Low-voltage driving liquid crystal lens with precise control of pretilt angles using E-beam lithography

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Abstract

A liquid crystal (LC) lens with precisely controlled pretil angles using E-beam lithography is introduced in this paper. Pretilt angles are determined by different proportions of vertical and horizontal alignment domains. Our LC lens uses uniform electrodes and cell gap, which simplies the fabrication process. More importantly, it needs low voltage to drive. The focal length can vary from several centimeters to around 1 meter within 10 volts. Lenses with both positive and negtive optical power can be fabricated using our method.

Author Keywords

Liquid crystal lens; E-beam lithography; Variable pretilt angles; Low power consumption.

1. Introduction

Liquid crystal (LC) lenses, due to the tunable focal length characteristic, are becoming more and more promising in many optical and photonic systems, which require variable optical power and optical zoom applications. Compactness in size and easy tenability have made such lenses preferable for portable devices. The main principle of LC lenses is to create a lens-like phase difference by controlling the distribution of orientations of LC directors. In order to achieve this, it normally requires a non-uniform LC layer by using inhomogeneous cell gap [1], a spatially non-uniform electrical field applied to a uniform LC layer [2-7] or an alignment layer with spatially varying pretilt angles. For the first kind, the thickness of the lens is large which causes slow response time. Moreover, it's difficult for alignment inside the lens-like substrate and also it will have disclination line as the LC molecules rotate under a certain voltage. To generate spatially non-uniform electrical field, a hole-patterned electrode is used [2], which requires a thick intermediate substrate to create a desired lens-like electrical profile which leads to a high driving voltage. There is an improvement using high resistive film, which is called modal LC lens [3-5]. However, the fabrication process and electrical control are both rather complicated. Besides, the quality of the lens will be sacrificed due to the light absorption of the resistive film. Another method is to utilize a multi-ring electrodes to get a spatially varying electrical field [6, 7], but the fabrication of the patterned electrodes and the driving scheme are very complex. Also there will be light diffraction and scattering problems. Recently, LC lenses fabricated by stacked layers or photoalignment technology have been introduced [8, 9]. However, such approaches impose limitations of controlling the alignment quality and fabrication procedure. Another method using sandwiched structure called two-mode switching approach is also introduced [10]. But it needs very high voltages to drive. Here we introduce a method using E-beam lithography. By changing the proportion of vertical alignment and horizontal alignment domains, spatially varying pretilt angles can be obtained. Our method only needs uniform electrodes (ITO layer) and homogeneous cell gap, which simplifies the fabrication process and electrical control scheme. In addition, the focal length can change in a wide range within low voltages. Both convex and concave lenses can be made by utilizing our method.

2. Methodology

As one can see from Fig. 1, ITO glasses are used as substrates. Firstly, a layer of polyimide (PI) material is coated on top of the substrate, which has vertical alignment (VA) at the beginning. Then a layer of photoresist (PR) is coated on top of it. Afterwards, PR is treated with standard E-beam lithography process following a certain pattern and then rinsed later. At this point, a patterned PR is achieved, as shown in Fig. 2. Later on, after the RIE dry etching process, the VA PI without the protection of the PR will become planar alignment (PA). While on the other side, due to the protection of the PR, VA PI under the PR will not be affected by the dry etching process and alignment will remain vertical. Lastly, all the left PR will be rinsed off and we will get different proportions of vertical and horizontal alignment within periodic domain size.

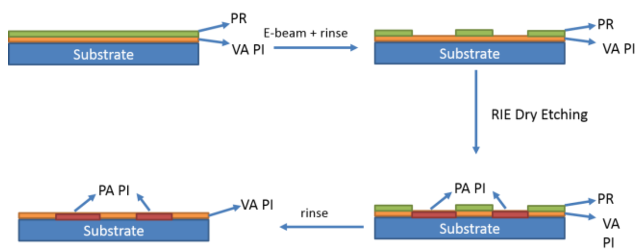

Figure 1. Fabrication process of variable pretilt angles of LC lens

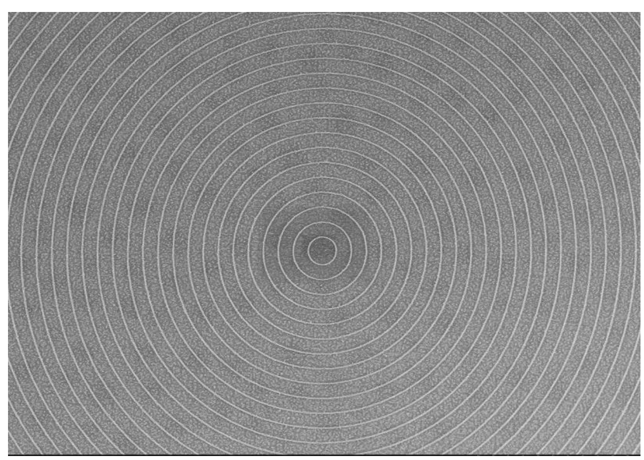

Figure 2. Partial image of the PR pattern before dry etching

The domain size is 1 μm and within it, the width of the vertical and horizontal alignment will change accordingly. As one can see from Ref. 11, if the width of the inhomogeneous alignment width is much larger than the extrapolation length $l = K_{11} / W$, the average pretilt angle will have a linear relation with the domain ratio $p = \lambda_H / (\lambda_H + \lambda_V)$:

$$\theta_{APA} = p\theta_H + (1-p)\theta_V \quad (1)$$

K_{11} is the LC splay distortion elastic constant. W is the polar anchoring energy strength of the alignment layer. λ_H and λ_V are the width of horizontal alignment and vertical alignment. θ_H and θ_V are the pretilt angle of horizontal alignment and vertical alignment areas. θ_{APA} is the average pretilt angle of the area with the combination of VA and PA. Due to different proportions of VA and PA domain sizes, we can get variable pretilt angle so that the lens-like profile can be achieved.

3. Results

After preparing the substrate mentioned above, it's assembled with another vertical PI substrate to form a LC cell, which is filled with E7. In order to characterize the tunable LC lens we made, the phase profile in the direction that is parallel to the azimuthal direction has been measured. Polarization microscopy and a red filter with transmission peak at 632 nm were used. Then the fabricated LC lens was placed between crossed polarizers with azimuthal direction at 45º in the plane. The preliminary result is shown in Fig. 3. This lens profile has proven that our design concept is successful and it's also the first time to prove that variable pretilt angles can be achieved by inhomogeneous surfaces mentioned in Ref. 11.

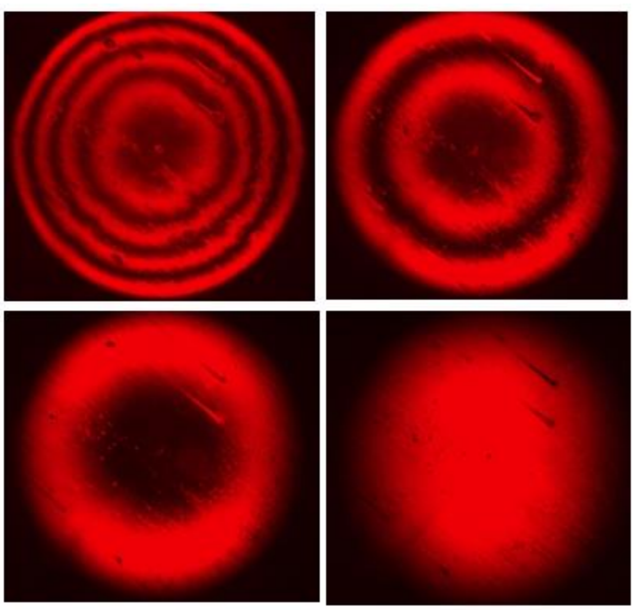

Figure 3. Lens profile under voltage of 0V, 1.1V, 2V, 4V

An AC signal with 1 KHz frequency was applied to tune the LC lens. The microscopic photographs under different voltages are shown in Fig. 3. The transmittance at different points of the lens profile can be calculated using Eq. (2),

$$T = \sin^2\left(\frac{\pi d \Delta n}{\lambda}\right) \quad (2)$$

where d is the cell gap, Δn is the average birefringence and λ is the light wavelength. The transmittance values of the profile from the center to the border were extracted from the photos, which were then used for the calculation of the retardation parameter. The retardation parameter is defined as $\frac{\pi d \Delta n}{\lambda}$, of which the profiles for the fabricated LC lens at different voltages are shown in Fig. 4. All the retardation parameter profiles show very fitting parabolic character, which is the best case for lens design.

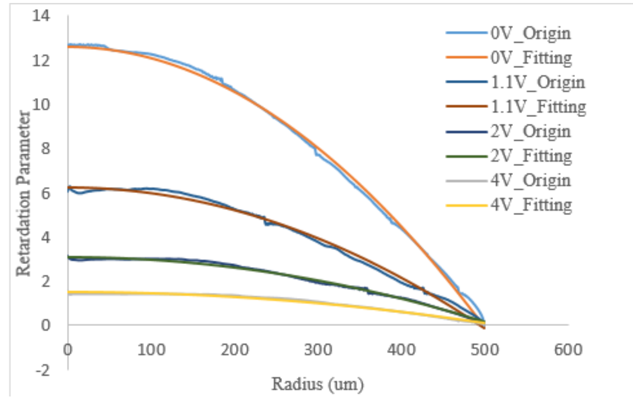

Figure 4. Retardation parameter profiles under different voltages. (*Origin* line represents the original experimental data, while the *Fitting* line represents the parabolic fitting with the former.)

The focal distance of the LC lens can be calculated by Eq. (3), as shown below:

$$f = \frac{r^2}{2d\Delta n_e} \quad (3)$$

where r is the radius of the LC lens, d is the cell gap and Δn_e is the effective refractive index difference between the center and border of the LC lens. The higher the applied voltage is, the larger the focal distance of the LC lens becomes. The focal lengths under the voltages shown in figure 4 are 5cm, 10cm, 21cm and 44cm respectively. A large scale from 5 cm to around 1 m can be realized within 10 volts, which means the LC lens can be tuned in a broad range by a relatively low voltage, resulting in low power consumption.

4. Conclusion

The LC lens introduced in this paper only needs uniform electrodes and cell gap, which simplifies the fabrication procedure to a great extent and avoids light scattering and diffraction. In addition, the varying pretilt angles can be controlled precisely, which makes the result repeatable and stable. More importantly, our designed lens needs low voltage driving, leading to low power consumption. Both lenses with positive and negative optical power can be realized using this method. By changing LC material, aperture size of the lens and cell gap, we can design lenses with different characteristics. Nano-imprint technology is already under trial run to achieve mass production.

5. Acknowledgement

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6. References

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