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Multilayer photo-aligned thin-film structure for polarizing photonics

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In this Letter, an advanced multilayer photo-aligned liquid crystal polymer (LCP) thin-film structure with multiple optical functions is introduced. Within each LCP layer, a spatially distribution of local optical axes can be controlled by a patterned photo-alignment layer. As an embodiment of the proposed structure, a two-layer structure with pixelated controlled light-propagation directions and polarizations has been studied, which has shown the potential to be used as a photomask for generating multi-domain photo-alignment structures with a single exposure step. The combination of the multilayer structure with patterned photo-alignment technology provides a new perspective of designing optical structures for polarizing photonics applications.

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The study on patterned liquid crystal photo-alignment has drawn more and more attention in recently years [1–8], for the reason that the complex patterned photo-alignment structures can be easily defined to offer various kinds of optical functions. Many LC devices are developed based on various patterned alignment structures, such as polarization gratings [1,2], binary gratings [3], LC lenses [4,5], polarization sensor [6], and axial waveplates [7–9], etc. For most of these patterned photo-alignment LC devices, a single patterned photo-alignment layer is applied to control the LC director distribution on a two-dimensional (2D) surface. With the 2D LC distribution, many optical functions can be achieved, such as controlling of diffraction, phase profile, or polarization distribution, which offers the versatility for many photonics applications.

With the improvement of patterned photo-alignment technology and emergence of new optical function requirement, we are now proposing a new optical thin-film structure with the extension of controlling the LC director distribution from the 2D surface to a new three-dimensional (3D) volume design. The proposed thin-film structure is based on a multilayer structure with multiple liquid crystal polymer (LCP) layers, in each of which an independent photo-alignment layer is applied to control the LC director distribution. The whole multilayer thin film structure is coated layer-by-layer on the same substrate that guarantees the extreme small distance between each layer. When light passes through such a multilayer thin film, there is very small light deviation and diffraction between each another LCP layers, so the functions of each LCP layer can be directly integrated, which offers the freedom to design a multi-functional thin-film optical device. The proposed multilayer optical structure offers a new perspective of designing the functional thin films based on patterned photo-alignment.

In this Letter, one embodiment of such an optical structure is designed both theoretically and experimentally. The optical structure uses two LCP layers, with which both the light propagation directions and polarizations are controlled simultaneously in a pixelated structure. This optical structure is specially designed to work as a photomask for preparing multi-domain LC cell [4,10,11]. It will show that, by applying the photomask, a pixelated multi-domain LC alignment structure with controlled pretilt and azimuthal angles can be fabricated with a single exposure step, which simplified a lot the fabrication process for multi-domain LC displays (LCDs). With the embodiment structure as the example, it strongly proved the powerful optical function and extremely usefulness for the proposed new thin film structure.

The proposed optical structure is formed by two photoaligned LCP layers, where each layer is used either to control the propagation directions or to control the output polarizations. The key structure for controlling the light propagation directions is a LC polarization-grating (PG) structure [1,2,12,13]. The PG is a birefringent film with optical axes continuously varying along the grating vector, as shown in Fig. 1(a) where the grating vector is along the x-axis. The optical axis distribution can be described as $\alpha(x) = \pi x/P$, where α is defined as the angle between the slow axis and the x-axis, and P is defined as pitch of the PG. When the retardation of the birefringence film satisfies the half-waveplate (HWP) condition, the PG will change the propagation direction of a circularly polarized light (CPL) [1,12]. This optical phenomenon is described in Jones matrix:

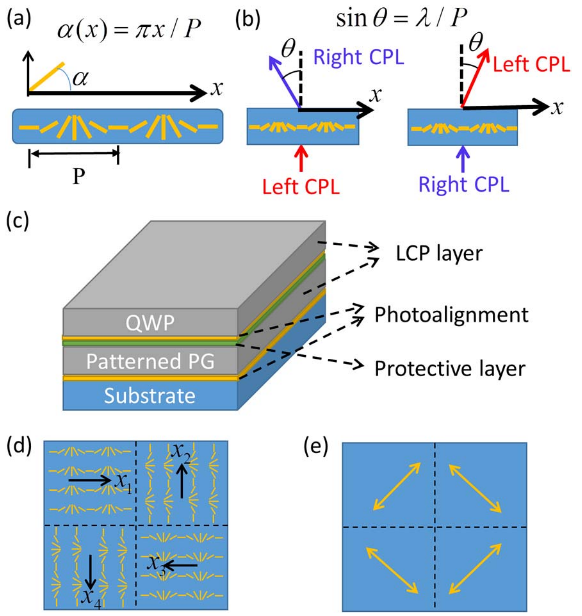

Fig. 1. (a) Alignment structure of the polarization grating. x axis denotes the grating vector direction; the yellow lines represent the optical axes' direction. (b) Beam steering effect with left and right CPL light passing through the PG. (c) Multilayer structure of the designed photomask with a patterned PG layer and a QWP layer. (d) An example for four-domain structure of the patterned PG. (e) An example for four-domain structure for the patterned QWP.

$$E_{\text{out}} = R(-\alpha(x))M_{\text{HWP}}R(\alpha(x))E_{\text{in}} = \begin{bmatrix} \cos\alpha(x) & -\sin\alpha(x) \\ \sin\alpha(x) & \cos\alpha(x) \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & \exp(-i\pi) \end{bmatrix} \begin{bmatrix} \cos\alpha(x) & \sin\alpha(x) \\ -\sin\alpha(x) & \cos\alpha(x) \end{bmatrix} \begin{bmatrix} 1 \\ \pm j \end{bmatrix} = \exp\left(\pm j\frac{2\pi}{P}x\right)\begin{bmatrix} 1 \\ \mp j \end{bmatrix} \tag{1}$$

where R is the rotational Jones matrix, M_{HWP} is the Jones matrix of the HWP which forms the PG, and the input light is CPL, described as $E_{\text{in}} = [1, \pm j]$ ($\pm$ denotes right and left CPL). We can see that when CPL passes through the PG, the output light will still be CPL but in reversed handedness. The extra phase part $\exp(\pm j2\pi x/P)$, which is known as the Pancharatnam–Berry (PB) phase [14,15], offers a linear phase variation along the grating vector, which leads to a shift on propagation directions. With the linear phase variation, we can get that for a normal incident CPL, the output light will be steered with an angle, where λ is the wavelength of the incident light [Fig. 1(b)]. For incident CPL with reversed handedness, the output light will be steered to the opposite direction. Moreover, to achieve larger steering angles, additional layers of PG can be stacked to make a multi-layer structure. Taking into account that each PG layer reverses the handedness of the CPL passing through it, the neighboring PG layers is required to have the opposite grating vectors. As a result, the extra phase part will be described as $\exp(\pm j2\pi x(1/P_1 + 1/P_2 + 1/P_3 + \ldots))$ where P_1, P_2 and P_3 represent the pitch of each PG, and the resulted steering angle is increased to be $\theta = \arcsin(\lambda(1/P_1 + 1/P_2 + 1/P_3 + \ldots))$ [1].

The LCP layer for controlling the output light polarization is a retardation layer, stacking on top of the PG layer. By controlling the retardation value and the local alignment of the optical axis, the output light polarization can be controlled. The Jones matrix description of the PG and the retarder is shown in Eq. (2):

$$E_{\text{out}} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & \exp(-i\Gamma) \end{bmatrix} \begin{bmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{bmatrix} \exp(\pm j2\pi x/P) \begin{bmatrix} 1 \\ \mp j \end{bmatrix}, \tag{2}$$

where Γ is the retardation value, and β is the angle of retarder optical axis with the grating vector of the PG. If the retardation film is a quarter waveplate (QWP) with optical axis in the angle $\beta = \pi/4$, for input light with right CPL, the output light can be described as

$$E_{\text{out}} = \exp(j2\pi x/P)[1, 0], \tag{3}$$

which is linearly polarized light (LPL) with a steering angle $\theta = \arcsin(\lambda/P)$. As a result, the proposed structure provides the flexibility of controlling light propagation direction and polarization, which is crucially important for generating liquid crystal photo-alignment structure with fully controlled azimuthal and pretilt directions [11,16].

To build the thin film with independent control of light propagation directions and polarizations in a pixelated structure, a multi-layer thin-film structure formed by stacking a patterned PG layer with a patterned QWP is designed, as shown in Fig. 1(c). The patterned PG is engineered with a pixelated structure where each pixel contains a PG domain with independent grating vector. Figure 1(d) shows one embodiment of the patterned PG structure. The QWP is also engineered with a pixelated structure containing spatially varying optical axes. By precisely matching the pixel position of the two layers, the light propagation directions and polarizations can be controlled independently in each pixel. The example structures shown in Figs. 1(d) and 1(e) represent a unit of a four-domain periodic structure, which can be used as the photomask for the fabrication of a LCD with four-domain patterned alignment [11,17,18]. Moreover, by playing with the geometrical pixel structures, the optical structure provides the flexibility of copping with the requirement of fabricating various photo-alignment layers.

To prove the principle of the optical structure, a periodic two-domain thin film structure is successfully fabricated and tested for working as a photomask. In the experiment, the liquid crystal polymer (LCP) films with optical axes distribution precisely controlled by the photo-alignment layers are used for building both the patterned PG and the QWP layers in the photomask. Generally, the alignment direction of the photo-alignment layer is determined by the polarization direction of the exposure light [16,19]. Thus the optical axis distribution can be controlled by exposing the photo-alignment layer with a beam in spatially varying polarizations. In our experiment, we use the sulfonic azo dye SD1 [from Dai-Nippon Ink and Chemicals (DIC), Japan] as the photo-alignment material, and UCL017A (from DIC) as the LCP material. SD1 has the property that the alignment is generated upon exposure by

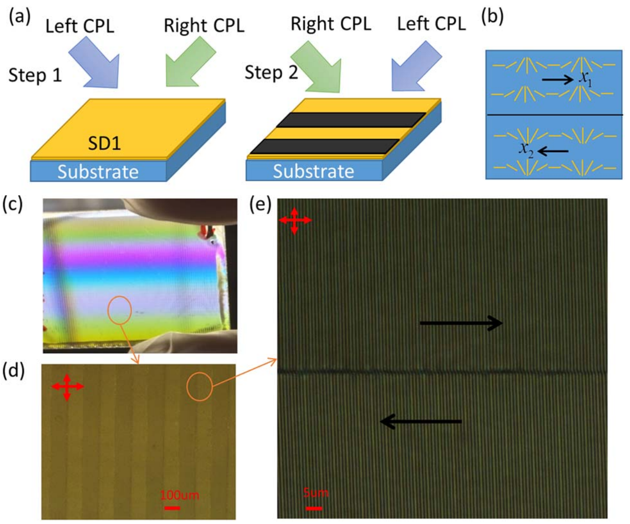

Fig. 2. (a) Preparing the two-domain patterned PG alignment structure in a two-step exposure. (b) The alignment structure of the patterned PG. (c) The photo of the prepared patterned PG. (d) and (e) The microscopic photos of the patterned PG under cross polarizers in different magnifications.

polarized light, where the alignment direction is perpendicular to the light polarization direction and can be reoriented by an additional exposure with light in a different polarization direction [16,19]. To prepare the patterned PG film, first, the SD1 layer with thickness ∼10 nm is coated on top of a quartz substrate, which is then exposed by the interference of two circularly polarized laser beams (365 nm) with orthogonal handedness [1,2,20] to generate the continuous PG alignment structure [Step 1 in Fig. 2(a)]. The pitch of the PG is designed to be 2 μm. Then a mask with periodic metallic strip in 100-μm width is used to cover the SD1 substrate, which is then exposed by a second exposure using the same interference method but with the two orthogonal CPL beam in reversed handedness [Step 2 in Fig. 2(a)]. Due to the reorientation property of SD1 [16,19], the exposure with the second interference pattern will generate the PG alignment structure having reversed grating vector with respect to the previous one. With this two-step exposure, a patterned PG alignment structure [Fig. 2(b)] is fabricated. Thereafter, a layer of LCP UCL017A is coated on top of the alignment layer, and the LCP molecules follow the local alignment directions of the pre-treated SD1 layer to make a patterned PG. After that, the LCP layer is polymerized under UV exposure to form a solid film as shown in Fig. 2(c), wherein Figs. 2(d) and 2(e) show the microscopic photos under crossed polarizers for different magnifications. The thickness of the LCP is designed to satisfy half-wave condition according to the working wavelength of the photomask. For this case, a patterned PG for 325-nm wavelength has been fabricated with thickness of LCP ∼600 nm.

After finishing the preparation of the patterned PG layer, a standard PECVD process [21] is used to deposit a SiO_2 layer (∼50 nm) on top of the PG layer [Fig. 1(c)]. The SiO_2 layer is used as a protective layer to avoid interference on the existing bottom layer caused by the processing of the additional layers. SiO_2 is chosen because of its optical transparency and good stability. Then another layer of SD1 is coated on top of the SiO_2 layer and aligned with polarized UV light. The alignment direction has $\pi/4$ angle with the grating vector of bottom PG layer. Thereafter, a second UCL017A layer with thickness (∼300 nm) satisfying quarter wave retardation condition for 325-nm wavelength is coated on the alignment layer. The alignment of UCL017A is defined by SD1, and an additional UV exposure polymerizes the film. After all these steps, the whole photomask is fabricated, with structure illustrated by Fig. 1(c). When a uniform Right CPL beam passes through the photomask, the output light will be LPL with spatially varying propagation directions, as described in Eq. (3). The overall thickness of the multi-layer thin film is less than 1 μm, which guarantees the generation of high-resolution pixelated wavefront with controlled light propagation directions and polarizations.

The performance of the photomask is tested with another photo-alignment material, CPL024 (from DIC) [4], which provides vertical alignment with controllable pretilt and azimuthal angle corresponding to incident direction and polarization of the exposure light. As described in Ref. [4], under oblique exposure by a polarized UV light with a certain exposure dosage, CPL024 shows pretilt angle ∼89°. As the tilt of CPL024 tends to align in parallel with the electric field vector of the incident light, both the light incident angle and polarization direction needs to be controlled during the exposure process [4]. In the experiment, CPL024 is coated on top of an ITO glass substrate and exposed by CPL light with 325-nm wavelength through the photomask, which is in direct contact with the CPL024 layer. The optical property of the photomask is shown in Fig. 3(a), and the resulted alignment structure of CPL024 layer is shown in Fig. 3(b). To measure the alignment structure of CPL024, a LC cell is assembled with the prepared CPL024 substrate and a new alignment substrate with ideal 90° pretilt angle made of polyimide 5661 (from Nissan, Japan).

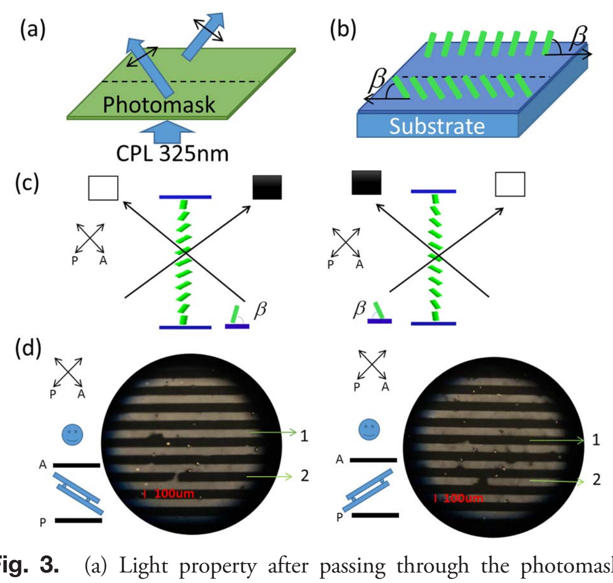

Fig. 3. (a) Light property after passing through the photomask. (b) Alignment structure prepared by the photomask. (c) Simulation result of the LC director distribution using Mouse-LCD; also shows different transmittances for oblique observation in different directions. (d) Micrographs of the obliquely observed LC cell under crossed polarizers.

The cell gap is 5 μm, and a LC material NA0383 (from DIC) with negative dielectric anisotropy is filled into the LC cell.

To verify the two-domain alignment structure in the LC cell, the LC cell is put under a microscopy with crossed polarizers for observation. A 1-kHz AC voltage with square wave peak-to-peak 2.4 v is applied on the LC cell to generate different LC director distribution of the two domains in the bulk, which is simulated by a commercial software Mouse-LCD [22] (HKUST, Hong Kong). As shown in Fig. 3(c), we can see that for the two-domain structure with different pretilt directions, the director of the LC molecules rotates in opposite directions under the applied electric field. Thus the retardation value, as well as the transmittance, of the two domains will be different when examined obliquely under crossed polarizers. Figure 3(d) shows the microscopic photos that are taken under microscope by placing the LC cell obliquely. As expected, the dark and bright lines represent the two domains respectively in the LC cell, which will be reversed by placing the LC cell obliquely in an opposite direction. The result shows that the multi-domain LC alignment structure is successfully fabricated using the designed photomask.

From the above experiment results, the effectiveness of the proposed thin film structure has been successfully verified, which guarantees an advanced photomask in producing multi-domain photo-alignment structure in only one step exposure. The developed thin-film photomask can effectively support the manufacturing of multi-domain LCDs including the multi-domain vertical alignment LCDs [17] and multi-domain twisted nematic LCDs [11]. Moreover, to the best of our knowledge, this thin film is also the first photomask having such a multiple functions and having the capability to support the multi-domain LCDs manufacture.

The photomask structure developed in this Letter is an embodiment of the proposed multilayer photo-aligned liquid crystal polymer thin-film structure. The thin-film structure contains 3D LC director distribution that varies both on the film surface and on different stacked film layers. For a single patterned LCP layer, light properties including phase, polarization, and intensity can be easily controlled spatially. When several patterned LCP films are stacked to form the multilayer structure, the optical function in each layer can be integrated to achieve complex and multiple optical functions. Moreover, in the proposed structure, the total thickness of the multilayer thin film is very small, so the light diffraction within the film is suppressed, which leads to a highly controllable thin-film structure design. With specially designed combination of the patterned alignment structures and multilayer thin film structures, a new series of optical devices with powerful and multiple optical functions can be developed. These new optical devices have great potential to be used in laser beam modulation, polarization image processing, optical communication, holographic displays, and many other advanced polarizing photonics applications.

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