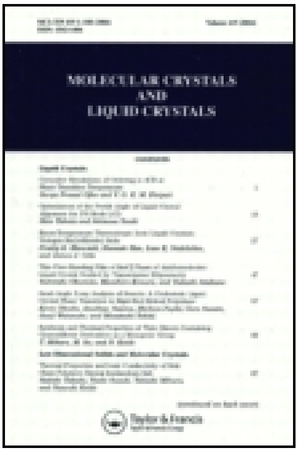

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Behavior of Disclination Lines Induced by a Nonuniform Electric Field in a Nematic Liquid Crystal Cell

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Behavior of Disclination Lines Induced by a Nonuniform Electric Field in a Nematic Liquid Crystal Cell

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The disclination lines appearing in the liquid crystal cell with a slit-patterned electrode structure are investigated in detail. Behaviors of disclination lines depend directly upon the motion of the reverse tilted molecular orientation domain, and there seem to be multi-stable molecular orientation states related to the disclination lines. Moreover, it is interesting that the disclination line has a zig-zag structure with a well-regulated folding period under appropriate conditions. These phenomena are discussed in terms of the molecular orientation effects in the nonuniform electric field.

Keywords: Disclination, molecular orientation, nonuniform electric field

1. INTRODUCTION

Liquid Crystal (LC) molecular orientation states in a nonuniform electric field, which are produced by a hole-patternd electrode structure, have been investigated so far.[1–3] In this case, axially symmetric distribution properties of refractive indices; that is, an LC microlens can be obtained. Its structure is so simple that it is easy to miniaturize and to make a lens array, and the unique point is variable-focusing. By using the molecular orientation effects in the nonuniform electric field, a new type of LC optical device can be obtained. However, it has also been confirmed that the disclination lines, which are induced by the nonuniform electric field, appear and deteriorate the optical properties. Since the generation of disclination lines leads to a fatal deterioration of lens properties, developing novel methods for the elimination of such disclination lines is an indispensable task for the utilization of the LC molecular orientation in the nonuniform electric field.

On the other hand, disclination lines related to the nonuniform electric field have also attracted much attention as a serious problem in a liquid crystal display (LCD),[4–6] especially in TFT panels, which have a complex electrode structure. It is very important to investigate the behavior of disclination lines induced by a nonuniform electric field not only for the LC microlens but also for the LCD.

Standing on such viewpoints, we have investigated the disclination lines by using the LC cell with a simple slit-patterned electrode structure. Textures and behaviors of disclination lines which are induced by the nonuniform electric field have been investigated for various experimental conditions.

2. EXPERIMENTAL

Figure 1 shows the electrode structure of the LC cell which has been prepared in this work. A slit-patterned electrode is made by etching the Al thin film deposited on a glass substrate, where the deposited Al film is sufficiently thin (about 100 Å) to become semitransparent. Unpatterned ITO-coated glass substrate is used as a counter electrode. Both surfaces of the electrodes are coated with polyvinyl alcohol (PVA) and treated by rubbing to obtain a homogeneous alignment of the LC molecules, where the rubbing direction is basically perpendicular to the slit pattern. The thickness of the cell t is 25 μm and the width of the slit pattern varies from about 200 μm to 800 μm by adopting the slit pattern with a small tapered angle about 4.5°. The exactly parallel slit-patterned structure is also adopted for some measurements. A nematic liquid crystal with a positive dielectric anisotropy (K15:BDH) is put into the cell.

3. BEHAVIOR OF THE DISCLINATION LINE

Figure 2 shows the transmission images of the LC cell for the voltage application of 1.7 V and 3 V, respectively. The frequency of the applied voltage is 1 kHz and the threshold voltage for the Freedericksz transition under the parallel electrode structure is about 1.2 V. A laser diode ($\lambda = 670$ nm) is used as a light source and the LC cell is settled between crossed polarizers. When voltage is applied across the LC cell, interference fringes appear according to the molecular reorientation and then a disclination line appears at a low voltage level under the slit-patterned electrode of the particular side as indicated by a small arrow. It is seen that the disclination line seems to bend and it tends to become straight with increasing voltage. The disclination lines observed in very low voltage (Fig. 2(a)) may include a transient effect, because it disappears in a long time interval and the situation is discussed later. In this lower voltage level, only one disclination line can be observed near the edge of the electrode, because the electric field inside the slit pattern is so weak that LC molecules are not yet reoriented.

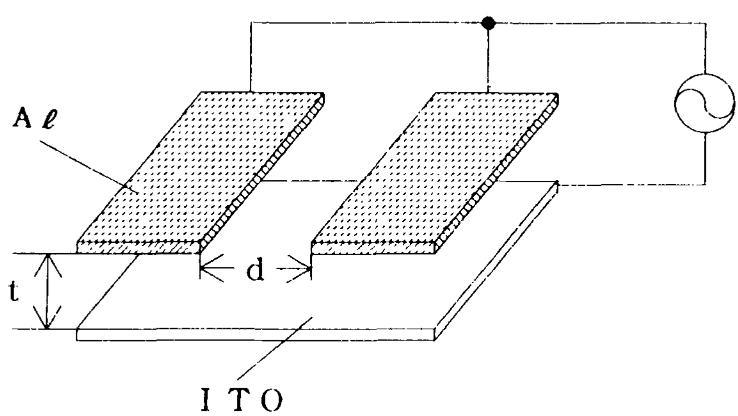


FIGURE 1 Schematic diagram of the LC cell with a slit-patterned electrode structure.

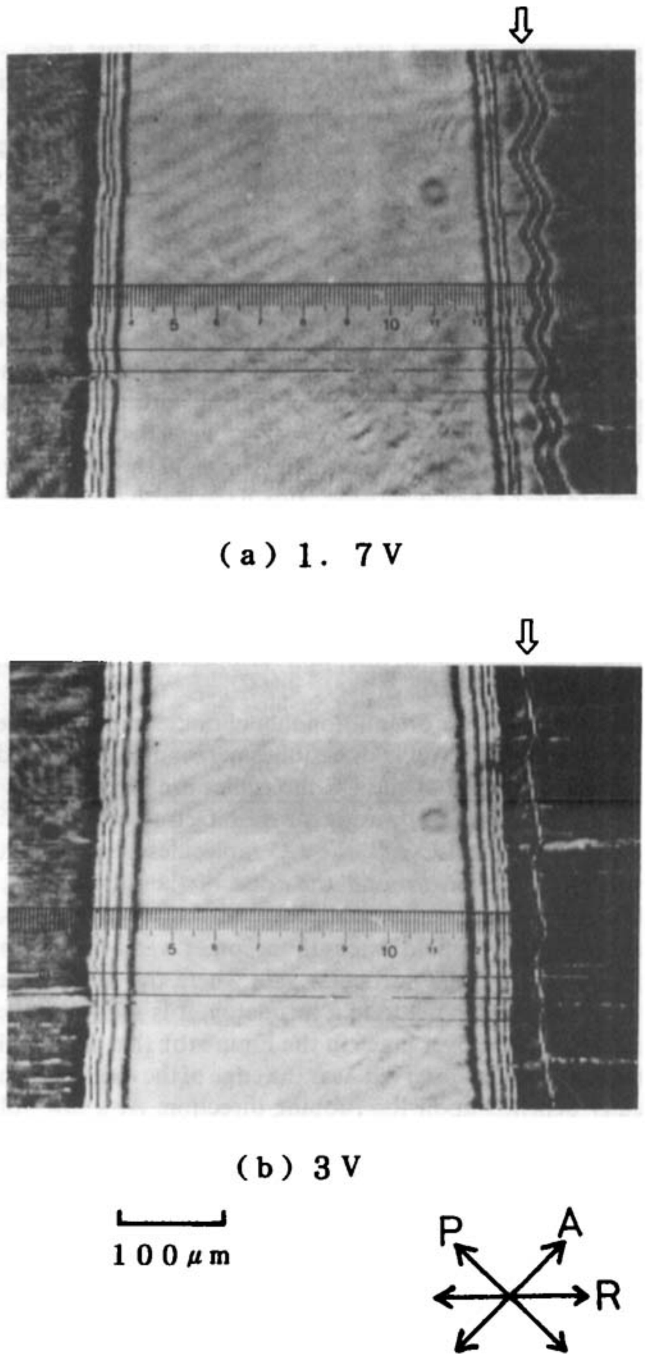


FIGURE 2 Transmission images of the LC cell for a lower voltage level, where the rubbing direction is perpendicular to the slit pattern. The applied voltages are (a) 1.7 V and (b) 3 V, respectively. P and A show the polarization direction of polarizer and analyzer, respectively. R is the rubbing direction.

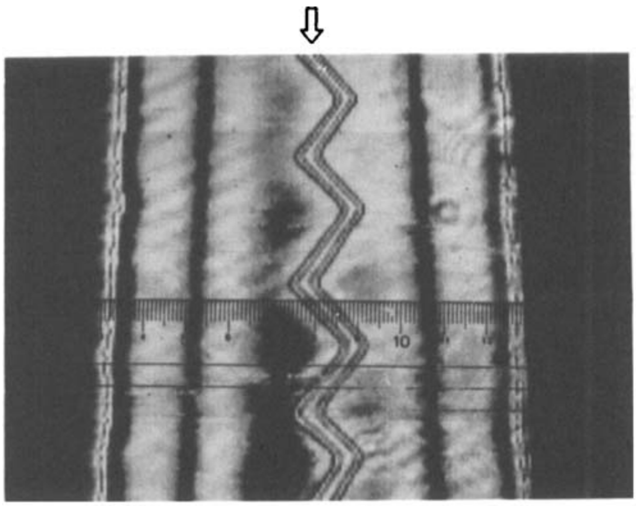
As the applied voltage increases, the LC molecules in the slit pattern also begin to tilt from the homogeneously aligned state. Around the voltage level where the LC molecules at the center of the slit pattern are also reoriented, another disclination line appears, as shown in Figures 3(a) and (b), where the applied voltages are 30 V and 50 V, respectively. A disclination line which appears in the lower voltage (Fig. 2) also exists under the electrode in both cases though this is not clear in the photos. It is very interesting that the disclination line has a folding structure with a well regulated period, although the rubbing direction and the directional force of the electric field are both in a plane perpendicular to the long direction of the slit pattern. It is seen that the folding angle tends to decrease and the shape becomes linear as the applied voltage increases. Such zig-zag structure can also be observed in the case of the disclination lines appearing under the electrode at low voltage as shown in Figure 2, but the dispersion of their folding periods is considerably large comparing with the case appearing at the center of the slit pattern.

Figure 4 shows the calculated distribution properties of the nonuniform electric field at the cross section of the LC cell, where the ratio of the width d to the separation t of the slit-patterned electrode is 2 which characterizes the electrode structure. Many lines in this figure show equipotential planes. It is seen that the intensity of the field is maximum around both the edges of the slit-patterned electrode and decreases as it approaches the center. Moreover, the direction of the field is most inclined around the edges of the patterned electrode and the inclined direction is opposite between the right-hand and left-hand sides.

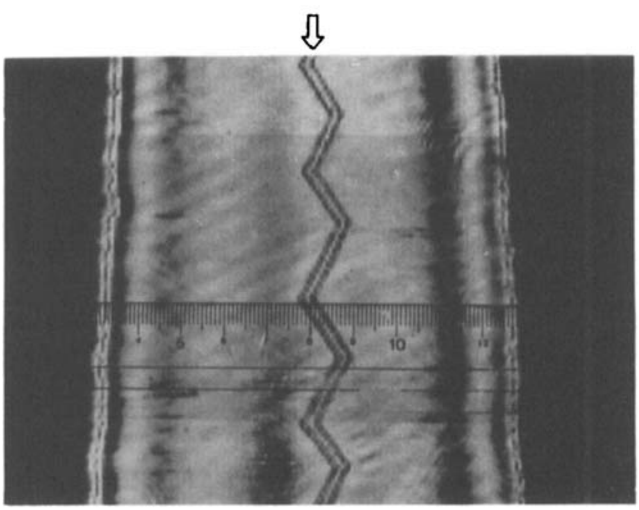
Figure 5 shows the molecular orientation model in the nonuniform electric field as shown in Figure 4, where the rubbing direction is perpendicular to the direction of the slit pattern. It is well known that the LC molecules are aligned on a surface of the substrate with a small pretilt angle by using the rubbing treatment (Fig. 5(a)). When the voltage is applied across the LC cell, the LC molecules begin to tilt according to the pretilt direction. However, around the edge of the slit pattern, the direction of the electric field strongly affects the tilt direction in the reorientation of the LC molecules, since the field strength becomes very large around the edge as is shown in Figure 4. On the particular side where the pretilt direction and the directional force of the electric field are a mismatch, it is seen that the reverse tilted domain appears as indicated by a brace in the Figure (b); that is, a disclination line at the low voltage can always be observed near the edge of the electrode on the particular side which usually depends upon the rubbing direction. At a low voltage level, the boundary at only one side of the reverse tilted domain shows clearly as indicated by a small arrow. Another boundary is not clear, because the molecular orientation is continuous and tilt angle varies gradually. Such a particular situation comes from the nonuniform electric field.

When a voltage becomes large enough, another boundary at the center also shows clearly, as is shown in Figure 5(c) by small arrows. Both disclination lines observed in Figures 2 and 3 are corresponding to the boundaries of the reverse tilted domain, and then these two disclination lines appear and disappear in pairs according to the behavior of the reverse tilted domain.

It became clear by the long time range observation that the disclination line appearing under the electrode was not so stable at a lower voltage. Then, the time until



3 0 V



(b) 5 0 V

FIGURE 3 Transmission images of the LC cell for a higher voltage level. The applied voltages are (a) 30 V and (b) 50 V, respectively. Here, the disclination line cannot be recognized under the electrode in this photo.

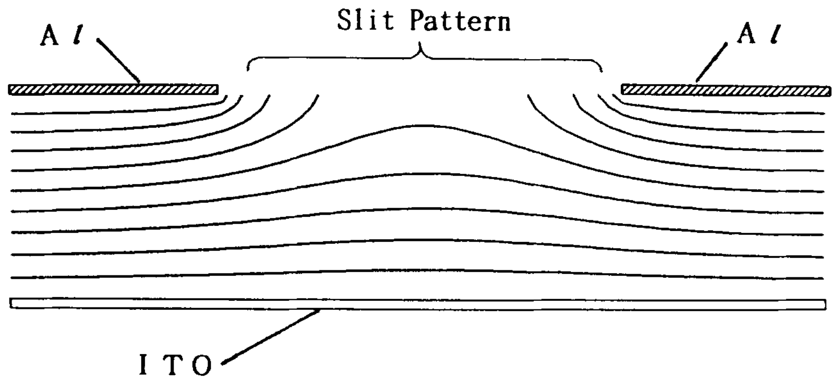


FIGURE 4 Distribution properties of the nonuniform electric field produced by the slit-patterned electrode structure.

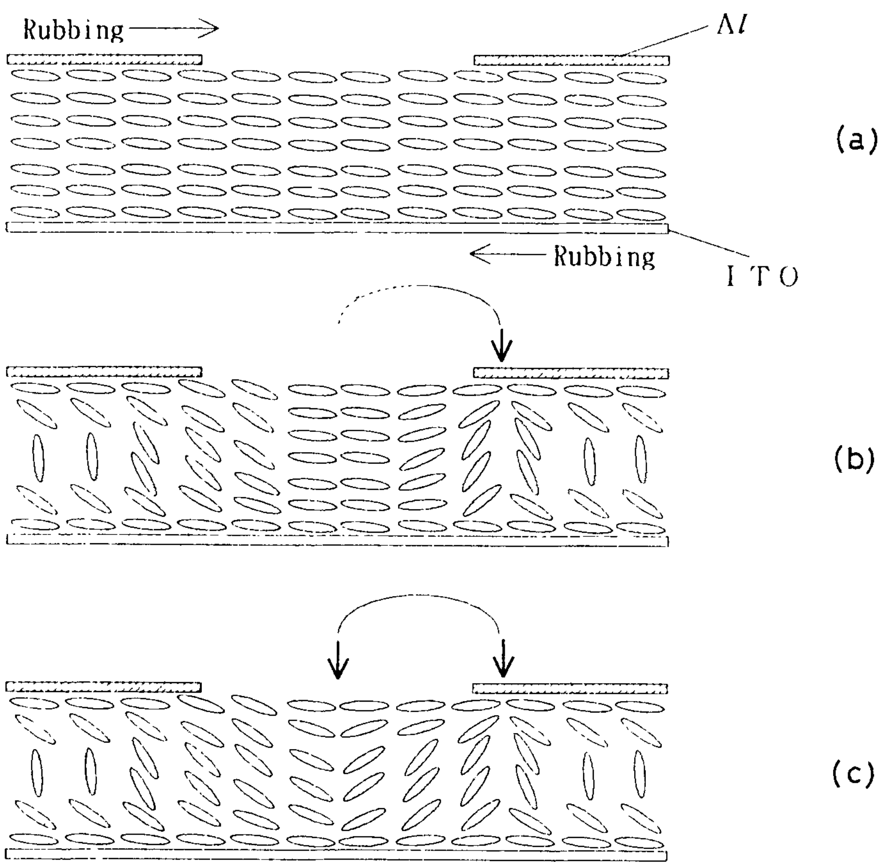


FIGURE 5 Molecular orientation models for various applied voltage levels.

the disclination line disappears (life time of disclination line) was measured as a function of the applied voltage, as shown in Figure 6. It is seen that the life span increases rapidly as the voltage approaches the critical value; that is, the disclination line becomes stable over this value, and there may be a threshold value for the stabilization of the disclination line.

If the voltage increases after the disclination line under the electrode disappears at low voltage, the disclination line cannot be observed any longer at the center of the slit pattern. This fact shows that another disclination-free molecular orientation state is also stable around the voltage level shown in Figure 3.

However, when the application of voltage is increased further in the disclination-free state, two disclination lines appear at the same time; that is, the reverse tilted domain is created around the edge of the patterned electrode. Once the disclination lines appear, they remain around a very low voltage level with decreasing voltage. Similar abrupt situations have been observed in the LC microlens which is utilizing the molecular orientation effects in an axially symmetric nonuniform electric field.[3] The disclination lines created by such very high voltage application may indicate the existence of one more different molecular orientation state from the cases described previously, as the zig-zag structure cannot be observed any longer even if the voltage decreases and reaches the same value in Figures 3(a) and (b), and both disclination lines disappear at the same time by combining each other at very low voltage. There may be multi-stable molecular orientation states related to the disclination lines induced by the nonuniform electric field. These molecular orientation states are also related to the transient molecular motion in the first stage of the voltage application, and it may be necessary to

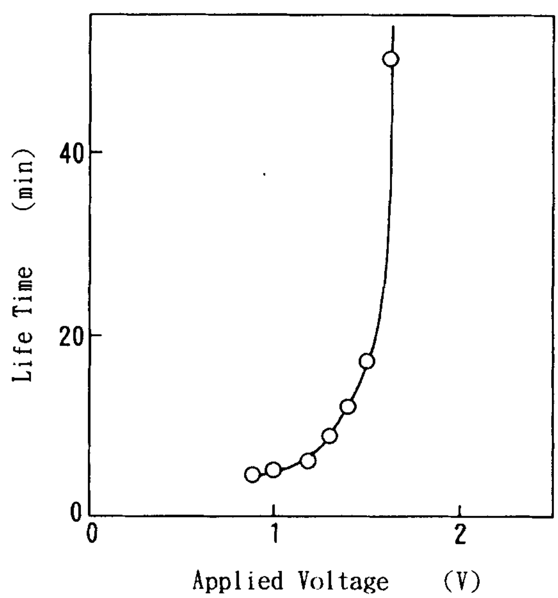


FIGURE 6 Life time of the disclination line observed under the electrode.

investigate the molecular orientation effects in more detail for understanding their microscopic phenomena.

4. ZIG-ZAG STRUCTURE OF THE DISCLINATION LINES

The appearance of the disclination lines related to the molecular orientation effects in the nonuniform electric field can be explained by the creation of the reverse tilted domain in the uniformly tilted molecular orientation state. But there seems to be more interesting behavior in the disclination line which shows the zig-zag structure, as shown in Figure 3. Since the zig-zag structure shows the twisted molecular orientation out of the plane along the rubbing direction, more detailed investigations are necessary for discussing such such phenomena. Figure 7 shows the dispersion properties of the folding periods in the zig-zag disclination line appearing at the center of the slit pattern. They were measured by using an exactly parallel slit-patterned electrode. There are some dispersions in the measured values, but the maximum value is coincident with the mean value.

The folding angle in the zig-zag structure decreases as the applied voltage increases; that is, the disclination line tends to become linear. However, the folding period itself seems to be almost independent of the voltage level. The nonuniform electric field distribution is determined by the slit-patterned electrode structure which is characterized by the ratio of the width d to the thickness t (Fig. 1). We have investigated the folding period for various electrode structures with different d/t values by varying the width d. But no clear relationship between the folding period and the width of the slit pattern can be observed.

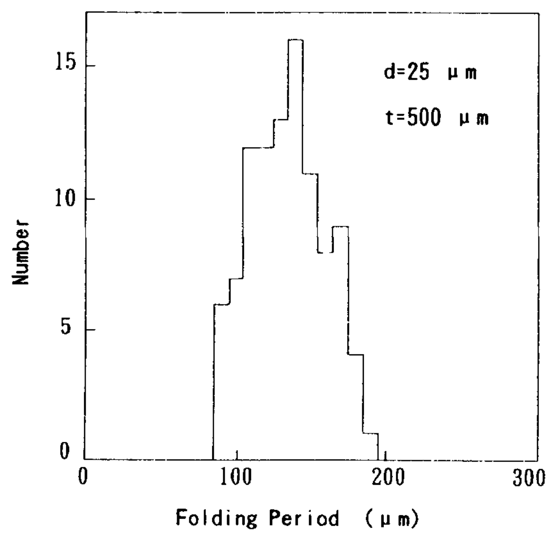


FIGURE 7 Dispersion properties of the folding period for the disclination lines which are observed at the center of the slit pattern.

On the other hand, the maximum value for various LC cells has a clear dependence on the thickness t, as shown in Figure 8. The folding period of the disclination lines is almost proportional to the thickness of the cell, and the value is about $4 \sim 5$ times the thickness of the LC cell.

When a rubbing direction is deviated from the direction perpendicular to the slit pattern, the zig-zag structure becomes asymmetrical, as shown in Figure 9(a), where θ is the angle between the rubbing direction and the long direction of the slit pattern. It is seen that the zig-zag structure disappears for the smaller angle of the rubbing direction, as shown in Figure 9(b).

The asymmetric factor of the zig-zag structure is defined as $R = s/l$, where l and s are the length of the long and short arms of the zig-zag disclination line, respectively. The relationship between the value of R and the rubbing direction is investigated as shown in Figure 10. When the zig-zag structure is symmetric, R becomes unity, and the value decreases as the symmetry decreases. Around the rubbing angle of 90°; that is, the rubbing direction is perpendicular to the slit pattern, R becomes maximum, and it decreases with the decreasing angle. At the rubbing angle of 90°, the R value is expected to become unity. The deviation of the experimental result may come from the dispersion of the folding angle and a small disagreement of the rubbing direction from 90°.

When the rubbing direction becomes about 65°, R becomes 0; that is, the zig-zag structure disappears around there and the straight-shaped disclination line is observed for the smaller value of the angle, as shown in Figure 9(b). It becomes clear that the

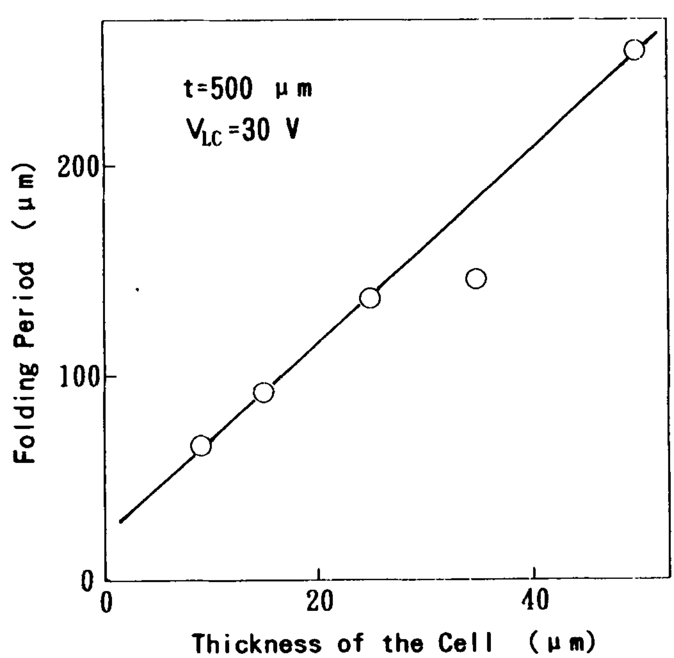


FIGURE 8 Relationship between the folding period of the zig-zag structure and the thickness of LC cell.

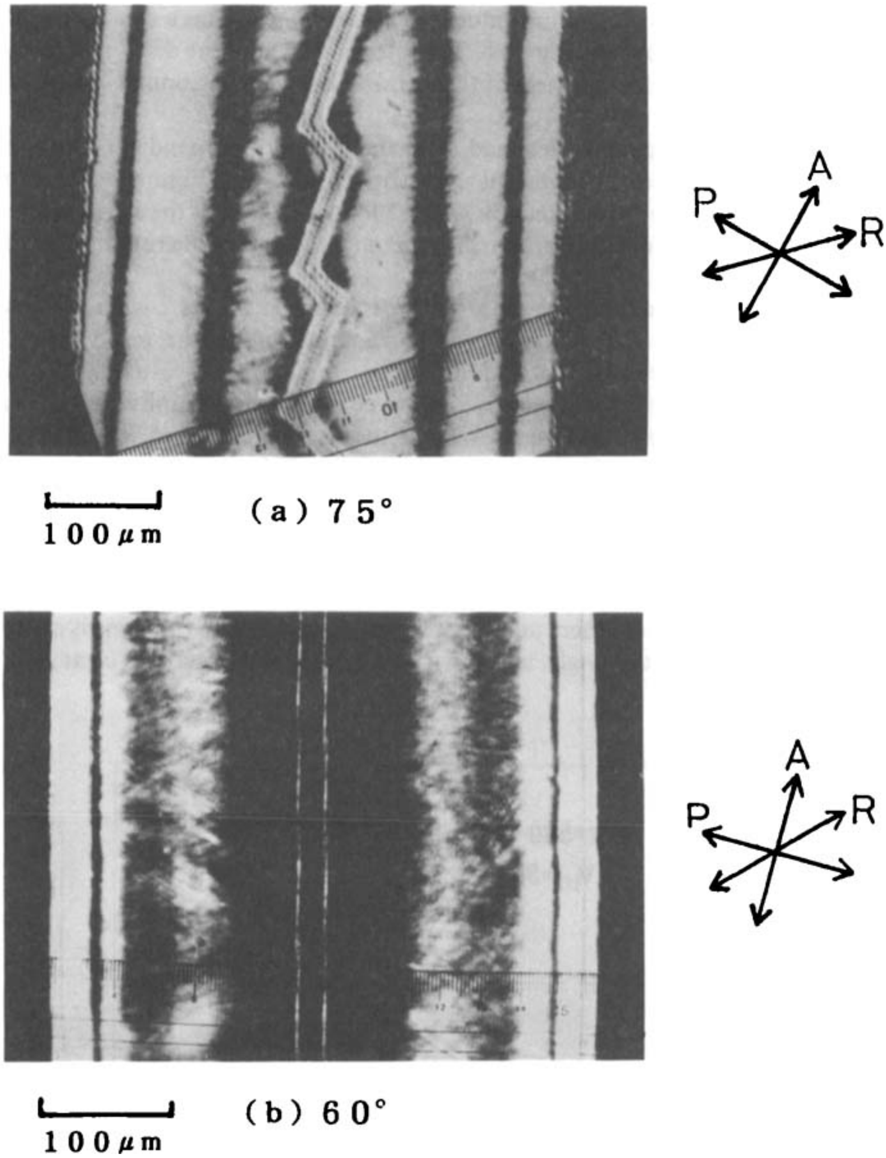


FIGURE 9 Structure of disclination lines observed in the LC cell of which rubbing direction is deviated from the direction perpendicular to the slit pattern. θ is the angle between the rubbing direction and the slit direction.

zig-zag disclination line can be observed within the deviation of $\pm 25°$ from the value of 90°. The origin of the zig-zag structure is not yet clear, but it is confirmed that the zig-zag structure can be observed only under such limited appropriate conditions.

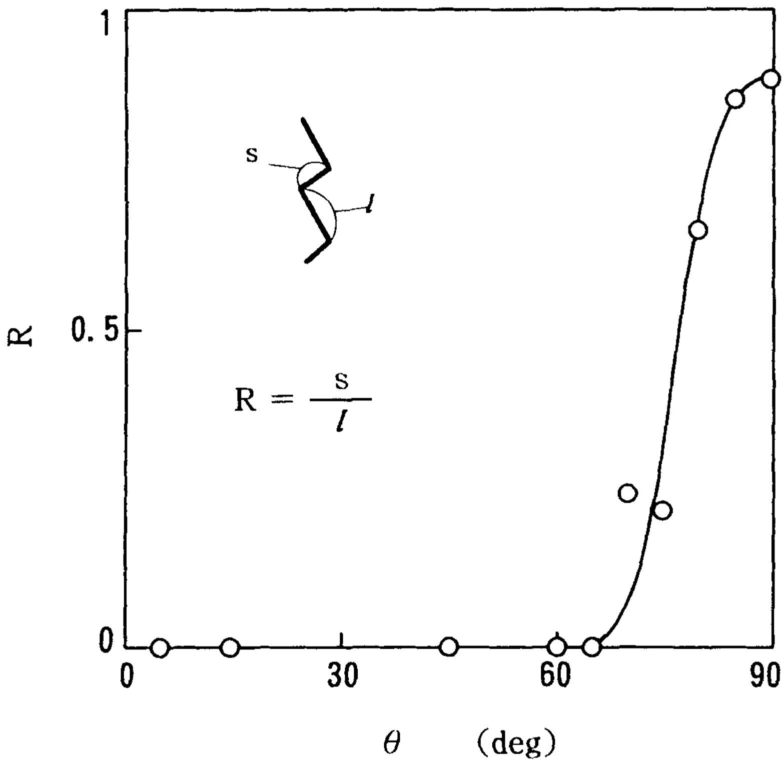


FIGURE 10 Relationship between the asymmetry factor R and the rubbing direction θ, where θ is the same parameter as in Figure 7.

5. CONCLUSIONS

The behavior of the disclination lines, which are induced by the molecular orientation effects in a nonuniform electric field, are investigated by using the LC cell with a slit-patterned electrode structure.

When an applied voltage is considerably low, a disclination line appears near the edge of one side of the slit-patterned electrode. As the voltage increases and the LC molecules within the slit pattern begin to align, another disclination line appears at the center of the slit pattern. Appearance of these disclination lines is corresponding to the creation of the reverse tilted domain which is produced in the uniformly tilted molecular orientation state.

The disclination line appearing under the electrode is unstable around the low voltage level. Once the disclination line disappears, any disclination lines cannot be observed even if the voltage increases; that is, there may be another stable disclination-free state. However, when very high voltage is applied, two disclination lines appear at the same time; that is, the molecular orientation becomes more stable state. These phenomena may show the multi-stability of the molecular orientation states related to the disclination lines induced by the nonuniform electric field.

One more very interesting fact is that the structure of the disclination lines becomes zig-zag with a well regulated folding period. More detailed investigations of the zig-zag phenomena are necessary to understand their geometrical structure and the origin of the folding structure. But it becomes clear at least that the zig-zag structure is related to the twist motion of the LC molecules and we can see it only under a very limited condition.

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