

Achieving high focusing power for a large-aperture liquid crystal lens with novel hole-and-ring electrodes

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Abstract: Aiming to equip commercial camera modules, such as the optical imaging systems with a CMOS sensor module in 3 Mega pixels, an ultra thin liquid crystal lens with designed hole-and-ring electrodes is proposed in this study to achieve high focusing power. The LC lens with proposed electrodes improves the central intensity of electric field which leads to better focusing quality. The overall thickness of the LC lens can be as thin as 1.2 mm and the shortest focal length of the 4 mm-aperture lens occurs at 20 cm under an applied voltage of 30 V at 1 KHz. The inner ring electrode requires only 40% of applied voltage of the external hole electrode. The applied voltages for this internal ring and external hole electrodes can simply be realized by a pre-designed parallel resistance pair and a single voltage source. Experiments are conducted for validation and it shows that the designed LC lens owns good image clearness and contrast at the focal plane. The proposed design reduces the thickness of LC lens and is capable of achieving relative higher focusing power than past studies with lower applied voltage.

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1. Introduction

In the applications of optical lens for commercial imaging systems or communication devices such as cell phones, a desirable feature is to dynamically control the optical properties of the lens; in this way, the functions of focusing and/or zooming can be realized. In recent years, the on-line tunability in the focal length of a traditional variable focus lens, the auto-focusing capability, is achieved by the mechanical motions of the individual lenses in compact camera module (CCM) in mobile devices. The lens is actuated by voice coil motor (VCM), stepping motor or piezo actuator. However, the control mechanism for lens motion is generally complicated, and the movement of the lenses usually implies more space. To remedy these problems, several past studies of tunable focal length LC lens are proposed [1-5] and aimed to use in the auto-focusing CCM of mobile phones.

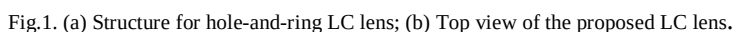
The focal length of LC lens is tuned by adjusting the applied electric field to the LC cell and redistributing the LCs inside the lens. The LC lens is first proposed by Sato [1] with the focal length switched between 150 and 230mm. Several studies are presented in designing the stacked planar electrode geometry [5] or forming a certain electric field [6-9] by spherical electrode, to lead LC lens acting as a gradient index (GRIN) lens. Previous studies proposed the high resistance electrode [11], the hexagonal-hole-patterned electrode [12], double LC layers [13] and four sub-electrode [14]. Different LC material such as ferroelectric material was also proposed for improving the electro-optics properties [15]. Several studies on different LC material instead of nematic type are proposed by using polymer-separated composite film (PSCOF) as a Fresnel zone plate [16], polymer stabilized liquid crystal (PSLC) [17] and polymer-dispersed liquid crystal (PDLC) [3].

Past studies also show the LC microlens is applicable to a generalized auto-focusing system. A non-uniform electrode field micro-LC lens was proposed with small aperture size around 200 μ m [7]. A stacked LC microlens with 200 μ m of aperture with applied voltage about 3-5 V was also reported for improving the aberration properties [18]. However, conventional LC lens with large aperture size [19] usually required high applied voltage, about 50 V, to form the electric field but the focal length is too far, 760 mm, to be applied in the camera applications.

In the conventional hole type electrode LC lens, a trade-off exists between the high focusing power and low driving voltage. This trade-off problem becomes more serious as a large-aperture lens (> 4 mm) is considered, which is however required to be implemented in commercial CCMs for mobile devices. Since the distribution of electric field is determined once the geometrical dimensions, such as cell gap and hole diameter, are designed; the only approach to increase the focusing power is to increase the applied voltage. According to the previous researches [6, 20, 21], large aperture (> 4 mm) hole type LC lenses are always have

This study is then proposed a hole-and-ring type electrode to improve the distribution of electric field, which only requires lower applied voltage than the conventional one and also meet the required optical performance, i.e. the minimum focal length. The applied voltage is reduced to 30 V with the shortest focal length around 200 mm. The thickness of lens is less than 1.2 mm which implies the potential to be equipped in the mobile camera module. This paper is organized as first to describe lens design. A LC lens with proposed electrode is next fabricated and the detailed structure is given. A series of experiments are then conducted to verify the focusing capability and imaging behavior under operations. Finally, the concluding remarks are presented.

Conventional hole type LC lens has hollow ITO electrode at the top of upper glasses [19]. This structure forms the electric field in a normal distribution which is the field with the weakest intensity at the central of electrode hole. The liquid crystal molecules are orientated by the electric field cross the LC cell, and are aligned on the rubbed surfaces, i.e. the lower side of upper glass and top side of lower glass, with their axes parallel to the rubbing directions. In this study, the rubbing directions of two surfaces are identical and this arrangement is widely known as parallel alignment. Due to the optical property, the birefringence index, of liquid crystal, the distribution of molecule could be form as a gradient index under the electric field. This gradient index (GRIN) LC lens is thus owns the focusing capability since the optical path length (OPL) through LC layer is the shortest on center optical axis and the largest on the edge axis of lens.



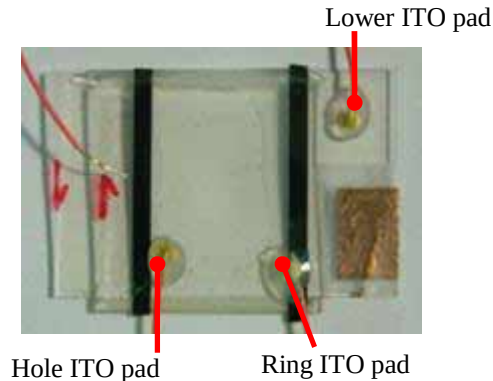


Fig. 2. Photography of proposed novel hole-and-ring LC lens.

To have high focusing capability, the edge of the hollow electrode hole requires steep slope of field intensity variation, which leads high gradient of refraction of index, for providing the sufficient focusing power. In large aperture LC lens, however, is difficult to naturally form a sharp slope except applying high voltage. This arise the trade-off when the LC lens is aimed to be equipped in the mobile device and operated with battery cell. Therefore, this study proposed a hole-and-ring type electrode for LC lens to improve the gradient of refraction of index. The proposed LC lens, as shown in Figure 1, consists of hole-and-ring type ITO electrode on the top of upper glass, rubbed polyimide (PI) films in the inner of upper and lower glasses, liquid crystal cell and ITO electrode on the bottom of lower electrode.

Conventional hole type LC lens forms the electric field in a normal distribution which is the field with the weakest intensity at the central of electrode hole. The proposed design is placed a ring electrode inside of a hollow electrode hole which is 4 mm in diameter (D_h). The ring electrode is 2 mm in diameter (D_r) with 20 μm width. The ring electrode provides the sufficient intensity of electric field in the central area. The applied voltage to the ring electrode, V_r , is 40% of the voltage applied to the hole electrode, V_h , and could be realized by a pair of external parallel resistors with ratio of 1:0.4 which serial connecting with a single voltage source. It is preceded that the intensity of electric field will be enhanced at the central hole which means that the focusing power will be higher due to the central LC are affected by higher electric field.

3. Fabrication

The designed hole-and-ring LC lens is fabricated by common processes. Two 0.55 mm glasses are coated with 450 $\text{\AA}$ ITO and the transmittance of the ITO glass is 94%. One of ITO glasses is etched in the desired hole-and-ring patterned and the polyimide (PI), AL-1426B, from Daily-Polymer Corp. is coated on these two glasses. Both PI layers are rubbed for forming the micro-grooved surface and this will lead the LC pretilt in 2° . The two glasses are then stacked with 50 μm Mylar spacer in between. The LC, E7 from Merck, is filled in the space between two glasses. E7 owns the ordinary refractive index, n_o , of 1.5183; and extraordinary refractive index, n_e , 1.7371. The elastic constant K_{11} , K_{22} and K_{33} are 1.1, 5.9 and 17.1 pN, respectively; and the dielectric constants, $\epsilon_{\parallel}$ and $\epsilon_{\perp}$, are 19.28 and 5.21 in parallel and perpendicular directions respectively. The rational viscosity is 233 mPa.

Figure 2 shows the fabricated hole-and-ring LC lens with three electrode pads, one for lower ITO as the ground, one for upper hole electrode and the rest one for the ring electrode.

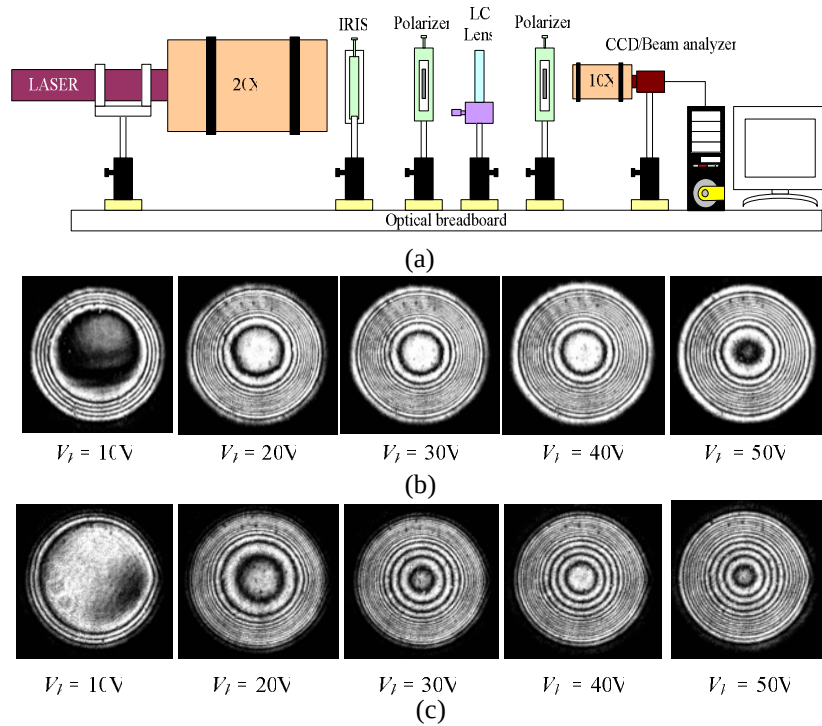


Fig. 3. (a) Experiment apparatus; Interference ring patterns of (b) conventional hole type LC lens and (c) Novel hole-and-ring type LC lens.

Note that the two ITO patterned glasses are stacked and the overall thickness of the proposed hole-and-ring type LC lens is only about 1.2 mm, which is extremely thin for being equipped as an auto-focusing module in the commercial mobile camera device.

4. Experiment

Figure 3 (a) shows the experiment setup for observing the focusing performance of LC lens. A 632nm He-Ne laser is used as light source with an iris to concentrate the spot point. Two crossed polarizer are placed with a LC lens which owns $\pi/4$ angle respect to the rubbing direction and the polarizer. A high resolution CCD is utilized for capturing the interference ring patterns right after the polarizer. Figure 3 (b) and (c) shows the interference ring patterns of conventional hole type and hole-and-ring type respectively. In this study, the conventional hole type is simply achieved by using the proposed hole-and-ring design without applying voltage to the ring electrode. It is obviously that the interference ring patterns of hole-and-ring electrode are more concentrated at the central part than the hole type one, especially with increasing voltage. This phenomenon also implies that the superiority of proposed design in focusing capability.

The interference ring pattern represents the phase retardation of the lens [22] which arising from a combined path length and initial phase angle difference. Figure 4(a) denotes the phase retardation, which is always an integer multiple of 2π , of hole-and-ring type electrode LC lens. Note that the steepest gradient occurs when 30 V at 1 KHz is applied and represents the highest focusing power under this condition. Based on the ring number of the pattern, N , one could obtain the focal length [4]

$$f = r^2 / 2\lambda N, \quad (1)$$

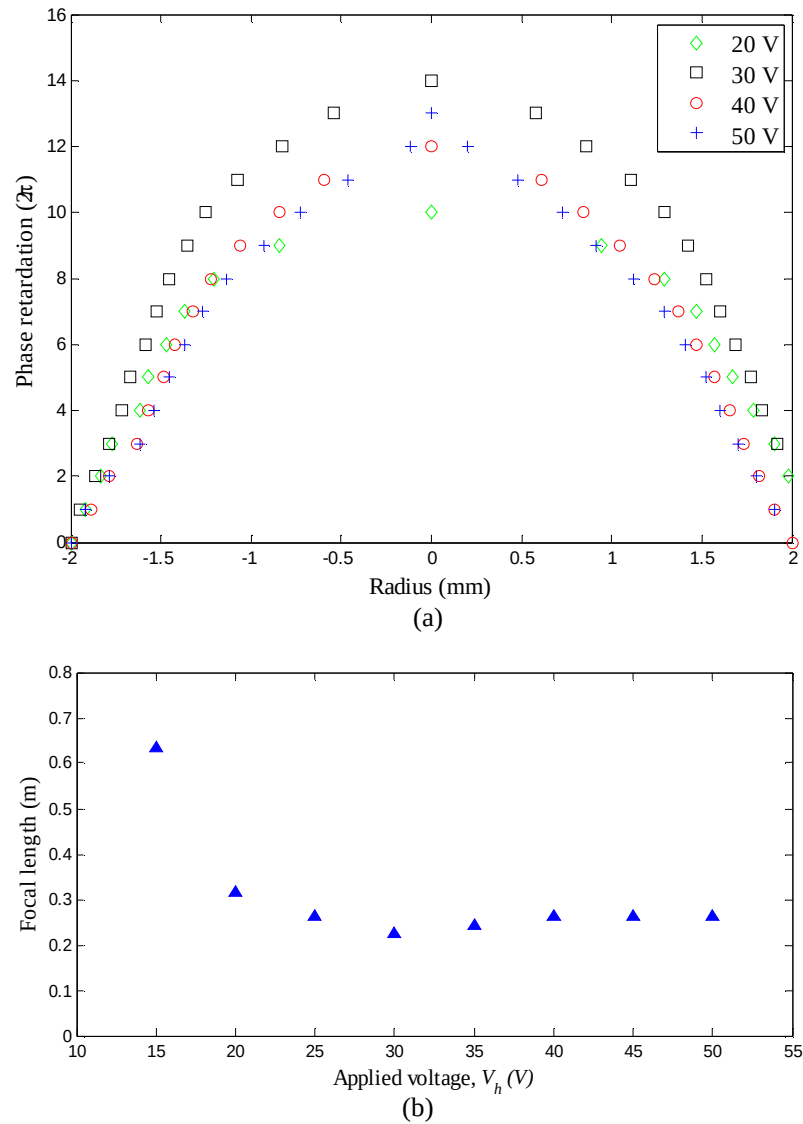


Fig. 4. (a) Phase retardation under different applied voltages; (b) Focal length versus applied voltage.

where r is the radius of hole electrode and λ denotes the wavelength of incident laser. Figure 4(b), therefore, shows the focal lengths of the hole-and-ring type LC lens under different applied voltage, V_h . Note that the shortest focal length occurs under applied voltage 30V. To observe the power distribution after the light passing through the proposed lens, a beam analyzer, Ophir FX-50, is placed right after the second polarizer instead of CCD camera. Setting the observing plane on the shortest focal length, the location of maximum focusing power, the power intensity distribution is then could be analyzed. The intensity distribution of proposed LC lens with 30 V at 1 KHz applied voltage at the external hole and 12 V at the internal ring is shown in Fig. 5. It is obviously that the distribution of the conventional hole type owns the lower peak intensity and poor sideband while the proposed hole-and-ring type is relatively with better concentration of power intensity. This also reflects the same

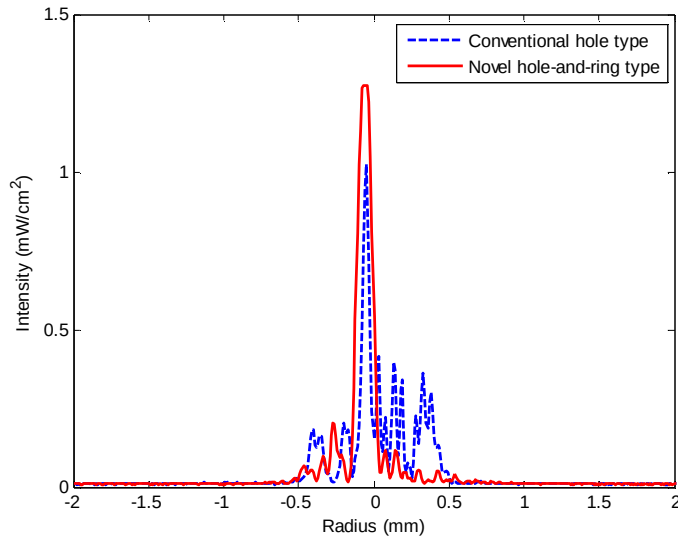


Fig. 5. Power intensity on the focal plane.

perception shown in Fig. 3 that the interference pattern of hole-and-ring type owns centralized ring pattern.

Figure 6 shows the experiment apparatus for testing the image quality. A standard USAF chart is placed 20 cm in front of the lens, which is considered as the focal plane of the lens, for testing image quality. A fixture for holding the proposed LC lens is placed in front of the 3M CMOS image sensor from Micron Image Inc. (now is Aptina Image Inc.). Figure 7 shows the photos which are taken by the proposed LC lens. It is obviously shown that the image is clear when the LC lens is operated at 30V applied voltage. The numbers and lines on the USAF chart present the high contrast, which imply the focusing capability and the superiority of the lens quality, under the operation of the highest focusing power.

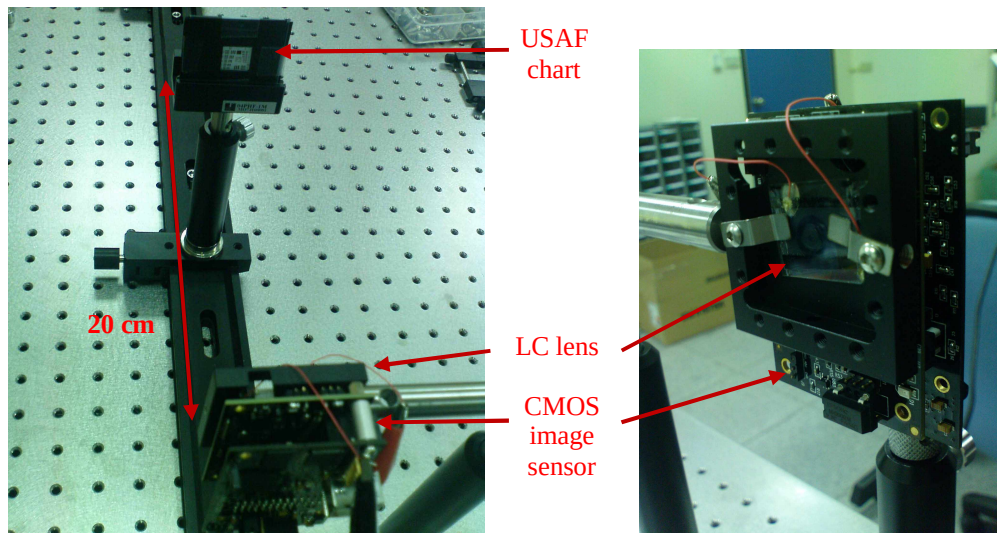


Fig. 6. Experiment apparatus for testing image quality.

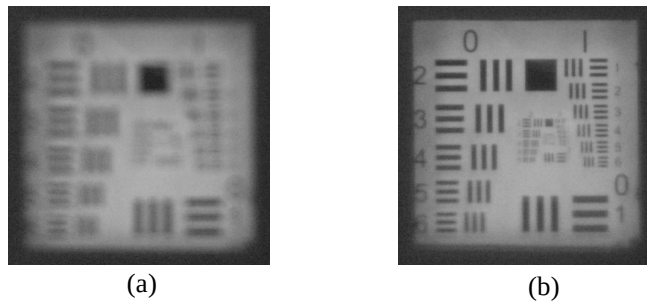


Fig. 7. Images taken by a CMOS camera module with proposed LC lens under the applied voltage (a) $V_h = 0$ V; (b) $V_h = 30$ V.

5. Conclusion

A novel hole-and-ring electrode of LC lens with large aperture (>4 mm) is designed for improving the focusing quality with low applied voltages. The LC lens is fabricated using a standard processes with two 0.5 mm ITO glasses spaced by 50 μm which makes the overall thickness is as thin as 1.2 mm. The applied voltages for the internal ring and external hole electrodes can simply be realized by a pre-designed parallel resistance pair and a single voltage source. Design and experiment conform that the internal ring electrode requires only 40% applied voltage of the external hole electrode and could simply be achieved by tuning the resistance ratio between parallel resistors. Based on the interference pattern of LC lens, it is obviously seen that the proposed electrode design provides better optical power concentration than the conventional hole type electrode under arbitrary applied voltage. The shortest focal length of 4 mm-aperture LC lens occurs at 20cm with 30V applied voltage. The proposed design overcomes the previous barrier that high voltage or thick spherical lens are needed for large-aperture lens to provide sufficiently short focal length. This significant improvement makes possible the proposed LC lens in the commercial CCMs in camera phones.

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