the absence of the electric field. As is shown in Fig. 3(a), the black line represents the voltage dependent intensity curve at 1kHz, and thus the light intensity decreases from its initial value $I(0)$ to the minimum with the increase of the electric field. When the voltage reaches $6V_{rms}$, all LC molecules in the HPAN DFLC FL cell are vertically aligned, resulting in a disappearance of FL effect. The red line shows the voltage dependent intensity performance at 40kHz, accordingly the light intensity goes up from $I(0)$ to the maximum with the increase of the electric field. When the voltage gets saturated ($\sim 6V_{rms}$) at 40kHz, the far-field diffraction pattern with maximal diffraction efficiency appears as is shown in the inset of Fig. 3(b), which characterizes the focusing feature of the HPAN DFLC FL with the polarization of the incident light along the x-axis. To demonstrate the polarization independence of the HPAN DFLC FL when a high frequency signal was applied, a rotatable polarizer was utilized to modulate the polarization state of the probe laser. Figure 3(b) presents the almost overlap of the voltage dependent intensity curves in the cases that the polarization directions of probe laser are 0°, 45°, 90°, respectively, indicating an excellent polarization-independency of the sample. Their corresponding diffraction patterns are shown in the inset of Fig. 3(b).

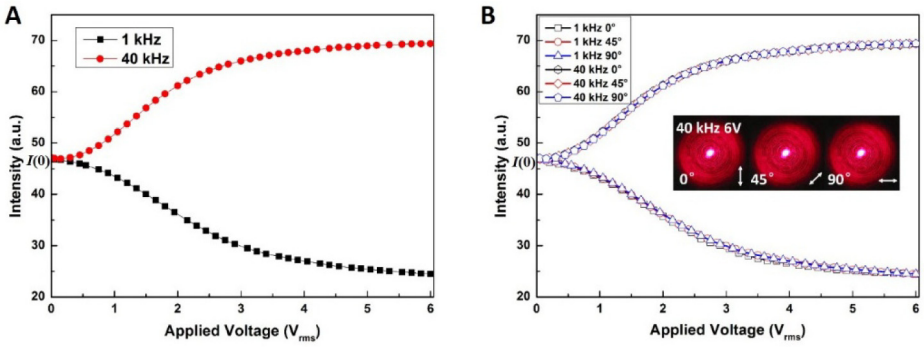

Fig. 3. (A) The voltage dependent intensities at 1kHz (low frequency) and 40kHz (high frequency); (B) Polarization-independent performances of HPAN DFLC FL as a 40kHz voltage was applied. The white double arrows indicate the polarization of the incident light.

The responsiveness of the sample was tested by applying a $6V_{rms}$ signal with alternate frequencies of 1kHz and 40kHz (Fig. 4). The rise and decay times, which were defined as the duration times of the intensity from 10% maximum to 90% maximum and from 90% maximum to 10% maximum, were 1.725ms and 893μs, respectively. Such response time can be further shortened by optimizing the parameters of materials. In addition, increasing the applied voltage is another way of decreasing the response time, however, a high electric field at high-frequency brings about the thermal effect disturbing the refractive index distribution which is a common issue for most of the DFLCs.

Optical Materials EXPRESS

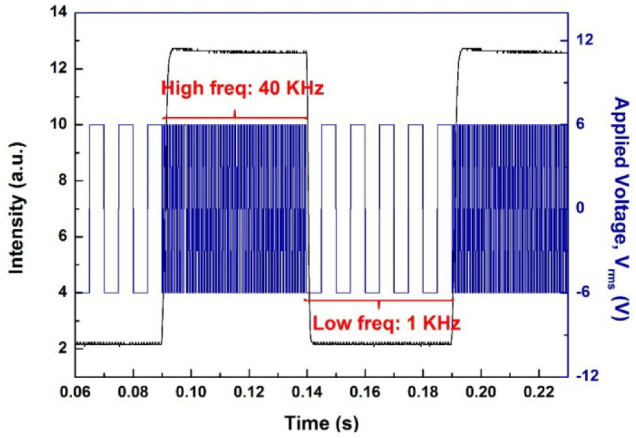

Fig. 4. Electro-optical response of the HPAN DFLC FL by applying a $6V_{rms}$ voltage with alternate frequencies of 1kHz and 40kHz.

4. Conclusions

A switchable polarization independent HPAN DFLC FL with the diffraction efficiency of ~38.5% has been demonstrated. Two clear switching states of the fabricated HPAN DFLC FL were achieved by applying the electric field with alternate high frequency and low frequency signals. The rise and decay times were measured to be 1.725ms and 0.893ms respectively, which can be further reduced down to sub-millisecond by optimizing parameters of DFLC. Compared with the existing devices, the proposed HPAN DFLC FL with a low crossover frequency is faster and highly efficient device. Moreover, the photo-alignment in association with a fixed homeotropic alignment layer on one glass substrate makes the fabrication of microstructural photonic devices much simpler and less costly. The proposed HPAN DFLC FL is not only an electrically switchable device, but also an optically controllable focus/defocus switch by irradiating the sample with a blue polarized laser, thereby enabling its perspective applications in the next generated display, photonics and others beyond.

Funding

Shanghai Pujiang Program (16PJ1402200); National Natural Science Foundation of China (NSFC) (Grant Nos. 61435008, 61575063); State Key Laboratory on Advanced Displays and Optoelectronics Technologies, ECE Department; CERG (614410, 612409) HKUST, Hong Kong.