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A liquid crystal microlens obtained with a non-uniform electric field

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A homogeneously aligned nematic liquid crystal cell with a hole-patterned electrode and with an indium–tin oxide (ITO-) coated counter-electrode has been prepared. A non-uniform electric field can be produced by the asymmetrical electrode structure. The liquid crystal director can be reoriented by applying a voltage across the electrodes, and this produces an axially symmetrical profile of the refractive index. This liquid crystal cell is expected to have a lens effect and so its optical properties have been investigated. The profile of the output light intensity was measured by using a detecting system with an optical fibre. Some relationships between the lens properties, the diameter of the hole and the thickness of the liquid crystal layer have been examined. The liquid crystal cell becomes a convex (converging) lens with a relatively low voltage. A focal length of several millimetres can be obtained by applying voltages of 3–4 V. As the applied voltage increases, the focal length becomes longer, and the cell changes to a concave (diverging) lens when a high voltage is applied ($\gtrsim 20$ V). These properties are discussed from the viewpoint of the director orientation effects resulting from the non-uniform electric fields in the cell.

1. Introduction

The director orientation in liquid crystal cells can easily be controlled by surface treatment of the substrates; the optical properties of the liquid crystal cells can be changed by applying a relatively low electric field across the cells. The application of the cells as display devices has been well investigated. In addition to display devices, some applications of liquid crystals as optical devices such as a liquid crystal prism [1] and lenses [2, 3] have recently been reported. In most conventional liquid crystal display devices the director is reoriented by a uniform electric field produced by a pair of plane parallel electrodes. However, the liquid crystal director can also be reoriented by a non-uniform electric field [4–7] and new optical devices can be produced by using this effect.

In this work a homogeneously aligned liquid crystal cell was prepared so that a non-uniform electric field could be produced by the asymmetric electrode structure with a hole-patterned electrode and with an indium–tin oxide (ITO-) coated counter-electrode. These liquid crystal cells are expected to have an axially symmetric distribution of refractive indices, and new liquid crystal optical devices are expected. The optical properties of the cell have been measured and they are discussed in terms of the director orientation effects resulting from the non-uniform electric field in the cell.

2. Experimental

Liquid crystal cells with asymmetric electrodes were prepared by using a hole-patterned electrode and an ITO-coated counter-electrode. The hole-patterned electrode was made from thin aluminium films deposited on glass substrates

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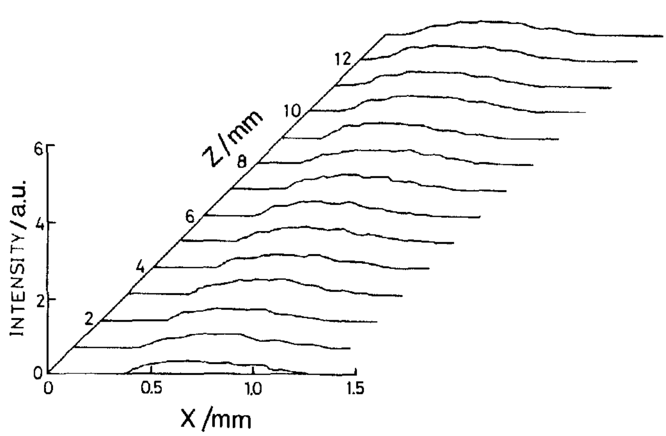
photolithographically. Both electrode surfaces were treated with polyvinylalcohol (PVA) and by rubbing to give a homogeneous orientation. A nematic liquid crystal with positive dielectric anisotropy (BDH Chemicals; K15) was placed in the cells fabricated with a polymer spacer of suitable thickness, the substrate with the hole-patterned electrode and the ITO-coated glass plate.

A He–Ne laser was used as a collimated light source and the direction of polarization was adjusted to be an extraordinary ray. The intensity profile of the transmitted light through the cell was measured by using a detecting system with an optical fibre (diameter 100 μm). One end of the fibre was connected to a photodiode and the other end was fixed on an *XY* stage. The incident light into the end of the fibre was guided to the photodiode. The *XY* stage could be moved along both axes parallel and perpendicular to the direction of the laser beam. In this way some relationships between the optical properties and the diameter of the hole pattern and the thickness of the liquid crystal cell were measured as a function of the applied voltage.

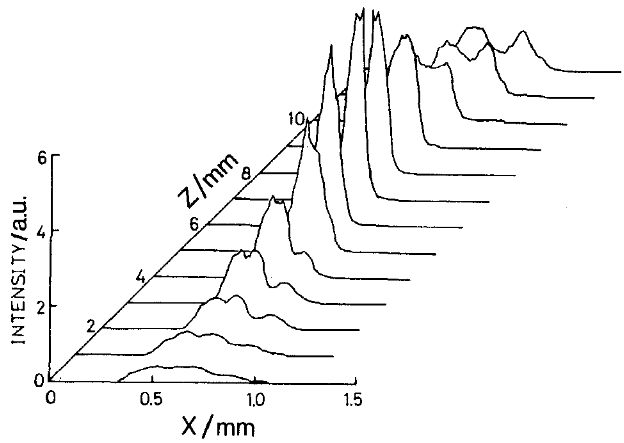
To examine the lens properties by another method, photographs of the image of a character through this microlens were taken by using a microscope system.

3. Results

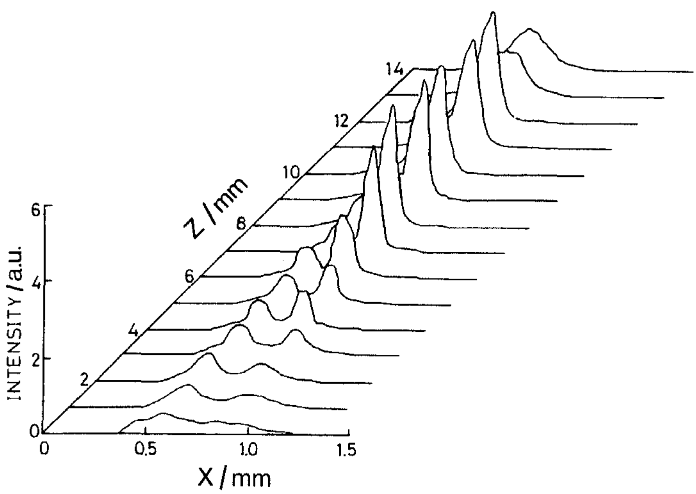
Experimental results for the transmitted light intensity profile through the liquid crystal cell are shown in figures 1 (*a*)–(*d*); the diameter of the hole-pattern was 750 μm and the thickness of the liquid crystal layer was 50 μm. The direction of the *X* axis was perpendicular to that of the laser beam; that is, parallel to the surface of the cell. The *Z* axis shows the direction of the laser beam, and its value is the distance from the surface of the liquid crystal cell. Figure 1 (*a*) shows the light intensity profile without an applied voltage. It is seen that no focussing effects are observed and the profile of the output light beam through the cell is unchanged. The liquid crystal cell behaves just as a transparent plate with a small hole. Figure 1 (*b*) shows the light intensity profile for a relatively low voltage (4 V). In this case the beam width through the hole pattern becomes narrower as the distance from the cell increases. The peak of the light intensity becomes maximum at the point where $Z = 6$ mm (i.e. the focal point); a focussing effect has therefore appeared. These results show that the liquid crystal cell becomes a convex (converging) lens for a relatively low voltage.



(*a*)



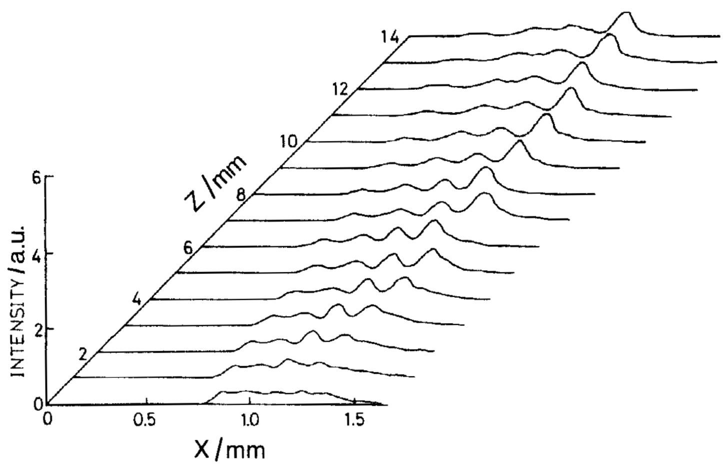
(*b*)



(*c*)

Figure 1 (*c*) shows the light intensity profile for a higher voltage (8 V). The distance between the peak point and the cell surface becomes large; that is, the focal length of this converging lens increases as the voltage increases. When a high voltage ($\gtrsim 20$ V) is applied across the liquid crystal cell, the peak of the light intensity cannot be observed and the width of the beam becomes gradually wider as the distance from the cell increases, as shown in figure 1 (*d*). This result shows that the liquid crystal cell acts as a convex (diverging) lens for a high voltage.

It is seen that the liquid crystal microlens can be constructed using an axially symmetric electric field. The focal length of this lens is several millimetres and depends on the applied voltage. The focal length of the microlens increases with the voltage and finally the liquid crystal cell changes to a diverging lens. By using a CCD linear

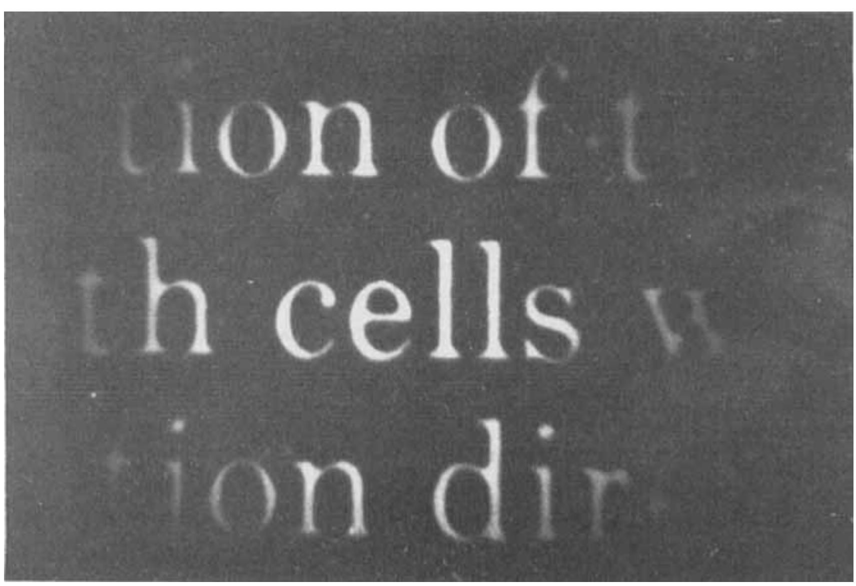


(*d*)

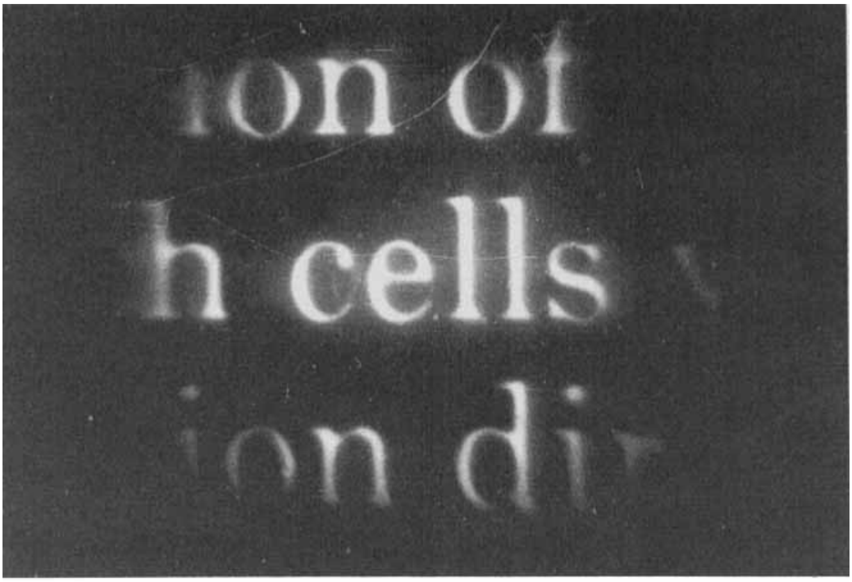
Figure 1. Light intensity profiles through the cell for various applied voltages: (*a*) $V_{LC} = 0\,V$; (*b*) $V_{LC} = 4\,V$; (*c*) $V_{LC} = 8\,V$ and (*d*) $V_{LC} = 20\,V$.

array sensor the spot size of the converging lens was measured; it was $< 20\,\mu m$ under suitable conditions.

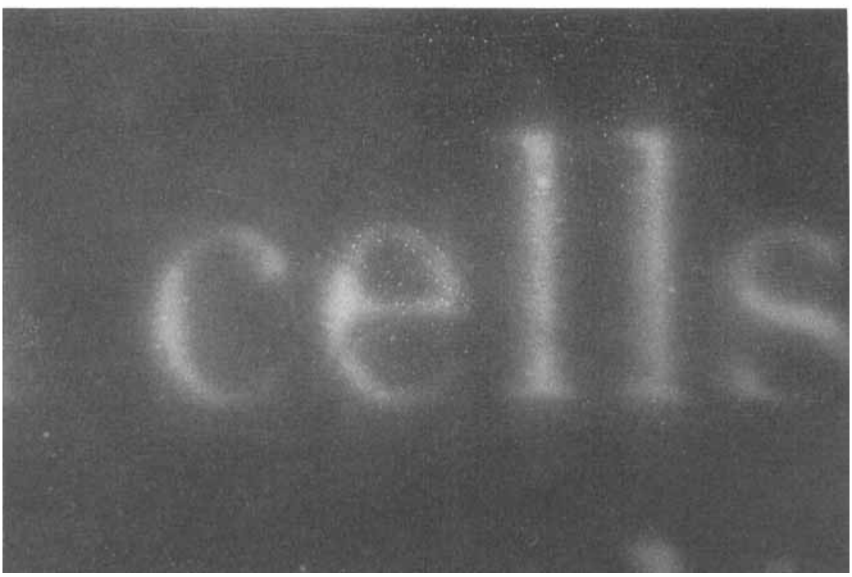
Figures 2(*a*)–(*e*) show the images of some characters observed through the hole pattern by using a microscope, for various applied voltages. Figure 2(*a*) shows the image without the applied voltage and figure 2(*b*) shows the same image with an



(*a*)

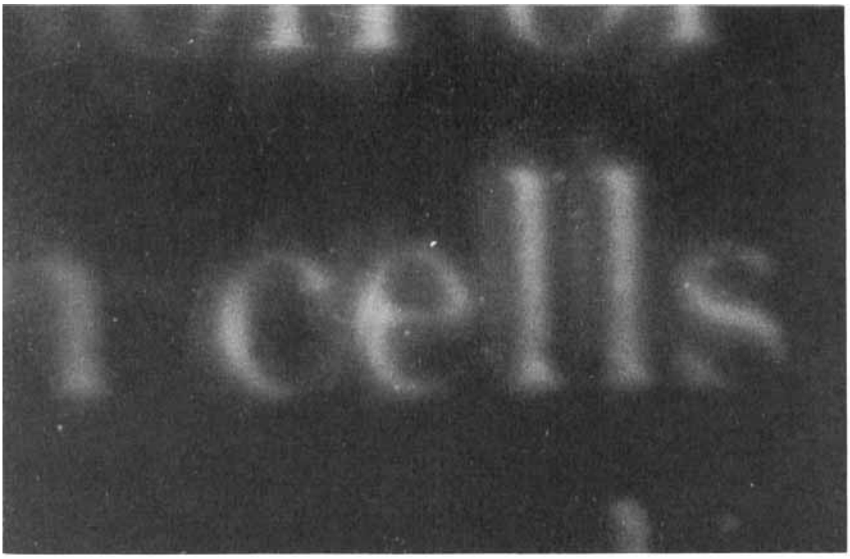


(b)

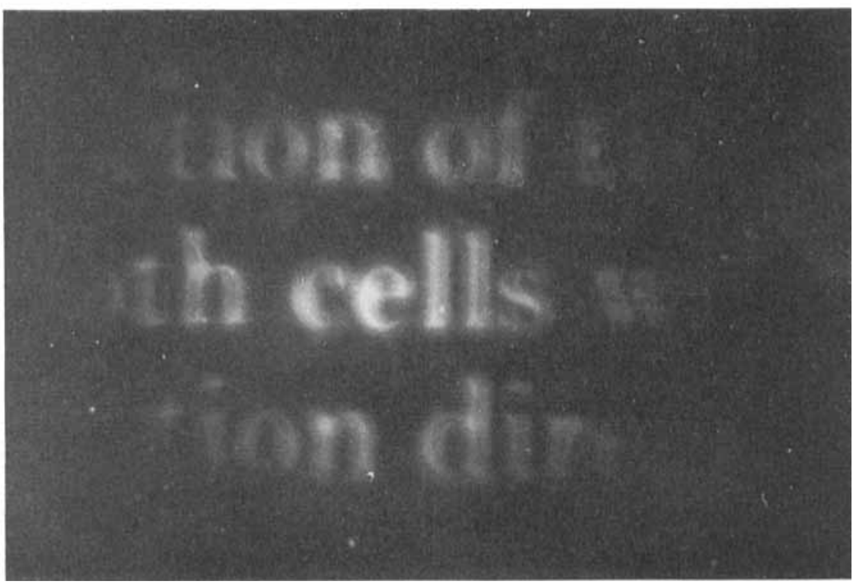


(c)

applied voltage of 2 V. It is seen that the size of the character image becomes larger with the voltage increase. This result also shows that the liquid crystal cell acts as a converging microlens. When the voltage is 4 V, as shown in figure 2 (c), the size of the image becomes a maximum, where the focal length becomes a minimum. Figure 2 (d) shows the image when the applied voltage is 6 V. In this case the size of the image



(*d*)



(*e*)

Figure 2. Images of some characters through the cell for various applied voltages: (*a*) $V_{LC} = 0\,V$; (*b*) $V_{LC} = 2\,V$; (*c*) $V_{LC} = 4\,V$; (*d*) $V_{LC} = 8\,V$ and (*e*) $V_{LC} = 20\,V$.

becomes smaller than that shown in figure 1 (*c*), and then the focal length becomes longer. Figure 2 (*e*) shows the image when the applied voltage is 20 V, where the size of the image is smaller than that of the initial size shown in figure 2 (*a*). The microlens seems to have a negative focal length; that is, the liquid crystal cell becomes a diverging lens. These experimental results are confirmed by the results shown in figure 1.

4. Discussion

The optical properties of the liquid crystal cell with a hole-patterned electrode and with a plane electrode can be discussed in terms of the director orientation effects resulting from the non-uniform electric field inside the cell. Figure 3 shows a cross section of the liquid crystal cell along the diameter of the hole-pattern, where the electric field produced by the hole-patterned electrode and by a plane electrode is shown as small arrows. The lengths of arrows correspond to the field strength and the directions show that of the field. Two important factors should be noticed in this non-uniform electric field at the hole pattern; that is, the distribution of the field intensities and that of the field directions. The intensity of the electric field becomes a maximum at the edge of the hole pattern and it becomes smaller approaching its centre. Similarly, the angle between the direction of the electric field and the direction perpendicular to the substrate becomes a maximum at the edge of the hole pattern. At the centre of the hole pattern the direction of the electric field becomes perpendicular to the substrate because of the symmetry.

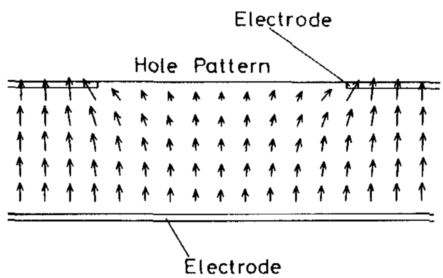


Figure 3. Cross section of the non-uniform electric field produced by a hole-patterned electrode and a plane electrode in the cell.

The situation of the director orientation in the liquid crystal cell is controlled by the non-uniform distribution of the electric field. Figures 4 (*a*)–(*c*) show models for the director orientation in this non-uniform electric field. Figure 4 (*a*) shows the director orientation without the applied voltage, where the director is uniformly oriented parallel to the surface of the substrates. The refractive index is n_e (extraordinary ray) and its distribution is uniform. Then the liquid crystal cell is the same as a transparent flat panel.

Figure 4 (*b*) shows the director orientation in the cell when the applied voltage is relatively low. In this case the director near the edge of the hole pattern is forced to align along the directions of the electric field. Then the refractive index near the edge becomes smaller than the value of n_e. The director near the centre of the hole pattern, however, remains parallel to the substrate, and so the refractive index does not change and is n_e. In this non-uniform director orientation the refractive index gradually changes from the minimum value at the edge of the pattern to the maximum value of

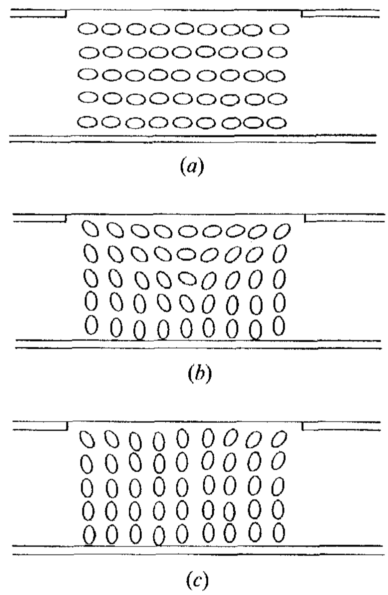


Figure 4. Models for the director orientation produced by the non-uniform electric field in the cells: (*a*) No voltage; (*b*) relatively low voltage and (*c*) relatively high voltage.

n_e at the centre. Then the liquid crystal cell is expected to behave like a graded index converging lens. When the applied voltage increases, the director near the centre of the hole pattern begins to move and the refractive index at the centre also becomes smaller than n_e. Then the gradient of the refractive index becomes less steep and the focal length becomes longer. The experimental results shown in figures 1 (*b*) and (*c*) and figure 2 (*c*) and (*d*) confirm this model.

Figure 4 (*c*) shows the director orientation under high applied voltages, where the director is oriented almost perfectly along the direction of the non-uniform electric field. The director near the edge of the hole pattern is tilted along the direction of the electric field. On the other hand, the director near the centre of the hole pattern is oriented perpendicular to the substrate. In this case the refractive index near the edge of the hole pattern takes the maximum value, which is determined by the tilt angle at the edge, between n_e and n_o for the refractive index of the ordinary ray. The refractive index becomes smaller with decreasing distance from the centre of the hole pattern, and it tends to be minimum value of n_0 for the refractive index of the ordinary ray. In this case the distribution profile of the refractive index is opposite to that shown in figure 4 (*b*), then the liquid crystal cell behaves like a diverging lens under a high applied voltage. This explanation is confirmed by the experimental results shown in figures 1 (*d*) and 2 (*e*).

5. Conclusions

A homogeneously aligned liquid crystal cell with a hole-patterned electrode and with an ITO-coated counter-electrode has been prepared. The liquid crystal director is reoriented by a non-uniform electric field and an axially symmetric profile of the refractive index is achieved. The liquid crystal cell becomes a convex (converging) lens with a relatively low voltage. The focal length of several millimetres is obtained by applying voltages of about 3–4 V. As the applied voltage increases, the focal length becomes longer, and the liquid crystal cell changes to the concave (diverging) lens for high voltages ($\gtrsim 20$ V). These properties can be explained from the director orientation effects by the non-uniform electric fiels in the liquid crystal cell.

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