Electronically controlled liquid-crystal microlens array with plane swing focus and tunable focal length

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ABSTRACT

In this study, a kind of electronically controlled liquid-crystal microlens array (LCMLA) with plane swing focus and tunable focal length instead of a commonly microlens array with a fixed focal length and then focus distribution for high-resolution image acquisition, wavefront measurement, and distortion wavefront correction, is proposed. The LCMLA mainly consists of two glass substrates coated with a film of indium-tin-oxide (ITO) transparent material on one side. Each sub-unit top layer is composed of four sub-square electrodes, and the bottom layer is a circular electrode. The key technological steps in electrode fabrication contain an ultraviolet lithography, a dry etching (ICP etching), and final electron beam evaporation and overlay. The current LCMLA can be realized in three operating modes under external driving circuitry, including intensity image acquiring, wavefront measurement and distortion wavefront correction. The LCMLA is only in the image acquisition mode under the condition of no driving electrical signal. As the same driving electrical signals are applied onto the top four sub-electrodes of each sub-unit, the LCMLA is in the wavefront measurement mode. The LCMLA is in the key wavefront correction mode when different driving electrical signals are simultaneously applied onto the top four sub-electrodes of each sub-unit. Experiments show that the focal point of the LCMLA can be moved along the optical axis and over the focal plane by applying appropriate driving voltage signals.

Keywords: Liquid-crystal microlens array, Plane swing focus, Tunable focal length, Driving electrical signal

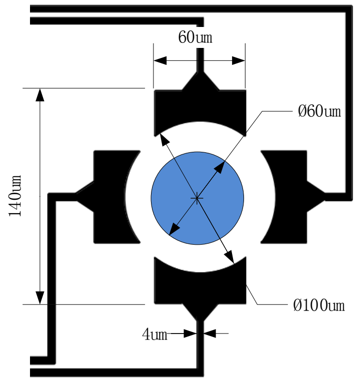
1. INTRODUCTION

Traditionally, the microlens array used for imaging and wavefront measuring optical devices are usually made of a fixed refractive index material, so that the focal length of their microlens is fixed. Generally, Multi-lens combination and mechanical adjustment are used to realize multi-mode function. As a result, the equipment tend to be bulky and complicated in structure and can not automatically switch modes and adjust focus according to different conditions. Thus, many schemes have been put forward to solve this problem. Among them, the study of tunable microlens has become the mainstream research goal of hardware improvement methods. Liquid crystal material is a good photoelectric material with excellent anisotropy in electrical and magnetic[1,2]. Its directors distribution can be effectively controlled by electric and magnetic fields, so that its refractive index can be adjusted. In 1979, Sato, a scientist at Akita University in Japan, proposed for the first time the use of liquid-crystal with a hole pattern and a planar electrode to create a tunable focusing microlens model, and gave the relationship between focal length and voltage, and focal length versus temperature[3]. Since then, scientists have continuously improved the material and structures of liquid-crystal microlens, and have developed liquid-crystal microlens with various optical properties such as convergence, divergence, and focusing[4-9].

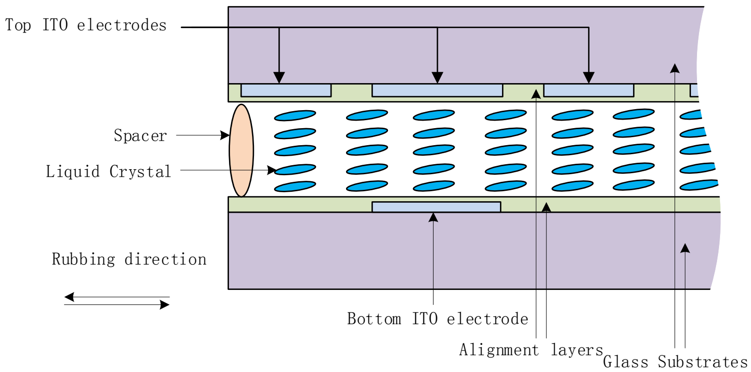
Based on the detection principle of Shack-Hartmann wavefront sensor and the unique optical properties of liquid-crystal, a kind of electronically controlled liquid-crystal microlens array (LCMLA) is proposed[10]. The LCMLA can not only realize the function of automatically adjusting the focal length with the change of the driving electrical signal, but also realize the function of the focal point swinging with the driving electrical signal in the focal plane. Instead of Shack-Hartmann's traditional microlens array, three modes of intensity image acquiring, wavefront measurement and distortion wavefront correction can be switched freely and quickly by simply changing the driving electrical signal. It greatly simplifies the structure and operation of the detector equipment, and has the characteristics of miniaturization and lightweight simultaneously.

2. FABRICATION AND SIMULATION

The main structure of the LCMLA consists of two glass substrates with transparent patterned electrodes on one side and a thin film liquid crystal layer. Two layers of ITO electrodes are separated by spacers with a diameter of about 20μm, and the gap is filled with liquid-crystal material (E44 of Merck). The main structure of each LCMLA sub-unit is shown in Figure 1 and its size is 140μm×140μm with the wire width is 4μm. Figure 1(a) shows the top viewport and the dimension of a LCMLA sub-unit. Figure 3(b) shows the sectional view of a LCMLA sub-unit. The top layer is composed of four sub-square electrodes, symmetrically distributed on four sides, and having a circular hole in the center. The bottom layer is a circular electrode. According to the accuracy requirement of 4μm, we designed and verified a complete electrode fabrication plan. The key steps include ultraviolet lithography, development, electron beam evaporation, overlay, and dry etching (ICP etching). Figure 2 is a physical map of the top and bottom patterned electrodes, and then the two layers of electrodes are placed face to face. Finally, the LCMLA is connected to an external integrated driving circuit by wire bonding to complete the fabrication of the entire device.



(a)



(b)

Figure 1. The structure of a LCMLA sub-unit. (a)The top viewport and the dimension of a LCMLA sub-unit. (b)The sectional view of the structure of a LCMLA sub-unit.

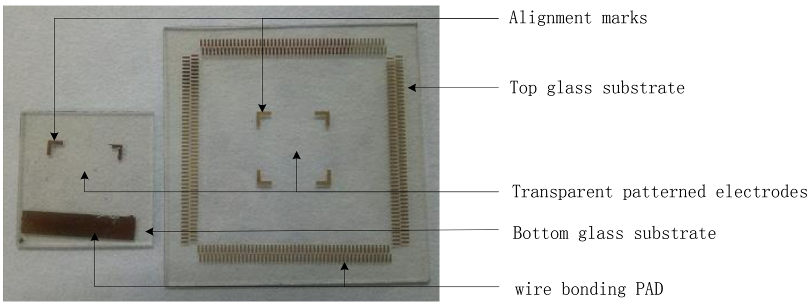


Figure 2. The physical map of top and bottom patterned electrodes.

Liquid-crystal material have excellent dielectric anisotropy and birefringence characteristics. The liquid-crystal molecules in the electric field are redirected and their tilt angle of the director is changed. Thus, the formula for its effective refractive index can be calculated using equation (1)[11].

$$n_{eff}^2(\theta) = \frac{n_e^2 n_o^2}{n_e^2 cos^2(\theta) + n_o^2 sin^2(\theta)} \quad (1)$$

Where n_e represents the extraordinary refractive index, n_o represents the ordinary refractive index, and The liquid-crystal material of Merk E44 has a refractive index of n_e = 1.7904, n_o = 1.5277. θ is the angle between the optical axis and the incident light.

A non-uniform electric field is formed when a driving electrical signal is applied to the ITO electrodes. The reorientation of liquid-crystal molecules under the influence of an electric field forms different gradient refractive index distributions. As a result, the focal point of the microlens can move along the optical axis and swing within the focal plane. Figure 3 shows schematic maps of electric swing focus. The first sub-map shows that the top four sub-electrodes are applied with the same driving electrical signals, resulting in focusing. The next four sub-maps indicate that different driving electrical signals are simultaneously applied onto four sub-electrodes with the focus swing over the focal plane.

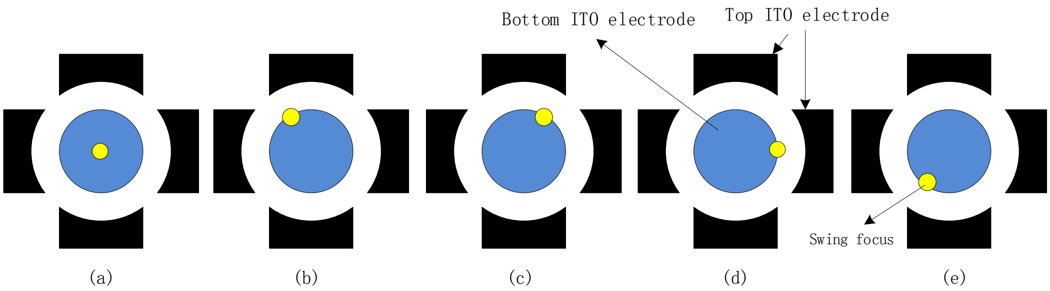


Figure 3. The schematic diagram of electric swing focus

In order to further study the electric field distribution of the liquid-crystal layer under external driving circuitry, we conducted a simulation experiment according to the typical electro-optical characteristics of nematic liquid-crystal material. Figure 4 shows the electric field distribution of the liquid-crystal layer under different driving electrical signals which verified the feasibility of the LCMLA we proposed. The focal point of LCMLA can not only move along the optical axis, but also swing in the focal plane.

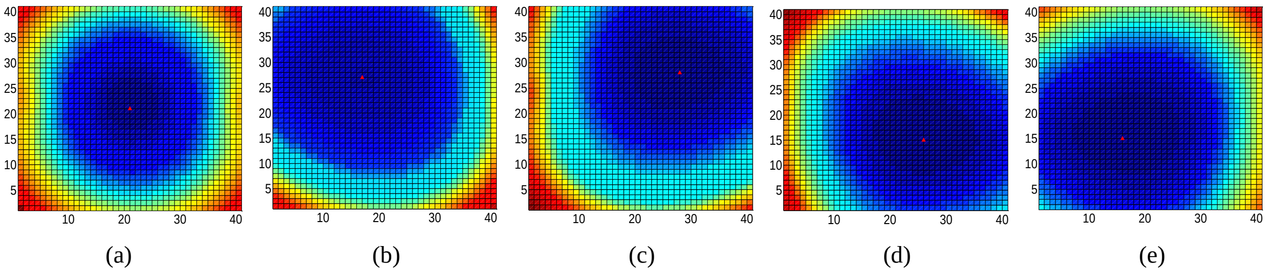


Figure 4. The electric field distribution of the liquid-crystal layer

3. CONCLUSION

In this paper, we propose an electronically controlled LCMLA instead of a commonly used microlens array with constant refractive index. The focal point of LCMLA can not only move along the optical axis, but also swing in the focal plane. Feasibility was verified and a complete fabrication process was developed according to the principle. By simply modifying the driving electrical signals, three operating modes of image acquisition, wavefront detection, and wavefront correction can be freely switched. Its simple operation and powerful functions greatly simplify the structure and optimize the performance of traditional optical devices.

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