A liquid-crystal microlens with dual-layers arrayed pattern electrode for the effective modulation of incident light beams

Mao Ye[1,2], *Han* Chen[1,2], *Zhe* Wang[1,2], *Kewei* Liu[1,2], and *Xinyu* Zhang[1,2*]

[1]National key Lab of Multispectral Information Intelligent Processing Technology, Huazhong University of Science and Technology, 430074 Wuhan, Hubei, China

[2]School of Artificial Intelligence and Automation, Huazhong University of Science and Technology, 430074 Wuhan, Hubei, China

Abstract. In this paper, an electrically controlled liquid crystal (LC) microlens array based on dual-layer arrayed planar pattern electrode is reported for effective light wave modulation. By adjusting the voltages applied to two planar arrayed electrodes within one substrate of the LC microlens, an adjustable focused circular ring or point-shaped light spot can be formed. Dual-layers arrayed pattern electrode with a minimum interval spacing of approximately ~10μm and a maximum of 130μm are achieved on one substrate by using standard microelectronic lithography, etching, coating film, and other processes. Experimental results are presented and discussed to illustrate outstanding performance of electrically focusing and modulation capability of the proposed LC device. This approach will serve as inspiration for the continued development and design of LC optical elements, enabling applications such as light field imaging, wavefront detection/correction, and the advancement of imaging augmented systems.

1 Introduction

Liquid-crystal (LC) microlenses with tuneable focal lengths under applied electric fields fascinated scientists and optical engineers due to their advantages of excellent stability, miniaturization [1]. Single-layer planar electrode LC microlens have been widely applied in fields such as lightfield imaging, polarization imaging and wavefront imaging, presenting favorable imaging results [2–4]. Although single-layer planar electrode LC microlens exhibits commendable performance in terms of electrically adjustable focal length, its imaging field of view is inherently constrained by the electrode aperture and remains unalterable. M. Chen et al. have proposed the realization of multi-aperture microlens imaging using single-layer planar electrode to acquire images with an extended depth of field [5]. However, despite the two different aperture sizes on the one planar electrode, they both occupy the same physical location, leading to decreased effective pixel spatial resolution on the photosensitive sensors.

This paper develops a dual-layers arrayed pattern electrode within one substrate for constructing LC microlens, providing another effective spatial electricfield modulation parameter compared with conditional LC microlens. Dual-layers arrayed pattern electrodes consist of two layers of ITO electrodes separated by a silicon dioxide insulating layer, ensuring optimal light transmission performance. By selecting the suitable voltages applied to two planar arrayed electrodes within LC microlens, an adjustable focused circular ring or point-shaped light spot can be formed, which means an effective modulation of incident light, leading to potential applications for lightfield imaging, wavefront detection or correction.

2 Fabrication method

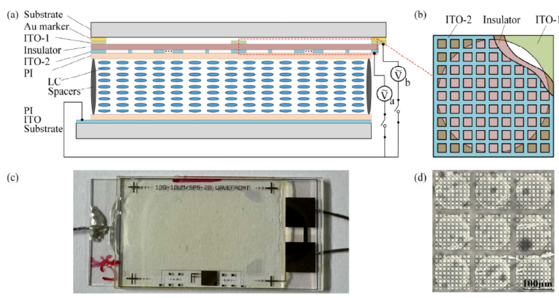

Fig. 1. An essential configuration of the proposed dual-layers arrayed pattern electrode LC microlens array. (a) A side view of the LC microlens architecture proposed by us. (b) The schematic depicting the relative positions of ITO-1 and ITO-2. (c) Fabricated LC microlens chip. (d) The microscopic view of the two ITO electrodes.

An essential configuration of the proposed dual-layers arrayed pattern electrode LC microlens array is depicted in Fig. 1. A side view of the LC microlens architecture is illustrated in Fig.1(a). As shown, two silica wafers, ~1100μm thick for upper substrate and ~500μm thick for the bottom, are closely coupled to form a ~20 μm depth microcavity towards an LC microlens chip with a required geometry.

For the upper substrate, the aurum (Au) with a thick of 50nm is firstly deposited on the inner surface of substrate

* Corresponding author: x_yzhang@hust.edu.cn

as a marker layer by utilizing the lift-off coating technique (photolithography followed by deposition). Next, the indium tin oxide (ITO) circular holes array with a 130µm diameter and 150µm center-to-center spacing distance cover the surface of the marker layer, denoted as ITO-1. An insulation layer of silicon dioxide with a thick of 5µm is further coating on the surface of ITO-1 to prevent conduction between two planar electrodes. Another planar electrode, referred to as ITO-2, is designed in a square array that matches the size and alignment of the circle-shaped ITO-1 layer and is deposited onto the insulation layer surface. Each large square consists of a 9×9 array of small square apertures, with a ~10µm side length and a ~15µm center-to-center distance. It is crucial to conduct an alignment procedure with respect to the cross markers in the Au marker layer to guarantee that the positioning of ITO-2 and ITO-1 adheres to the predetermined configuration. The schematic depicting the relative positions can be found in Fig.1(b). In addition, to reveal the electrode pad of ITO-1 for voltage input, hydrofluoric acid is employed to etch the medium insulating layer, thereby creating an opening. Simultaneously, to safeguard against any potential reaction between hydrofluoric acid and ITO, the surface of ITO-2 is shielded with a layer of photoresist for protection. Furthermore, a gold pad is strategically positioned on the bottom of the electrode pad of ITO-1 during the deposition of the Au marker layer. Both the ITO-1 and ITO-2 layers utilize the lift-off technique, enhancing precision while reducing fabrication steps.

For the bottom substrate, opt for ~500µm thickness transparent glass coated with 200nm ITO directly. Then two substrates are deposited by a polyimide (PI) layer of ~1.2 µm thickness over its ITO surface for shaping an anti-parallel groove for aligning LC molecules. So, an arrayed LC microlens can be formed by fully filling LC materials into the micro-cavity. Fig.1(c) depicts the ultimate LC microlens chip crafted following the aforementioned procedure, while Fig.1(d) showcases a microscopic view of the physical position of the two ITO structures on the upper substrate.

3 Results and discussion

To evaluate the performance of the proposed dual-layers arrayed pattern electrode LC microlens chip, the point spread function (PSF) under different conditions is measured according to a common measurement system, as the results shown in Fig. 2.

The main experimental set-ups are demonstrated in Fig. 2(a). As illustrated, a laser beam (655nm) initially undergoes a beam expander, subsequently passing through two linear polarizers to facilitate the adjustment of incident power and polarization orientation before entering the proposed LC microlens. The beam emitted from the LC microlens chip is magnified by a microscope objective lens of ×40 and 0.65 numerical aperture, finally reaching the laser beam profiler. Fig.2(b) demonstrates the PSF result of LC chip under zero voltage conditions, indicating that the LC chip can be considered as a homogeneous phase plate. A 10v voltage is individually

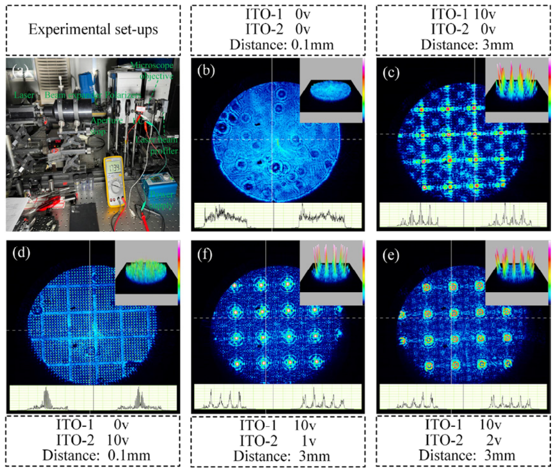

Fig. 2. The PSF results of the proposed LC microlens chip under different conditions is obtained according to a common measurement system. (a) The main experimental set-ups. (b) PSF result under zero voltage for the LC chip. (c) Focused PSF for circular electrode (ITO-1). (d) Focused PSF for square electrode (ITO-2). (e) PSF result under 10v voltage applied in ITO-1 and 1v on ITO-2. (e) Ring focused PSF result under 10v voltage applied in ITO-1 and 2v on ITO-2.

applied to the corresponding electrodes of the ITO-1 and ITO-2 to achieve a focused PSF with different focal length, depicted in Fig.2(c) and Fig.2(d) respectively. To demonstrate the effective incident light beam modulation capability of the proposed LC microlens chip, Fig.2(e) and Fig.2(f) illustrate that applying 10v to ITO-1 electrode can achieve different states of focusing or even ring focusing by adjusting the voltage of ITO-2 electrode, which establishes a solid theoretical foundation for wavefront detection or correction.

4 Conclusion

A dual-layers arrayed pattern electrode within one substrate for constructing LC microlens chip is investigated thoroughly by us, and experimental results of PFS validate the effective electric field modulation capacity achieved by adding a new layer of planar pattern electrode, in comparison to conventional LC microlenses. This methodology will provide inspiration for the ongoing advancement and design of LC optical components, facilitating applications in wavefront detection and correction.

References

1. S. Kim, J.-H. Na, C. Kim, and S. Lee, Liq. Cryst. **44**, 2121–2132 (2017).
2. M. Ye, Z. Gao, W. Zhu, K. Liu, Z. Wang, and X. Zhang, Opt. Express **32**, 7220 (2024).
3. Y.-H. Lin, Y.-J. Wang, and V. Reshetnyak, Liq. Cryst. Rev. **5**, 111–143 (2017).
4. H. Ren, Y.-H. Lin, Y.-H. Fan, and S.-T. Wu, Appl. Phys. Lett. **86**, 141110 (2005).
5. M. Chen, W. He, D. Wei, C. Hu, J. Shi, X. Zhang, H. Wang, and C. Xie, Sensors **20**, 4142 (2020).