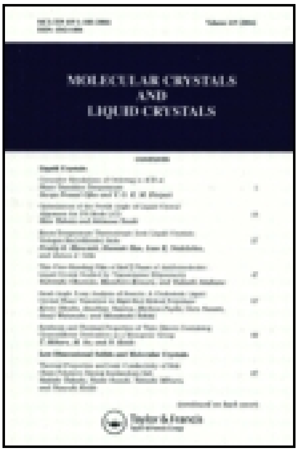

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Experimental Analysis to Avoid Migrating Zigzag Lines Occurring in Homogeneously Aligned Liquid Crystal Lenses with a Hole-Patterned Electrode

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For our beginning study in large apertures of liquid crystal (LC) lenses, both disclination line and zigzag line are usually occurred in cells. Disclination lines possibly appear and then disappear if we slowly increase applied voltages and/or fabricate LC lens with thicker upper glass substrates. But, zigzag lines always appear near the edges of LC lens. Unfortunately, zigzag lines and disclination lines will possibly link each other, and permanently stay in cells to degrade performance of LC lens. In this paper, we experimentally study and conclude that the suitable rubbing conditions in cells will effectively prevent this problem of linked lines.

Keywords Disclination line; liquid crystal lens; zigzag line

1. Introduction

Due to unique electro-optical characteristics, liquid crystals (LCs) is usually used to study and fabricate some practical devices. Liquid crystal (LC) lens is just a typical example. The studies of LC lens had begun in the 1970s. Until now, numerous topics are also studied in progress such as aberration compensation for Blu-ray DVDs [1], ophthalmic applications [2], imaging systems [3,4] and 3D display systems [5] etc. Two review papers [6,7] related to LC lenses are worth referring for readers interested in this field. In general, the structures of LC lenses are very different from the conventional glass lenses. Typical LC lenses are composed of two glass substrates coated with conductive thin films, which gaps between two glass substrates are filled with liquid crystals. When LC lenses operated with electric voltages, the orientation of LCs will has a quadratic distribution of refractive index to achieve capabilities of lenses. In order to improve the performance of LC lenses, a few extra modifications are usually added such as usage of resistive composite polymer as electrodes [8],

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initial LC alignment with micro-rubbing [9], applying voltages with three electrodes [10], and polymer stabilization [11] etc.

The homogeneously aligned LC lens with a circular hole-patterned electrode is a popular structure for studying. In 2002, M. Ye and S. Sato proposed a modified structure with a circular hole-patterned electrode to achieve lens capabilities with any aperture dimension [12]. Although the simple structure in the cell realizes the functions of LC lens, it also has an annoying problem of disclination line. Many researches had pointed out the cause of disclination line and proposed methods to avoid it [13–15]. Due to homogeneous alignment in the cells, the LC directors along rubbing direction near the boundary of hole-patterned electrode possibly rotate with opposite directions so that disclination lines easily appear. In this paper, we experimentally study the phenomenon of linked lines between disclination and zigzag lines, and propose the suitable rubbing conditions to prevent this problem.

2. Fabrication and Characteristics of LC Lens

We referred to Sato's paper [12] to make LC lenses for our experiments. Figure 1 shows the illustrative structure of LC lens and a real lens made by us. The LC lens is composed of two glass substrates. One bottom substrate is coated with ITO film and processed with polyimide for homogeneous LC alignment, and the other upper substrate is coated with aluminum (Al) film and etched a circular hole-pattern, which opposite glass surface is processed with polyimide for homogeneous alignment. Liquid crystals (E7, purchased from Merck) is filled in the cell with Mylar spacer. The circular hole-pattern with 7 mm diameter is the aperture of LC lens. The thickness of upper glass substrate is 1.4 mm, which is double thickness of bottom substrate. The LC layer is controlled by Mylar spacer to keep about 125 μm.

Figure 2 shows the operational principle of a convex LC lens and variations of a text image when tuning focal length of LC lens. For an ideal convex LC lens, the maximum refractive index (n_{max}) appears in central position, and symmetrically radial distribution of refractive index is generated over whole hole-pattern area with gradually decreasing toward the boundary. The focal length (f) of LC lens is reason-

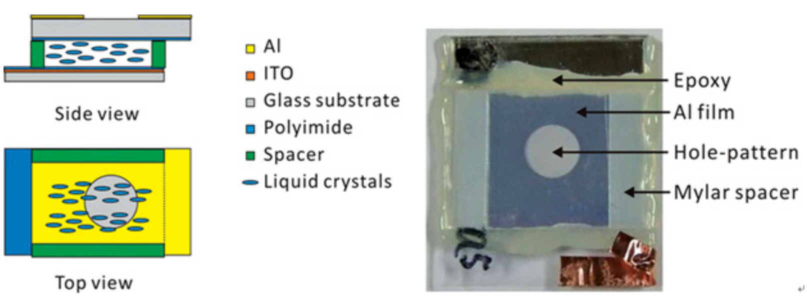

Figure 1. Schemes of LC lens with hole-patterned electrode. The homogeneously aligned cell with 7 mm diameter of hole-patterned electrode was filled with E7 LCs with 125 μm thickness of Mylar spacers. The thicknesses of upper and bottom glass substrates were 1.4 mm and 0.7 mm, respectively. The conductive thin film of upper substrate outside the cell was aluminum film, and the other substrate had another transparent ITO film inside the cell. A real LC lens in our experiment is also shown which edges are sealed with epoxy. (Figure appears in color online.)

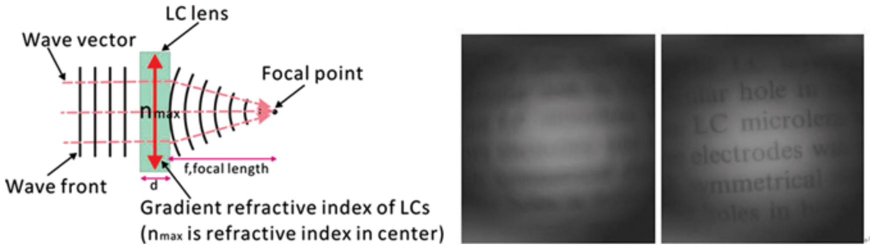

Figure 2. Principle of an operated convex LC lens. A plane wave is incident the LC lens. When the cell is operated and possessed a symmetrically radial distribution of effective refractive indices with maximum in central cell, the incident plane wave will be affected and become a convergent wave. In right chart, it shows the variations of text image when tuning focal length of LC lens. (Figure appears in color online.)

ably satisfied with the Eq. (1), which shows that r is the radial position, n(r) is the refractive index in r, and d is thickness of LC layer.

$$f = \frac{r^2}{2(n_{\max} - n(r))d}. \tag{1}$$

3. Experiment and Discussion

Figure 3 shows an operated LC lens has appearances of disclination and zigzag lines in our experiments. Two zigzag lines obviously appeared near the edges of cell, which directions were perpendicular to the rubbing direction. An annoying trouble is that disclination line and zigzag line possibly link each other when LC lens has been operated for a few days. Eventually, the linked lines permanently stay in the cells to degrade performance of LC lens.

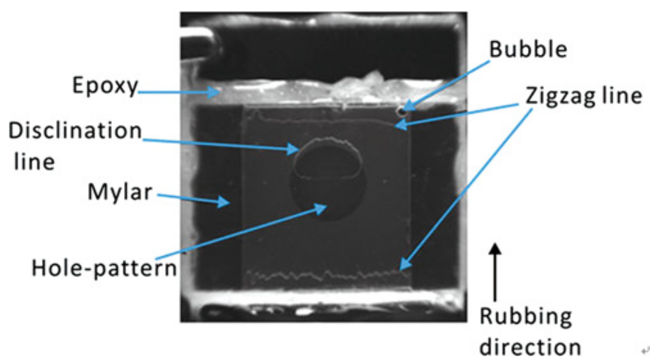

Figure 3. Observation of disclination line and zigzag lines appearances in LC lens with a hole-patterned electrode. Two zigzag lines individually appeared in top and down edges of cell. One disclination line appeared in top area of cell, which was closer to top zigzag line. Two stripe Mylar spacers were positioned in right and left edges of cell, which long sides were parallel to rubbing direction of LC alignment. All edges in the cell were sealed with epoxy. (Figure appears in color online.)

In order to find out the way to avoid this problem, we did a series of experiments as follows. Firstly, we want to understand why the zigzag lines appear in cells. We made homogeneously aligned non-hole-pattern LC cells with five different cell conditions and observed the appearances of zigzag lines or not. The experimental results and illustrative cell conditions are shown in Figure 4. Figure 4(a) and 4(b) show there is no appearance of zigzag lines in cells, which two glass substrates had the same 0.7 mm thickness, whatever the conductive films of upper substrates were inside or outside the LC cells. Figure 4(c) shows zigzag line appeared near one edge of LC cell, which was composed of a 1.4 mm thickness of upper glass substrate with conductive film outside the cell. Figure 4(d) and 4(e) show zigzag lines symmetrically appeared in cells when two substrates of cells were the same thickness (0.7 mm or 1.4 mm), and conductive films were outside the LC cells. Comparing Figure 4(d) and 4(e), we find that the zigzag lines further migrate toward the central area of cells if the cells are composed of thicker substrates. We conclude that zigzag lines always appear near the cell edges where upper and bottom glass substrates have unequal boundaries, and directions of zigzag lines are perpendicular to rubbing direction. Simultaneously, the thicker glass substrates with outside conductive films in cells will obviously appear zigzag lines. It may be relative to different fringe electric fields near the cell edges.

Secondly, we observed the phenomenon of linked lines (i.e., disclination line and zigzag lines link each other) in the LC lens, and found that the appearance of disclination or zigzag lines is obviously relative to rubbing direction. Figure 5(a) shows the gradually approaching process of linked lines between disclination and zigzag lines when LC lens operated for a few days. On the first day when the LC lens completed, disclination and zigzag lines simultaneously and separately appeared in the cell (Fig. 5(a) left chart). Their positions gradually approached on another day (Fig. 5(a) middle chart). Eventually, they linked each other on the 5th day (Fig. 5(a) right chart). The rubbing direction of cell in Figure 5(a) was parallel to the y-axis of coordinate. On the contrary, Figure 5(b) shows no linked lines appeared in the cell even though the LC lens had been operated over one month. The rubbing

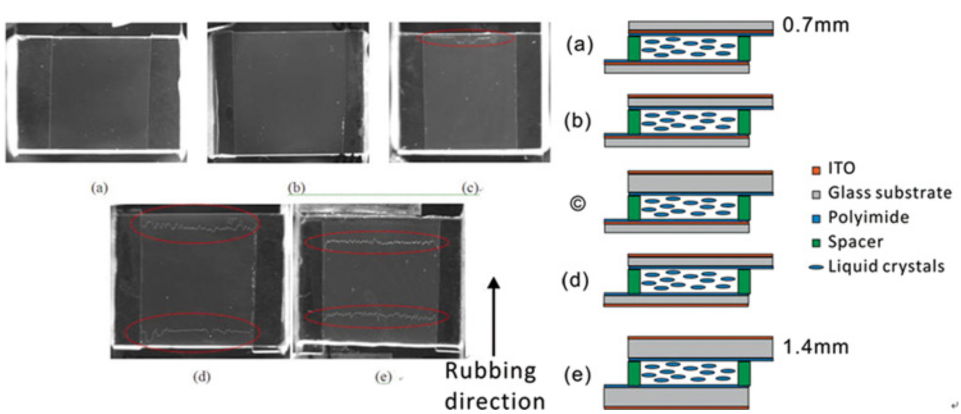

Figure 4. Observation of zigzag lines appearances in non-hole-pattern LC cells with five different conditions. In the left, it shows appearances of zigzag lines were very sensitive to cell conditions. In the right, it schematically demonstrated five cell conditions from (a) to (e). The detailed cell conditions are described in the content of paper. (Figure appears in color online.)

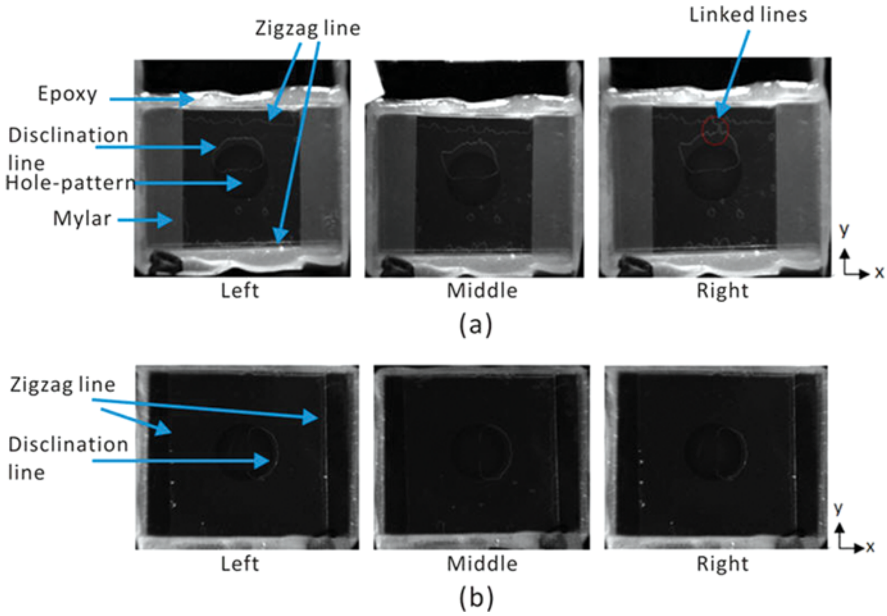

Figure 5. Observation of occurred linked lines. (a) It shows an unfortunate result. Initially, zigzag lines and disclination line simultaneously and separately appeared in the cell (left chart). The lines became closer on another day (middle chart). Finally, they linked each other (red closed circle in right chart). The rubbing direction is the y-axis of coordinate; (b) It shows a good result without occurred linked lines even though the LC lens had been operated for a long time over one month. The rubbing direction is the x-axis of coordinate. (Figure appears in color online.)

direction of cell in Figure 5(b) was parallel to the x-axis of coordinate. Obviously, appearance of linked lines is very sensitive to the rubbing directions. We conclude that it almost has no possibility to appear linked lines if the cell is rubbed with the direction perpendicular to long sides of Mylar spacer (i.e., the edges of cell where two glass substrates have equal boundaries). Using this rubbing condition, the zigzag lines appear near the edges of Mylar spacers and hardly migrate in cells so that linked lines will be not occurred.

We also demonstrate two typical different results of non-linked lines and linked lines in Figure 6. In Figure 6(a), it shows that a LC lens was operated and observed optical interference with a pair of crossed-polarizers, and the disclination and zigzag lines were simultaneously occurred in the cell. When waited for a few hours, the disclination line gradually shrank and finally disappeared. Fortunately, the linked lines did not occur so that LC lens possessed good performance. On the contrary, in Figure 6(b), the linked lines unfortunately occurred and permanently existed in the cell, which strongly degraded the performance of LC lens. In order to prevent this randomly occurred problem, we find out the suitable rubbing conditions will be absolutely efficient to avoid it. As long as the rubbing direction is perpendicular to the long sides of Mylar spacers, the zigzag lines will appear in nearby Mylar spacers, where zigzag lines are more far away the position of disclination line so that linked lines do not occur. We have processed many experiments with this way to prove that it is very efficient to prevent the problem of linked lines.

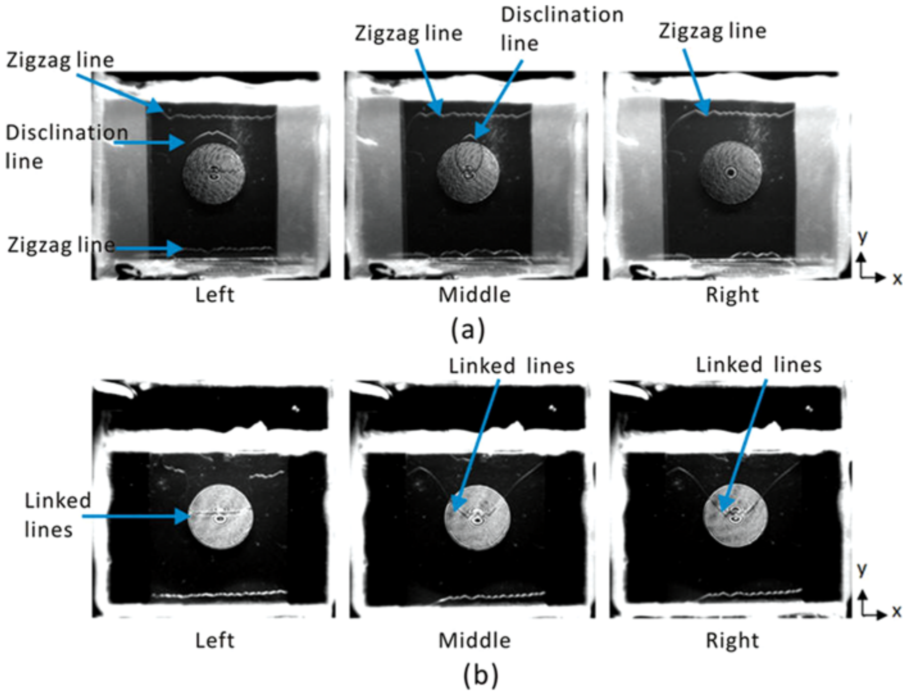

Figure 6. Influence of linked lines in LC lens. (a) The LC lens was operated with electric voltages of 100 V_{rms}. Initially, zigzag lines and disclination lines simultaneously appeared in the cell (left chart). When waited for a few hours, the disclination line gradually shrank (middle chart). Finally, the disclination line disappeared (right chart). (b) With the same applied voltages, linked lines were occurred in the cell. They permanently stayed in the cell to degrade the performance of LC lens. The LC cells had the same rubbing directions in the y-axis of coordinate. (Figure appears in color online.)

4. Conclusions

We demonstrate the suitable rubbing conditions for LC lens with a hole-patterned electrode to avoid the problem of linked lines. In our experiments, if we use the rubbing direction of LC alignment to perpendicularly orient to long sides of Mylar spacer (i.e., the equal boundaries of two substrates of cells), disclination line and zigzag lines will individually appear in cells. Due to zigzag lines hardly migrate so that there is no possibility to occur linked lines. We think the situation of migrating zigzag lines is relative to fringe electric fields in cell edges. It is very important for LC lenses to avoid linked lines because they seriously degrade the performance of LC lenses. Although disclination lines always exist in the cells, they are possibly avoided when we slowly increase applied voltages and/or fabricate LC lens with thicker upper glass substrates.

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