Arbitrary photo-patterning in liquid crystal alignments using DMD based lithography system

Hao Wu,[1] Wei Hu,[1,4] Hua-chao Hu,[1] Xiao-wen Lin,[1] Ge Zhu,[1] Jae-Won Choi,[2] Vladimir Chigrinov,[3] and Yan-qing Lu[1,*]

[1]*National Laboratory of Solid State Microstructures and College of Engineering and Applied Sciences, Nanjing University, Nanjing 210093, China*
[2]*Department of Mechanical Engineering, The University of Akron, Akron, OH 44325-3903, USA*
[3]*Center for Display Research, Department of Electronic and Computer Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
[4]*huwei@nju.edu.cn*
[*]*yqlu@nju.edu.cn*

Abstract: We propose and implement a technique for arbitrary pattern fabrication in liquid crystal (LC) alignments and local polarization control for light wavefront. A micro-lithography system with a digital micro-mirror device as dynamic mask forms arbitrary micro-images on photoalignment layers and further guides the LC molecule orientations. Besides normal phase gratings, more complex 2D patterns such as quasicrystal and checkerboard structures are demonstrated. To characterize the optical performances of the fabricated structures, the electro-optically tunable diffraction patterns and efficiencies are demonstrated in several 1D/2D phase gratings. Compared to other techniques, our method enables the arbitrary and instant manipulation of LC alignments and light polarization states, facilitating wide applications in display and photonic fields.

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OCIS codes: (160.3710) Liquid crystals; (110.3960) Microlithography.

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1. Introduction

Liquid crystal (LC) devices have been widely used in flat panel display, optical communication, information processing and sensing [1–5] for their advantages of low voltage, light weight, low cost, no moving parts, and low power consumption. LC alignment is the foundation of a wide variety of LC components. Recently, photoalignment technique has attracted intensive interests for it avoids the problems resulting from the conventional rubbing method, such as contamination, electrostatic charges and mechanical damage [6]. Besides, photoalignment also brings the possibility of fabricating certain patterns with different LC alignments, which contributes to the wide viewing angles in liquid crystal displays [7] and various photonic structures such as LC gratings [8–10]. Different approaches have been proposed to obtain patterned alignments. Presnyakov *et al* realized a grating using azo-dye alignment layer exposed with two interfering laser beams of opposite circular polarizations [11]. Exploiting UV photoalignment and amplitude mask, Kapoustine *et al* demonstrated switchable LC gratings through introducing a periodic variation of the alignment direction into one substrate of cells [9]. Zhao *et al* reported a micropolarizer array by using a linearly polarized light to define the orientation of LCs [12]. Hu *et al* presented both one dimensional (1D) and two dimensional (2D) liquid crystal gratings with alternate twisted nematic (TN)/homogeneously alignment (PA) and orthogonal PA regions respectively by two-step photo exposure [13, 14]. With multi interfering beams method, only periodic patterns such as 1D and 2D gratings have been demonstrated, for more complex structures it will be difficult to realize. While it would be arduous and cost inefficient to accomplish complex structures in multi LC orientations with conventional amplitude mask because of the employment of multiple masks as well as the inevitable registration issue. Besides, the beam expansion limits the resolution. Above shortcomings considerably constrain their applications.

To address these limitations, the Digital Micro-mirror Device (DMD) based micro-lithography could be considered [15, 16]. Herein, we use the DMD as a dynamic mask, generating arbitrary patterns by individually tilting angle control of each mirror, thus supply a one-mask-for-all method that complex patterns will be generated with great ease. Furthermore, mask registration problem in multi-exposure could be eliminated because no mechanical movements occur when changing masks, which also greatly simplifies the fabrication process. High resolution could be reached with a projection lens for it avoids beam expansion problem.

In this work, we utilize a DMD based micro-lithography system to control the LC alignments. Micro patterns generated by DMD are projected onto sulfonic azo-dye (SD1) films through a polarizer. By this means, arbitrary patterns such as 1D Fibonacci grating, checkerboard pattern and 12-fold symmetric quasi-period pattern are demonstrated. High resolution up to 5 μm is achieved, and further improvement is possible. Thanks to the image generating ability of DMD, combined with the good alignment rewritability of SD1, arbitrary azimuthal angle control of LC is also realized by rotating the polarizer. TN regions with twist

angles varying from 10° to 90° with an interval of 10° are accomplished in a single LC cell. The electro-optical properties of 1D phase grating are measured. The diffraction efficiency of the first order reaches over 22% and the intensity of the same order could be electrically suppressed by over 20 dB. New applications relying on free manipulation of LC alignments and light polarizations are achievable by this approach.
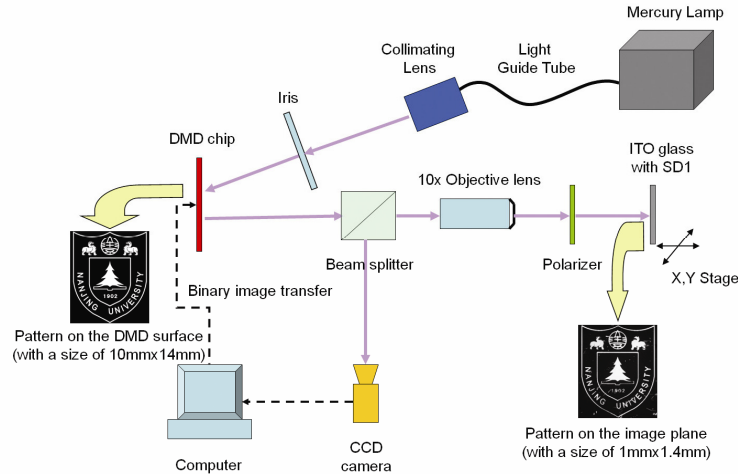
2. Design and fabrication

Fig. 1. Schematic illustration of DMD based micro-lithography system.

As shown in Fig. 1, the DMD based micro-lithography system consists of several sub-systems, including a light emission part, a dynamic pattern generation part, an image focusing part and a monitor part, all of which function in cooperation to provide correct exposure on the substrate. A mercury lamp (S1000, EXFO, Canada) filtered at 320-500 nm along with a collimating lens provide a uniform and collimated light beam. The beam illuminate onto the DMD surface through an iris. DMD (1024 × 768, Discovery 3000, Texas Instruments), as a dynamic mask, consists of more than 786,000 micro-mirrors. Independently tilted by an electrostatic force, each mirror (13.68 m × 13.68 m in size) can be switched between "on" and "off" states by toggling the applied voltage. The bundle of light reflected by the "on" state mirrors will form a desired light pattern [17]. Then the pattern will be focused by an apo-chromatically corrected projection lens (10 × , NA = 0.3, WD = 34 mm, Cinv Optics Co., China) and recorded on the substrate placed at the image plane. The light reflected by the substrate is then collected into a CCD, which is used to monitor the focusing of the image. In this system, several parameters are adjustable: the focal length of the collimating lens, the distance between the collimating lens and DMD and that between DMD and the objective lens. We optimized these parameters by ZEMAX^{TM} thus achieved a uniform illumination on DMD and a clear image at the substrate.

Two ITO-coated glass substrates are UV-Ozone cleaned and spin-coated with SD1 (0.5 wt.% in N-dimethylformamide) films. SD1 molecules tend to align their absorption oscillators perpendicular to the polarization of the activating light and then supply considerably high azimuthal anchoring energy (>10^{-4} J/m^2) comparable to that of rubbed PI [6, 13]. The two substrates are both uniformly irradiated by linearly polarized light to create a photoalignment in the same direction with a dose of ca. 5 J/cm^2. One of the substrates is then placed at the image plane of the system and exposed again with a desired pattern protracted by CAD or Photoshop software. Herein the light polarization is set different from that of previous exposure. SD1 shows excellent alignment rewritability [13, 14], therefore the exposed regions are realigned while the mask shadow domains still keep the previous alignment. An LC cell is assembled by the two substrates and then filled with LC mixture E7

at isotropic phase. After cooling to room temperature, the LC molecules show patterned orientations due to different alignment directions among adjacent domains.

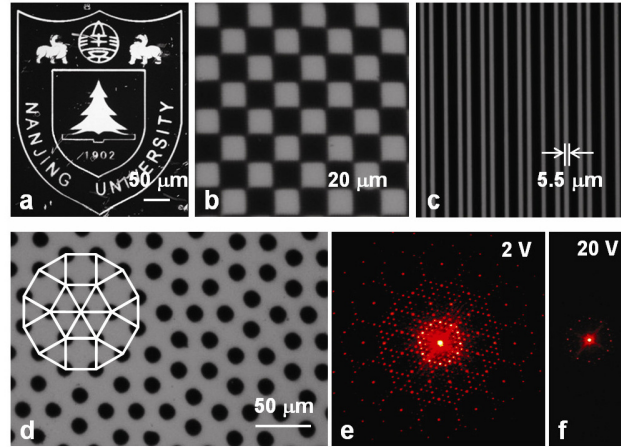## 3. Results and discussions

Fig. 2. Micrographs of different LC patterns under a cross-polarized microscope: a) logo of Nanjing University, b) checkerboard, c) Fibonacci grating, d) 12-fold symmetric quasi-periodic structure and e-f) diffraction patterns of the sample shown in d) under different applied voltages. All cell gaps are 6 μm.

We fabricated several kinds of phase patterns using this system, as presented in Fig. 2. The bright regions show TN alignment of LC while the dark regions show PA alignment. All samples are observed by a cross-polarized microscope with polarizer direction parallel to PA direction. Figure 2(a) shows an LC cell patterned with the logo of Nanjing University. As one can see, the brightness of different parts is uniform and the edge of the pattern is sharp. The line width of the frame measures 11 μm, well coordinate with our design (8 pixels on DMD). Figure 2(b) presents a 2D checkerboard grid. In spite of slight distortion due to the aberration of projection lens, the pattern keeps square. In previous work, we fabricated 2D gratings with a conventional mask, in which square patterns look more like circular disks [13]. While in this work, thanks to the projection system, no beam expansion exists and remarkable improvement is achieved in pattern quality. Moreover, 1D and 2D quasi-periodic LC patterns have also been fabricated. Figure 2(c) exhibits a Fibonacci structure [18] with feature size of 5.5 μm (4 pixels on DMD). In Fig. 2(d), we present a 12-fold symmetric pattern which was proposed by Zoorob *et al* [19]. From the diffraction patterns under different voltages shown in Figs. 2(e) and 2(f), we can easily figure out 12-fold rotation axes that would never occur in periodic structures. This is the first time that LC quasi-periodic patterns are realized. All above results prove a faithfully replication ability of the micro-lithography system. Therefore arbitrary structure fabrication could be achieved with this system as the free pattern design on DMD.
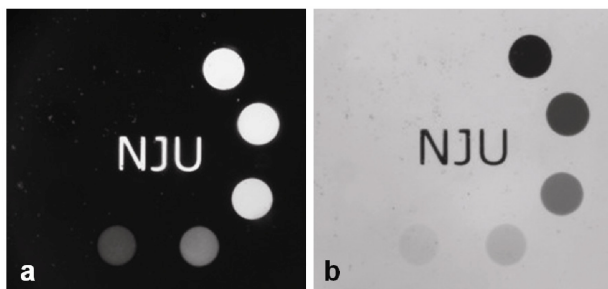
Fig. 3. Micrographs of LC polarization rotators with different twist angles under a polarizing microscope with a) crossed and b) parallel polarizers.

Beside flexible pattern manipulation, local alignment direction control is also realized by rotating the polarizer. We demonstrated a polarization rotator array with different angles in a single LC cell. The two substrates are photoaligned in parallel and then 9 regions on one of the substrates are realigned sequentially through changing the DMD pattern (disk position) as well as the polarization of activating light. Thus, 9 TN disks with twist angles varying from 10° to 90° at an interval of 10° are formed, observed as different gray scales in Figs. 3(a) and 3(b). During observation, the light is incident to the unpatterned substrate first, with its polarization parallel to the alignment direction, and then when passing through the cell, only components along the analyzer directions could be observed. The results suggest the possibility of arbitrary polarization control of any part of the wavefront. Furthermore, in the whole exposure process, no mechanical movements of either DMD or substrate are needed, avoiding the registration problem of conventional multi-step lithography.
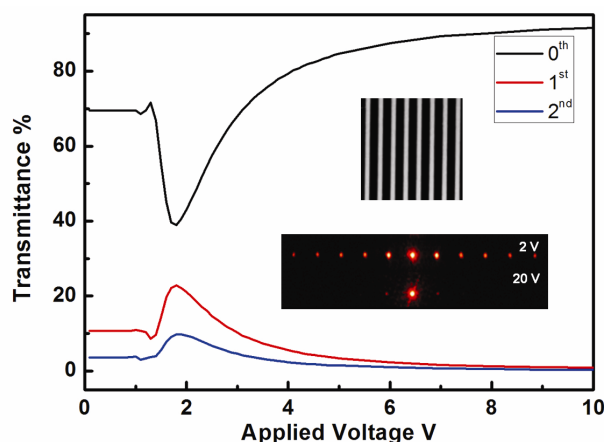

Fig. 4. V-T curves of an LC phase grating with alternate TN/PA regions. The transmittance of 2nd order is amplified by 5 times for better display. Insets show a micrograph and diffraction patterns at different voltages respectively. All given voltages are peak to peak values.

We also characterize the electro-optical properties of the samples. Taking an LC phase grating with alternate TN/PA regions for example, the voltage-transmittance (V-T) curve is measured and displayed in Fig. 4. The grating period and cell gap are both 15 μm. We apply a square wave signal at the frequency of 1 kHz to the cell. The insets show a micrograph and the diffraction patterns of the grating at different voltages. The diffraction efficiency of 1st order (defined as the transmittance of 1st order over total, $\eta = T_{1st}/T_{total}$) reaches 22%. As the voltage increases to 20 V_{pp}, the 1st order diffraction is nearly switched off with an extinction ratio (defined as transmittance maxima over minima) over 20 dB. These results show comparable tunability with previous reports [13], and have proved again the good

performance of this method. As the diffraction efficiency is determined by the phase retardation of adjacent regions [14], the tuning property of the 12-fold symmetric structure is similar to that of simple periodic gratings. Good switchability of this structure is also achieved, as shown in Figs. 2(e) and 2(f).

Experimental results reveal the following advantages of our system: 1) Arbitrary pattern fabrication and local polarization control are practical. 2) High resolution of 5.5 μm has been reached. The theoretical optical resolution of current system is 1.4 μm, according to the DMD pixel size and the minification of the projection lens. By further optimization such as substituting the projection lens with one of higher magnification, resolution up to diffraction limit could be achieved. 3) With the projection system, the substrate is exposed at the focus plane; so beam expansion problem can be overcome. Therefore, even after the substrates being assembled to a cell, high quality replication can still be obtained, allowing instant control of the alignment [6]. 4) No mechanical movements are needed in multi-step exposure, avoiding the registration problem of conventional lithography technique.

Above advantages of this technique permit wide range of applications, from LC display to photonic fields. Quasicrystals are attracting considerable interests because of their high level of symmetry, which makes them excellent candidates of photonic bandgap materials [18]. This should be the first demonstration of quasi-periodic structures in LC, which opens a new door to realize tunable photonic crystal devices. The technique also enables locally control of polarization states, which is significant for the use in generating vector beams [20], realizing integrated [21] and multi-stable LC devices [19].

4. Conclusion

An approach to realize the patterned LC alignment in LC cell has been proposed and implemented. By utilizing the DMD based micro-lithography system we developed, arbitrary patterns have been fabricated including 1D and 2D periodic and quasi-periodic gratings. Comparable electro-optical tunability with previous work has been demonstrated. Besides, a polarization rotator array is realized. We believe this approach should be a very competitive photoalignment technique because it offers a simple way to fabricate arbitrary patterns alignment with high resolution, based on which wide applications of LC devices are practical.

Acknowledgments