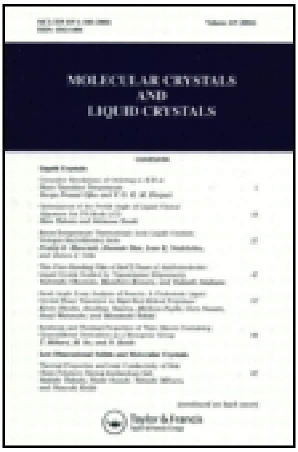

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

Liquid Crystal Lens with Double Circularly Hole-Patterned Electrodes

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Version of record first published: 14 Jun 2011

Mol. Cryst. Liq. Cryst., Vol. 542: pp. 176/[698]–181/[703], 2011

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421406.2011.570563

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Liquid crystal lens with a novel electrode structure of double circularly hole-patterned electrodes is developed for improving a lens power and effective diameter with the optimum lens property. The variable lens power of the liquid crystal lens with double circularly hole-patterned electrodes is about two times as large as that of the previous liquid crystal lens with a single circularly hole-patterned electrode and the liquid crystal lens preserves its optical quality entire variable range.

Keywords Focal length; interference fringe; liquid crystal lens; variable lens power

1. Introduction

Liquid crystal (LC) materials have a birefringent property and are widely used in display devices and tunable optical components. Millimeter and/or micro size LC devices with functions of a variable focusing [1–5], beam steering [6,7] and anamorphic lens property [8] have been developed. The LC device such as an LC lens with a radially-varying refractive gradient-index distribution can be realized by the LC molecular reorientation caused by axially symmetrical electric field in the circularly hole-patterned electrode of the LC lens. The relative phase difference ($d\Delta n$; d: a thickness of an LC layer, Δn: an effective birefringence of an LC material) from the center to the edge of the hole-patterned electrode can be changed and then the wave-front of the light through the hole aperture of the LC lens becomes a quadric function property. The LC lens has a very wide range of the focus length from the negative to positive lens properties by controlling the applied voltages to both the flat electrode and circularly hole-patterned electrode. When the circularly hole-patterned electrode is divided into several parts, the focal point can easily be controlled in three-dimensional positions by arranging the applied voltage to the each electrode of the LC lens. We have already reported an optical tweezers by using the LC lens with the anamorphic lens property in addition to both the variable focusing and beam deflection properties for controlling the positions and rotations of the trapped micro-sized spherical and slender particles [9]. The lens power and effective

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diameter of the LC lens depend on the structural lens parameters such as the aperture size of the hole-patterned electrode, material constants of the glass substrate and LC material, the thicknesses of glass substrates and LC layer. Both the effective diameter for using the lens property with the quadric function and the lens power has limitations by the structural lens parameters.

Therefore, we propose a novel LC lens structure with double circularly hole-patterned electrodes for improving the lens property such as the lens power and effective diameter of the lens area with preserving its optical quality by adjusting the applied voltages to the double circularly hole-patterned electrodes and external flat electrode.

2. Structure of a Novel LC Lens

The schematic diagrams of the side and top views of the LC lens with double hole-patterned electrodes are illustrated in Figures 1a and 1b. The LC lens consists of a top glass substrate with an transparent electrode (1.1 mm-thickness), thin glass substrate (100 μm-thickness) for an insulation layer, glass substrate with 1st and 2nd circularly-hole patterned electrode (thickness: d_g), thin glass substrate (100 μm-thickness), LC layer and glass substrate with the transparent electrode (1.1 mm-thickness). The hole-patterned electrodes are fabricated by a photolithography technique and the diameters of the 1st and 2nd apertures are set to be $\phi_1 =$ 3.8 mm and $\phi_2 =$ 3.8 mm $\sim$ 5.8 mm, respectively. The sine wave voltages ($f=10$ kHz); V_1, V_2 and V_3 are applied to the external flat electrode, the 1st and 2nd circularly-hole-patterned electrodes by using a function generator and an amplifier. The surfaces of the polyimide parallel alignment film coated on the glass substrates were rubbed by the rubbing machine and then two substrates were overlapped at anti-parallel rubbing directions as shown in Figure 1. The cell gap is controlled by using glass ball spacers at the diameter of 110 μm. The nematic LC material of

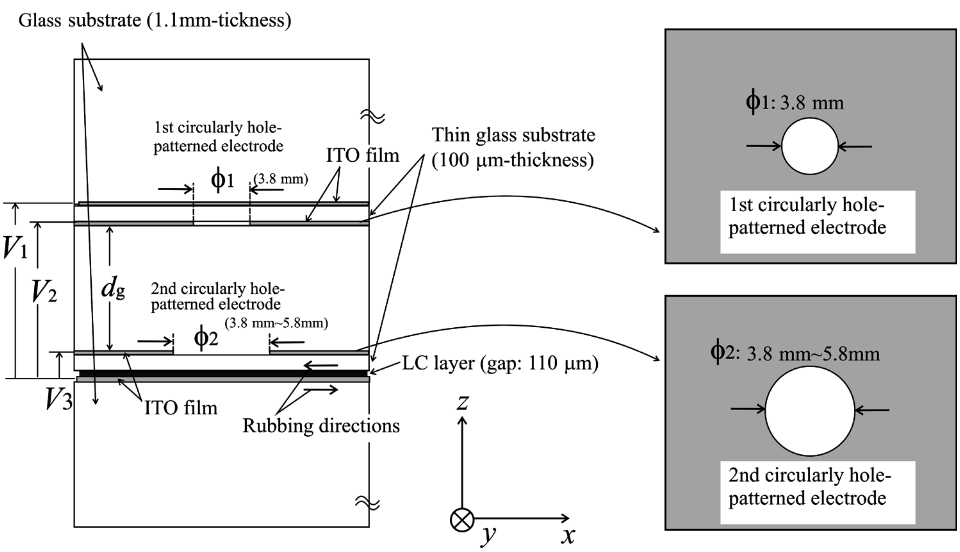

Figure 1. The cross-section of the LC lens with double hole-patterned electrodes.

MLC6080 (Merck Co.) is injected into the empty LC cell under the room temperature. The physical properties of MLC6080 in this study are $k_{11} = 14.4$ pN, $k_{22} = 7.1$ pN and $k_{33} = 7.1$ pN; $\varepsilon_{\parallel} = 11.1$, $\varepsilon_{\perp} = 3.9$; $n_e = 1.710$ and $n_o = 1.507$. The pretilt angle of the LC molecule at the alignment surface on the substrate is 2 deg.

3. Results and Discussion

Figures 2a–2j show the interference fringe pattern images of the LC lens with double circularly hole-patterned electrodes and external transparent electrode under crossed polarizers when the applied voltage V_1 to the external electrode is a constant value $13V_{th}$. The threshold applied voltage V_{th} was estimated to be about 1.2 V by measuring the capacitance-voltage characteristics of a homogeneous LC cell at the thickness of 10 μm filled in the same LC material. The thickness of the middle glass substrate is $d_g = 1.1$ mm. When the applied voltages V_2 and V_3 to the 1st and 2nd circularly-hole-patterned electrodes are controlled, the circular fringe at the inside of the hole-patterned aperture (3.8 mm) increases from Figures 2a–2j. The circular interference

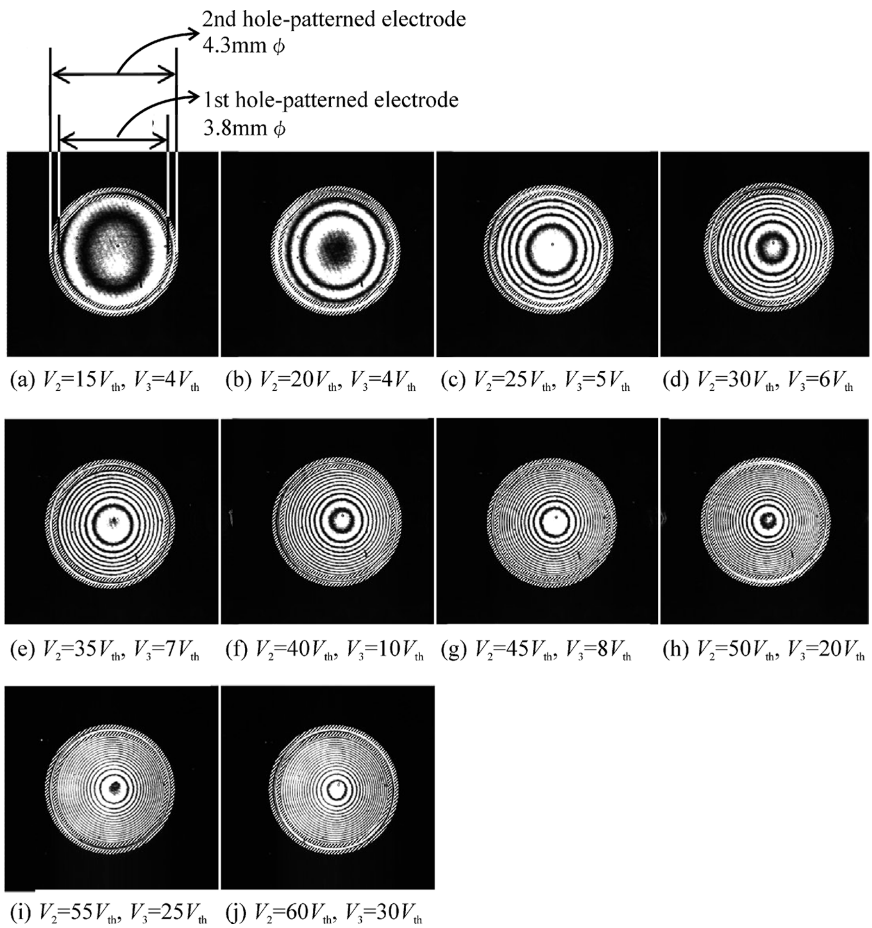

Figure 2. Circular interference fringe pattern images of the LC lens with double circularly hole-patterned electrodes.

fringe at the around the edge of the 2nd hole-patterned electrode (4.3 mm) increases by applying the voltage V_2 to the 1st circularly hole-patterned electrode at 3.8 mm in the diameter, since the LC molecules at this region begin to reorient along the nonuniform electric field. Since the electric potential at the external flat electrode is relatively smaller than that at the center of the 1st and 2nd hole-patterned electrodes, the electric potential becomes in quadric function from the center of the hole-patterned electrodes to the edge of the hole-patterned electrode. The radial distribution properties of the refractive index are obtained in the aperture. The behaviours of the reverse tilt and/or twist angle disclination lines at the boundary between the two different domains are not induced by the nonuniform electric field less than the applied voltage $V_3 = 30\,V_{th}$ to the 2nd circularly hole-patterned electrode.

Figure 3 shows the cross-sectional distribution of the relative phase difference corresponding to y-axis by estimating the circular interference fringes as shown in Figure 2. The parabolic relative phase difference can be obtained by controlling the applied voltages of V_2 and V_3. At the edge of the 1st circularly hole-patterned aperture, the phase differences of the LC lens with the double circularly hole-patterned electrodes seems to be fitting quadric function. Since the voltage to the 2nd circularly hole-patterned electrode of the LC lens is applied, the LC molecules at the near edge of the 1st circularly hole-patterned electrode can be re-orientated by controlling the nonuniform electric field. Therefore, the phase difference distribution at the diameter of 3.8 mm becomes the quadric function property within $\lambda/10$ and this LC lens has a good optical quality without the spherical aberration.

The lens power which is the reciprocal of the focal length can be estimated by calculating quadric curve fitting from the measured phase differences as shown in Figure 3. Figures 4a and 4b show the relationships between the effective diameter and lens power of the LC lens with a single circularly hole-patterned electrode and double circularly hole-patterned electrodes. The conventional LC lens with

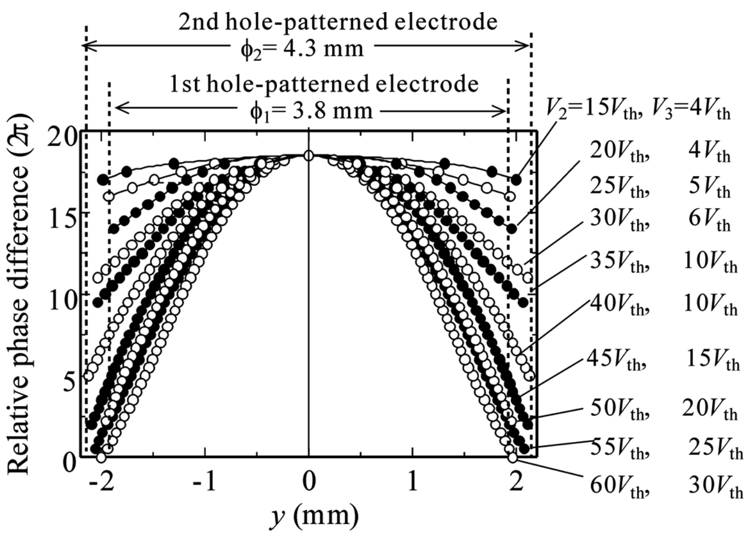

Figure 3. Relative phase difference distribution of the LC lens with a single circularly hole-patterned electrode at $y = 0$ mm.

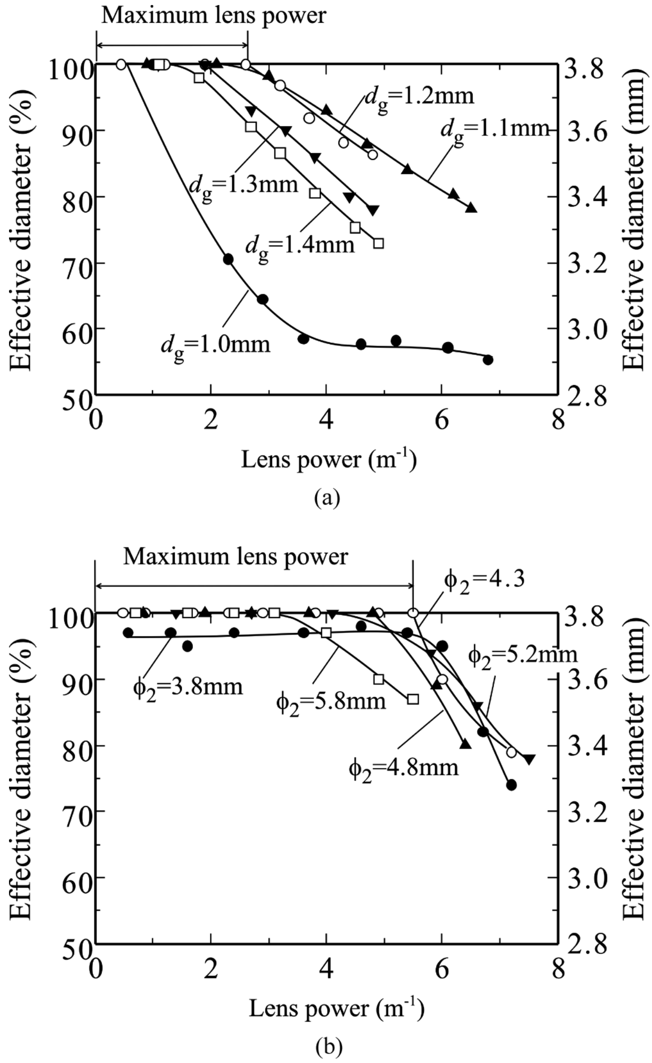

Figure 4. Relationship between the effective diameter and lens power of LC lens. (a) LC lens with a single circularly hole-patterned electrode; (b) LC lens with double circularly hole-patterned electrodes.

the single circularly hole-patterned was fabricated without the 2nd circularly hole-patterned electrode on the middle glass substrate as shown in Figure 1. The diameter of the hole patterned electrode is 3.8 mm and the thickness d_g of the middle glass substrate is controlled from 1.0 mm to 1.4 mm. In Figure 4a, the effective diameter for using lens property can be obtained under $\lambda/10$ of deviation value between the measured phase difference and quadric curve fitting value from the measured phase difference values. Both the effective diameter and lens power strongly depend on the thickness of the middle glass layer. The effective diameter has a constant value (100%) and decreases as increasing the lens power. When the thickness of the insulation layer is 1.2 mm, the maximum lens power can be experimentally estimated to be about $2.7\,m^{-1}$ with a 100% of the large effective diameter. On the other hand, when the diameter ϕ_1 of the 1st circularly hole-patterned electrode in the LC lens with the double circularly hole-patterned electrodes is fixed and the diameter ϕ_2 of the 2nd circularly hole-patterned electrode varies from 3.8 mm to 5.8 mm, both the effective diameter and lens power depend on the diameter of the 2nd-hole-patterned electrode as shown in Figure 4b. When the diameter of the 2nd hole-pattered electrode is $\phi_2 = 4.3$ mm, the lens power can be controlled from $0\,m^{-1}$ to about $5.6\,m^{-1}$ at the diameter of the 1st-hole-patterned-aperture 3.8 mm and then the effective diameter decreases as increasing the lens power. The maximum lens power at the diameter of 3.8 mm can be estimated to be $5.6\,m^{-1}$. Therefore the lens power of the LC lens with double circularly hole-patterned electrodes at the diameter of 3.8 mm can be improved as compared to that of the LC lens with the single circularly hole-patterned electrode.

4. Conclusion

We propose an LC lens with double circularly hole-patterned electrodes for improving the lens power and effective diameter of the LC lens with preserving its optical quality. The lens power and effective diameter for using the lens property can be improved by using double circularly hole-patterned electrodes. The lens power of the novel LC lens can be estimated to be about 2.1 times as large as that of the conventional LC lens with the single circularly hole-patterned electrode.

Acknowledgment

This work was partially supported by Grant-in-Aid for Scientific Research from CASIO Science Promotion Foundation and Grant-in-Aid for Scientific Research Young Scientists (B) from the Ministry of Education, Science, Sports and Culture, 2009. The authors would like to acknowledge the cooperation of Prof. Susumu Sato and Dr. Mao Ye (Akita Research Institute of Advanced Technology).

References

[1] Sato, S. (1979). *Jpn. J. Appl. Phys.*, *18*, 1679.
[2] Nose, T., & Sato, S. (1989). *Liq. Cryst.*, *5*, 1425.
[3] Masuda, S., Fujioka, S., Honma, M., Nose, T., & Sato, S. (1996). *Jpn. J. Appl. Phys.*, *35*, 4668.
[4] Ye, M., & Sato, S. (2007). *Jpn. J. Appl. Phys.*, *40*, 6012.
[5] Ye, M., Wang, M., Kawamura, M., & Sato, S. (2007). *Jpn. J. Appl. Phys.*, *46*, 6776.
[6] He, Z., Nose, T., & Sato, S. (1998). *Opt. Eng.*, *37*, 2885.
[7] Ye, M., Wang, M., & Sato, S. (2006). *Jpn. J. Appl. Phys.*, *45*, 6320.
[8] Kawamura, M., Ye, M., & Sato, S. (2008). *Jpn. J. Appl. Phys.*, *47*, 6404.
[9] Kawamura, M., Onishi, J., & Sato, S. (2009). *Inter. J. Optomechatronics*, *3*, 264.