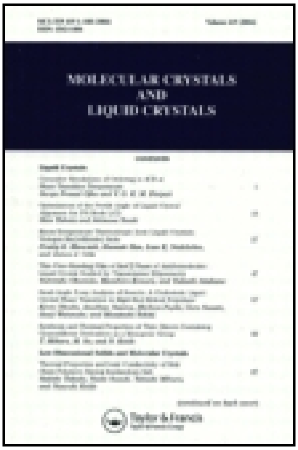

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The disclination lines appearing in liquid crystal (LC) cells with a relief ultraviolet (UV)-cured polymer layer under an applied voltage are investigated. Behaviors of the disclination lines are discussed using a LC molecular orientation model. The results indicate that the behaviors of the disclination lines are related to the angle between the alignment direction of the LC molecules and the direction of the grooves. Life time of the disclination lines is also measured as a function of the applied voltage.

Keywords: disclination lines; molecular orientation; polymer/liquid-crystal; relief structure

1. INTRODUCTION

Liquid crystal (LC) elements have found many applications in optical logic devices, display devices and beam steering devices.[1-3] Usually, the manufacturing process of the elements is relatively complicated. Recently, we have proposed a polymer/liquid-crystal grating with a relief structure fabricated by a single-step ultraviolet (UV) irradiation.[4,5] Using this fabrication method, the LC elements with various polymer surface profiles can easily be fabricated by changing the pattern of the mask. However, it is found that the disclination lines related with the relief structure inside the LC cell are observed, and they may deteriorate the optical properties of the polymer/LC elements. Therefore, it is very important to investigate the behavior of disclination lines for overcoming their influence.

In this paper, the disclination lines, which behaviors are closely related to the alignment direction of LC molecules and the surface profile, are investigated by using a microscope for a polymer/LC grating and a polymer/LC zone plate with a relief structure. The behaviors of the disclination lines are also discussed using a LC molecular orientation model.

2. EXPERIMENTAL

Nematic LC E7, prepolymer HX-620 and photo-initiator Irg-184 were used in these experiments. Their mixing ratio was 50 : 48.5 : 1.5 by weight. The mixture was sandwiched between ITO (indium-tin-oxide)-coated glass substrates which were coated with polyvinylalcohol (PVA) and treated by rubbing. The thickness of LC cells was controlled by using a polymer spacer with the thickness of 11 μm.

The cells were irradiated with collimated UV light through photomasks with a grating pattern or with a zone plate pattern. A high-pressure Hg lamp was used as the UV light source. The UV light intensity was 20 mW/cm^2 and the irradiation time was 10 min. The temperature during the polymerization and the phase separation for forming the relief structure was maintained at approximately 50°C using a hot plate. The LC cells were driven by 1 kHz sinusoidal AC voltage.

In our fabrication method, the cured polymer layer with a relief structure can be obtained. In order to observe the surface structure of the cured polymer layer, the fabricated LC cell was treated to remove one of the glass substrates, and the LC was washed away. The surface structure was observed by using an interference microscope.

3. DISCLINATION LINES IN THE CASE OF GRATING

3.1 Grating Structure

After the prepolymer was cured by UV irradiation, the polymer/LC grating with a relief structure was spontaneously fabricated. Figure 1 shows a micrograph of the polymer/LC grating under a polarizing microscope with crossed polarizers. The angle between the polarization direction of the polarizer and the grating lines is set at 45°. The grating period is 100 μm, where the rubbing direction is orthogonal to the grating lines. A good homogeneous alignment of the LC molecules along the rubbing direction is observed without applying voltage.

The surface profile of the cured polymer is observed. Figure 2 shows one of interference fringes of the cured polymer surface observed by an interference microscope. The interference fringe can indicate the surface profile of the cured polymer. The grating ridge corresponds to the area that is irradiated by UV light. In the polymerization process, the prepolymer molecules move from the shaded region to the region irradiated by the UV light, so that the grating groove of the cured polymer is generated in the shaded region, and the grating ridge is produced in the region irradiated by the UV light. The photo process is so fast that two hills on the grating ridge are generated at the edges of the UV light irradiating region. This surface structure induces disclination lines under a voltage application, when the alignment direction of LC molecules is deviated from the direction of the grating lines.

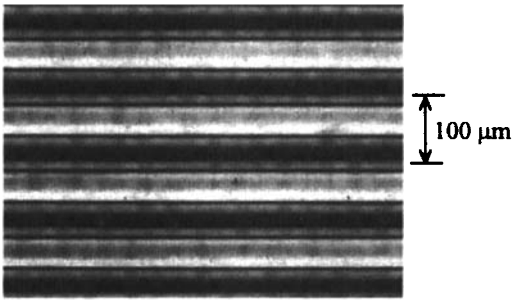


FIGURE 1 A micrograph of the polymer/LC grating under crossed polarizers.

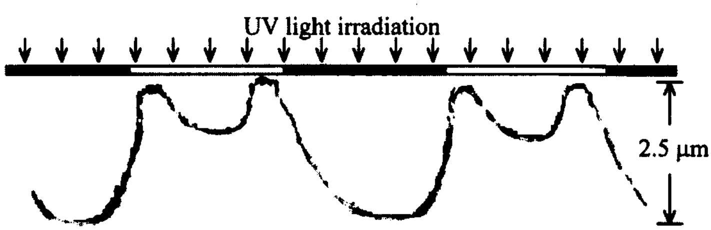


FIGURE 2 An interference fringe for the surface of the cured polymer.

3.2 Behaviors of the Disclination Lines

When the polymer/LC grating whose LC molecular alignment direction is perpendicular to the grating lines is driven by applying a voltage, the disclination lines appear. Figure 3 shows the disclination lines observed under a microscope, where the applied voltage is 12 V. The observed region is the same as shown in Figure 1. The rubbing direction is from bottom to top at the upper substrate (see Figure 4). When the voltage is switched on, the disclination lines appear at the centers of both the cured polymer groove and ridge, and the edges of the cured polymer ridge, as shown in Figure 3(a). There are four strings of disclination lines in per period (①, ②, ③ and ④).

The disclination lines at the center and the edge make a loop structure. The loops of the disclination lines become smaller and finally disappear as time goes on. The loops of the disclination lines at the cured polymer ridge disappear faster than that in the cured polymer groove. As shown in Figure 3(b), all of the loops of the disclination lines in the cured polymer ridge disappear within 20 s. All of the disclination lines disappear within 75 s after the voltage is applied, as shown in Figure 3(c).

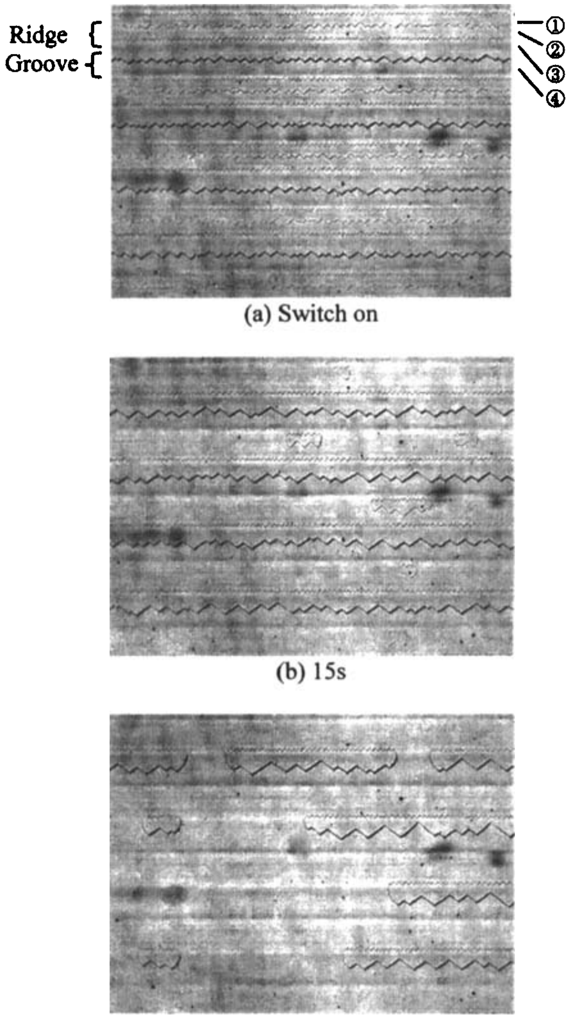
On the other hand, the disclination line does not appear in the polymer/LC grating whose LC molecular alignment direction is parallel to the grating lines. The results indicate that the behaviors of the disclination lines are related to the angle between the alignment direction of LC molecules and the direction of the grating lines.

3.3 LC Molecular Orientation Model

According to the surface observation illustrated in Figure 2, we speculate upon LC molecular orientation model as shown in Figure 4. The rubbing direction of the upper glass surface is perpendicular to the grating lines, and it is from right to left. It is well known that the LC molecules are aligned on a surface of the PVA-coated substrate with a small pretilt angle when using the rubbing treatment. The LC molecules near the cured polymer layer are aligned along the surface relief as shown in Figure 4. A good homogeneous LC molecular alignment along the rubbing direction is obtained, because the anchoring of the cured polymer/LC interface is weak.

When a voltage is applied across the LC cell, greater part of the LC molecules in the LC layer tend to tilt counterclockwise except the molecules around the region A and B. The LC molecules around A and B tilt clockwise; this is, the tilt direction is different from the others, and thus, the disclination lines appear in both side of the A and B. There are four disclination lines appear in per period. The disclination lines of ①·② are corresponding to the boundary of A; and the ③·④ are similarly corresponding to B. Zigzag structure is also observed in the relief type of the grating (see Figure 3) as observed in the slit electrode type LC cell.[6] Its folding period becomes shorter at the thinner LC layer region comparing the zigzag structure ①, ②, ③ and ④. This phenomenon is also coincident with the previous work.[6]

As illustrated in Figure 3, the disclination lines disappear as time goes on. The disclination lines of ①·② and ③·④ make a loop structure, respectively. The disclination lines of ① and ② must disappear together, because they are induced by the same reason (LC molecular reorientation in the region A). The same phenomenon is observed for the disclination lines of ③ and ④. The loops of the disclination lines of ①·② disappear faster than that of ③·④, because the LC layer around the region A is thinner than that around B.



(a) Switch on

(b) 15s

(c) 45s

FIGURE 3 Behaviors of the disclination lines.

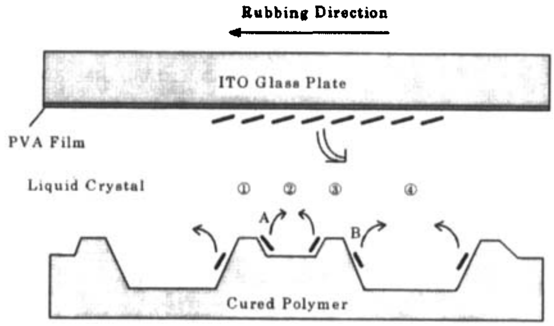


FIGURE 4 LC molecular orientation model.

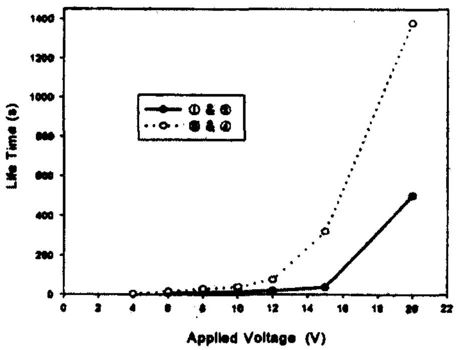


FIGURE 5 Life time of the disclination lines as a function of applied voltage.

Life time of the disclination lines is measured as a function of the applied voltage, as shown in Figure 5. Where, the life time of disclination lines is defined as the time until the disclination lines disappear. The closed and open circles show the life times of the disclination lines of ①·② and ③·④, respectively. Both the life times increase with increasing the applied voltage. It is also shows that the life times tend to increase rapidly at the higher applied voltage levels.

4. DISCLINATION LINES IN THE CASE OF ZONE PLATE

The disclination lines are also observed in a zone plate structure. Figure 6 shows a micrograph of the polymer/LC zone plate under crossed polarizers, where the rubbing direction is from bottom to top. The radius of each ring in the zone plate (R_n) is related to the focal length f and the wavelength λ which is shown as $R_n = \sqrt{n f \lambda}$, here, f = 5 cm, λ = 632.8 nm, n is an integer for the corresponding zone. The maximum n is set at 30, and the maximum radius is about 0.97 mm as shown in Figure 6. A good homogeneous alignment of the LC molecules along the rubbing direction is also observed without applying a voltage.

The disclination lines appear except in the region which the rubbing direction is parallel to the grating lines when a voltage is applied. As time goes on, the disclination lines also disappear. Figure 7 shows the behavior of disclination lines observed under a microscope, where the applied voltage is 12 V. The observation is carried out at 30 s after switch on. The picture is magnification of the upper part of the zone plate as shown in Figure 6.

Four strings of disclination lines in per relief period are observed as grating

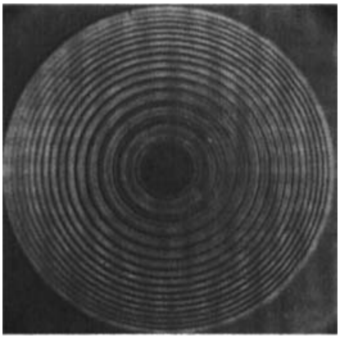


FIGURE 6 A micrograph of the polymer/LC zone plate under crossed polarizers.

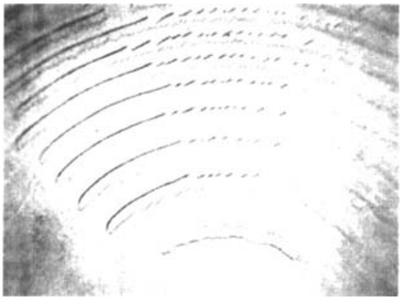


FIGURE 7 The observation of the disclination lines at 30s after switch on.

LC cells. Only two strings of disclination lines in per relief period are shown in Figure 7, because the other two strings have already disappeared. A loop structure of the disclination lines is also observed. The disclination lines disappear faster in the region with a smaller angle which means the angle between the alignment direction of LC molecules and the direction of the grooves. The results also indicate that the behaviors of the disclination lines are related to the angle between the alignment direction of LC molecules and the direction of the grooves. The zigzag structure of the disclination lines can be clearly observed around the limited region where the rubbing direction is perpendicular to the grooves. These phenomena are also similar to that in the disclination lines induced by the nonuniform electric field.[6]

5. CONCLUSIONS

In conclusion, the behaviors of the disclination lines have been investigated by microscope observation for the polymer/LC grating and the polymer/LC zone plate with a relief structure.

There are four strings of disclination lines (two pairs) appear in per period. Each pair of the disclination lines disappear in the same time. The pair of disclination lines in the ridge of the cured polymer disappear faster than those in the groove of the cured polymer, because the LC layer in former is thinner than that in latter. The results also indicate that the behaviors of the disclination lines are related to the angle between the alignment direction of LC molecules and the direction of the grooves. Moreover, the life times of the disclination lines depend on the applied voltage. The life times increase with increasing the applied voltage for both pairs of disclination lines.

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