Design and Simulation of Electronically Controlled Liquid Crystal Lens with Large Aperture

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Abstract: The aperture of traditional liquid crystal lens is usually only several hundred microns, which greatly limits its application. If the aperture of the liquid crystal lens can be enlarged, the liquid crystal lens will be more widely used. In the paper, a liquid crystal lens with a new type of electrode pattern is designed. The structure of this lens is similar to Fresnel lens. The electrodes of the whole lens are divided into upper and lower layers, the upper layer electrodes are designed into several concentric annular groups, and the lower layer electrodes are flat electrodes. This structure divides the liquid crystal layer into rings and the optical paths of adjacent rings differ by a wavelength, so that all regions of the light can be enhanced coherently in the imaging plane, and better focusing effect can be obtained. The design principle and simulation results of the lens are given in the paper.

1. Introduction

Many modern optical imaging systems require smart components or elements with variable optical power penetrating for auto-focus and optical zoom applications. The conventional mechanical approaches are very difficult to implement the operations as above. Recently, several new alternative approaches and materials have been explored to replace those low performance mechanical elements or setups. Liquid crystal (LC) materials have relatively large electrical and optical anisotropies, and then they can provide a very large electrically controlling refractive index shift without mechanical movements. Multiple attempts have been done to use this kind of setups and physical phenomenon for developing tunable focus lenses or mirrors. To generate lens effect in a LC layer with uniform thickness, it is important to design an electrode pattern capable of creating an axially symmetrical inhomogeneous electric field in the LC layer. A LC lens with one hole-patterned and one planner electrodes was first realized in 1979[1], its focal length can be continuously varied electrically. Since then, many kinds of LC lens with various patterned electrode have been developed[2-9]. The aperture of traditional liquid crystal lens is only several hundred microns, which greatly limits its application. If the aperture of the liquid crystal lens can be enlarged, the liquid crystal lens will be more widely used. It is difficult to enlarge the aperture of liquid crystal lens, which is related to the thickness of liquid crystal layer, voltage and liquid crystal material. When making liquid crystal lens, the empirical values of the thickness and aperture of liquid crystal layer are usually taken to obtain better focusing effect. According to the conventional design method, the thickness of the liquid crystal layer is changed to 20 microns, and other parameters remain unchanged. The simulation results show that the inclination of the director in the vertical section of the liquid crystal cell is very small. This is because the electric field below the circular hole is relatively small, which is not enough to deflect the liquid crystal molecules. The electric field intensity near the center of the circular hole is the smallest. The electric field intensity will increase as the angle decreases from the center down, left or right. When the thickness of liquid crystal layer is fixed, the aperture of liquid crystal lens can only be within a certain range. Increasing the voltage can improve this situation to some extent, but when the aperture is too large, this method can't do anything. In addition, with the increase of the thickness of the liquid crystal layer, the aperture of the lens can be made larger, and the corresponding driving voltage should be increased accordingly. However, in order to be safe, the voltage should not be too high.

2. Structure and principles

In order to fabricate large aperture liquid crystal lens, it is difficult to start with conventional factors. New methods and structures should be considered. The aperture of Fresnel lens can be made very large. Compared with traditional lens, it can be made very thin, making the weight and volume smaller. Fresnel lens is characterized by short focal length, thin thickness and large aperture, which can transmit more light. Because the refraction of light occurs at the interface of medium, removing the part of light propagating in a straight line in the lens and retaining only the surface where the refraction occurs can save a lot of materials and achieve the same focusing effect at the same time. Fresnel lens is thinned by this method. As shown in Fig.1, Fresnel lens with the same effect can be obtained by removing the shadow part and moving the surface part down. The thinner the surface is, the thinner the lens can be. Similar to Fresnel lens, a new pattern electrode can be designed on the basis of a single circular aperture lens, so that the light outside the circular aperture can converge to the focus of the central circular aperture area, which can make the focusing range of the lens wider and obtain a liquid crystal lens with a wide aperture.
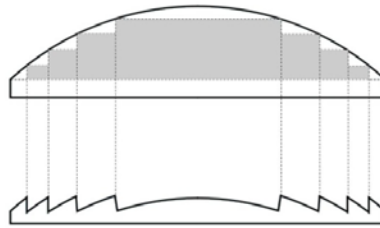

Fig.1 principle diagram of Fresnel lens

The liquid crystal layers of liquid crystal lenses are divided into rings. In order to make the light of each region converge to the point, the optical path of the same region should be equal, and the optical path of the adjacent region can be designed to differ by one wavelength. Starting from the central area, each area is numbered in turn, and the number of the central area is 0. The optical path of the adjacent region in the Fresnel zone plate differs by half wavelength. By occluding the even or odd region and not allowing light to pass through, the intensity of light in each ring can be enhanced coherently at the center of the imaging plane and a bright spot can be obtained. The design of this paper is to make the optical paths of adjacent regions differ by one wavelength, so that all regions of light can be enhanced coherently in the imaging plane, and get better focusing effect.

The device structure of the LC microlens is shown in Fig.2. Fig.2(a) shows the side view of the structure of the LC microlens. Fig.2(b) shows the vertical view of ITO electrodes. Fig.2(c) shows the cross section of liquid crystal cell. It is mainly composed of two glass substrates and a thin LC layer(E44 of Merck). The LC layer is sandwiched between the two substrates which are separated by spacer of 50µm thickness. The bottom and top substrates are both coated with a transparent ITO electrode and placed face to face. There is a thin alignment layer (polyimide) covered on the two electrodes, their rubbing directions are the same and both parallel to glass substrate surface, so the LC molecules are aligned homogenously. When the voltage is applied to the top and bottom ITO electrode layers, it would generate a symmetric non-uniform electric fields at the center aperture area of pattern electrode within the LC cell which intensity increases from center to border. Thus the tilt angle of the LC directors changes with the electric field E, which is smallest at the center and the largest around the border. As the refractive index and dielectric constant of LC have relationship with LC molecule alignment in order, they are anisotropy. LC molecule is easily deformed by external electric fields. Elastic free energy formula of deformation LC in unit volume is
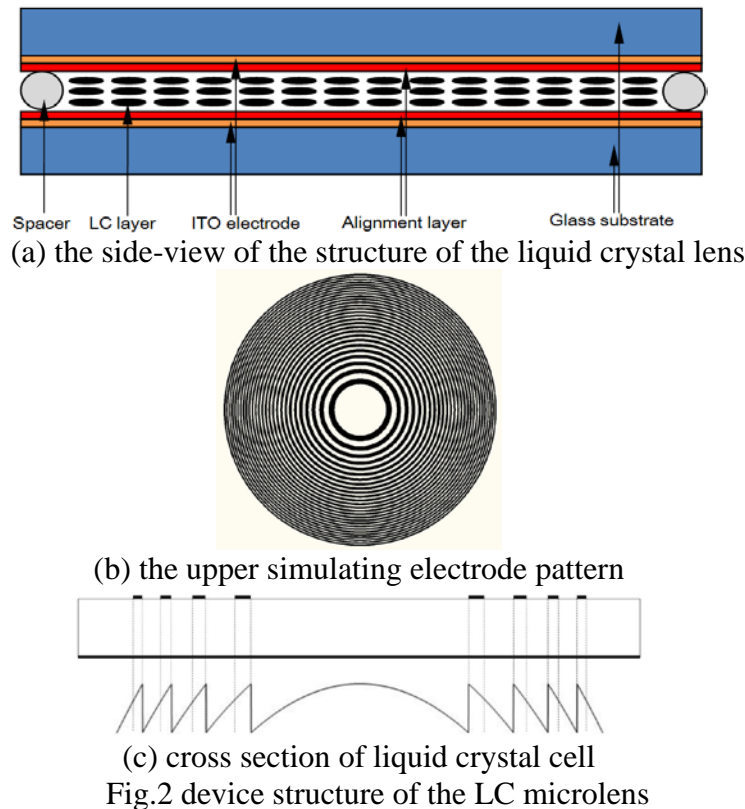
$$\mathrm{F}_d = (1/2)[K_{11}(\nabla \cdot n)^2 + K_{22}(n \cdot \nabla \times n)^2 + K_{33}(n \times \nabla \times n)^2] \tag{1}$$

Where K_{11}, K_{22} and K_{33} are the splay, twist and bend elastic constant of the LC[10]. The free energy of LC molecular is smallest when the direction of LC molecular is parallel to the direction of electric fields. If the incident light is parallel to optical axis, the electric field can be decomposed into orthogonal polarized components of Ex and Ey. As Ex and Ey are perpendicular to optical axis,

the refractive index of the LC is n_o. There is n_o phase difference. So the incident light does not change after penetrating LC. If the incident light is at an angle of θ to optical axis, the electric fields can be composed into major axis direction and minor axis direction. On minor axis direction, the refractive index is n_o. On major axis direction, the refractive index of the extraordinary line of an incident plane line is

$$n = \frac{n_o n_e}{\sqrt{n_e^2 \cos^2 \theta + n_o^2 \sin^2 \theta}} \tag{2}$$

where n_o and n_e denote the ordinary and extraordinary refractive indices of the LC respectively. The function curve of n_e has a bell-shaped profile which would produce a focusing effective like a common convex lens.

(a) the side-view of the structure of the liquid crystal lens

(b) the upper simulating electrode pattern

(c) cross section of liquid crystal cell
Fig.2 device structure of the LC microlens

3. Simulation and results

In order to detect the effect of the new electrode structure, we simulated it by computer, mainly simulating the distribution of the director and the equipotential line in the liquid crystal layer under the action of electric field control. In the simulating processing, the thickness of the liquid crystal layer is 50 microns and the width of the electrode is 20 microns. When the voltage of the upper electrode is 10 v_{rms}, the distribution of the simulated pointer is shown in the Fig.3. In order to make the optical path at the junction of the region close to the ideal situation, the optical path outside the electrode 0 should be as large as possible, that is, to reduce the electric field intensity at the location, to generate steep electric field in the region, and to make the optical path distribution close to the ideal profile. For this reason, the lower electrode is also designed as a ring from the original flat plate electrode. The black area is the same as the previous one, with a voltage of 0 v_{rms} and a non-zero voltage on the white area. The number of the electrodes in the white area is 2. The positions of the electrodes 2 and the upper electrode are staggered. If a non-zero voltage is applied to the electrode 2, the electric field in the opposite direction will be excited near the junction, so that the electric field at the junction will be reduced. When the electrode 0 and 1 are applied on 10 v_{rms}, and the electrode 2 is applied on 3 v_{rms}, the simulation results show the distribution of the directional vector as shown in Fig.4. It can be seen that the deflection angle of the directional vector

near the electrode 2 decreases and the optical path increases. At a distance from the new electrode, the inclination angle of the directional vector also decreases. Reducing the thickness of the liquid crystal layer can improve this situation, and make the maximum of region 0 and region 1 wavefront equal. It can also reduce the driving voltage of the lens. Taking the liquid crystal layer thickness of 20 microns, the voltage on electrode 0 and 1 is 5 v_{rms}, and the voltage on electrode 2 is 2 v_{rms}, the simulation results show the distribution of the direction vector as shown in Fig.5. When the thickness of liquid crystal layer is 50 microns, the potential distribution obtained by simulation is shown in Fig.6. The potential contours in the area below are fairly smooth, and the distribution of the electric field is exactly what we need.
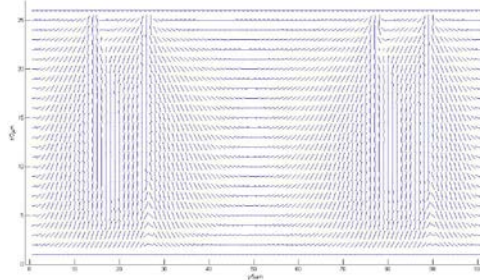

Fig.3 distribution of directional vector on vertical section
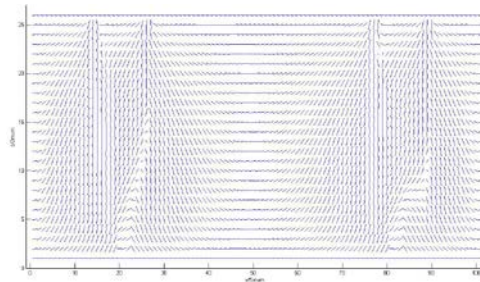

Fig.4 distribution of directional vector on vertical section with improved bottom electrode
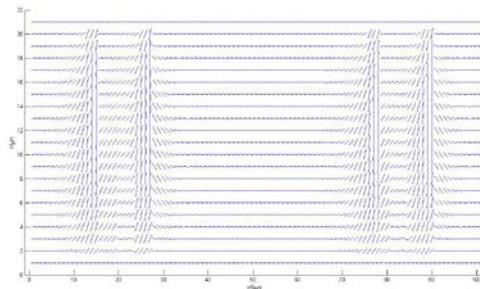

Fig.5 distribution of directional vector on vertical section while reducing the layer thickness
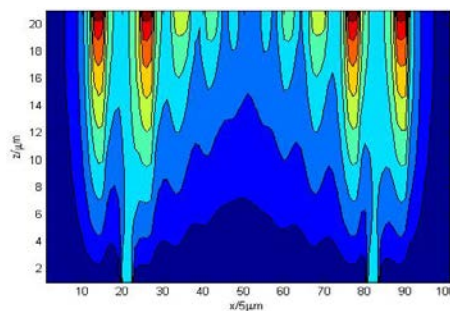

Fig.6 equipotential line on vertical section

4. Conclusion

Starting with the size of the aperture of the liquid crystal lens, the reason why the aperture of the liquid crystal lens is difficult to enlarge is analyzed. According to the principle of Fresnel lens, a

scheme for fabricating large aperture liquid crystal lens is proposed. Combined with theoretical calculation and simulation, a series of improvements have been made to the scheme. A new structure and pattern electrode have been designed. The simulation results show that the new large aperture liquid crystal lens can converge light.

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