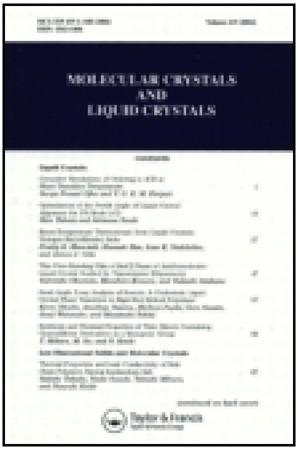

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Optical Properties of a Hybrid-Aligned Liquid Crystal Microlens

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Optical Properties of a Hybrid-Aligned Liquid Crystal Microlens

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Microlens effects have been obtained in homogeneously aligned liquid crystal cells prepared using a hole-patterned electrode and a plane electrode. In the asymmetric electrode structure, an axially symmetric non-uniform electric field is produced and a radial distribution of refractive indices can be obtained by the molecular orientation effects in the non-uniform electric field. However, a disclination line which makes the optical properties worse is observed in the homogeneously aligned microlens when a voltage is applied across the cell. In order to improve the lens properties, hybrid-aligned liquid crystal microlens cells are prepared. Their optical properties are investigated and discussed in terms of a molecular orientation model in the non-uniform electric field of the hybrid-aligned cell.

Keywords: microlens, optical devices

1. INTRODUCTION

In the conventional liquid crystal display devices, liquid crystal molecules are reoriented by using a uniform electric field which is produced by a pair of plane and parallel electrodes. However, the molecules can be reoriented by using a non-uniform electric field. The non-uniform molecular orientation; that is, the spatial distribution of the refractive indices can be obtained and new types of liquid crystal optical devices can be attained.[1-6] According to this concept, a homogeneously aligned liquid crystal cell which has an asymmetric electrode structure with a hole-patterned electrode and a plane electrode, and their optical properties have been investigated.[5] In this cell, the non-uniform molecular orientation; that is, the radial distribution of the refractive indices can be attained by the molecular orientation effects in the non-uniform electric field with an axially symmetric distribution of the intensities and the directions, then the lens properties (liquid crystal microlens) can be obtained. The properties of the liquid crystal microlens can be selected among flat properties, converging properties and diverging properties according to the applied voltage levels. Then, an application to the optical fiber switch or the coupler with variable coupling efficiency has been demonstrated.[4] The structure of the lens is so simple that it is easy to make a quite small lens and to arrange a large number of lenses. Focal length of the microlens is so short that light scattering properties can be obtained through the cell, then the display devices with the light scattering properties have been investigated by preparing the liquid crystal cell with a great number of microlenses in it.[6]

However, in the homogeneously aligned liquid crystal microlens, a disclination line which makes the lens property worse is observed in the perpendicular direction of the molecular orientation when a relatively low voltage is applied; that is, with the voltage level of the converging lens properties. The generation of the disclination line may be attributed to the fact that the initial homogeneous molecular alignment is different from the axially symmetric distribution of the induced non-uniform electric field. In this work, the surface of the hole-patterned electrode was treated for the homeotropic molecular orientations and ITO glass substrate as the counter electrode was treated by PVA and rubbing; that is, the hybrid-aligned[7] liquid crystal microlens cells were prepared and their optical properties were investigated. These results will be discussed with a molecular orientation model of the hybrid-aligned liquid crystal microlens.

2. EXPERIMENTAL

A patterned electrode was prepared using an A1 thin film deposited on a glass substrate and the hole-patterns were made by chemical etching with a photolithographic method. The surface of the hole-patterned electrode was treated by ZLI-3124 (Merck) to give a homeotropic molecular orientation. On the other hand, the surface of the ITO glass substrate was treated by PVA and rubbing to give a homogeneous molecular orientation. A nematic liquid crystal material with a positive (K15:BDH) or a negative dielectric anisotropy (ZLI-4318:Merck) was put into the cell and hybrid-aligned liquid crystal cells were prepared. A He-Ne laser was used as a light source and the light intensity profiles passed through the microlens were measured by CCD linear array sensor (Toshiba:TCD106C) which was fixed on an X-Y-Z stage. The size of a picture element of the CCD sensor is 7 μm, which determines the resolution of measurements. The light was incident from the ITO glass substrate and the polarization direction was adjusted parallel to the molecular orientation direction. Some relations between the lens properties and the lens parameters such as the diameter, the thickness and the applied voltage were investigated. By using a He-Ne laser and a polarization microscope system with a CCD camera and a personal computer, interference fringes produced by the interference between the ordinary and the extraordinary rays were measured and spatial distribution of refractive indices in a hole-pattern was investigated.

3. RESULTS AND DISCUSSION

3.1 Liquid Crystal Microlens with Positive Dielectric Anisotropy

Typical transmission light intensity profiles through the hole-patterned electrode in the hybrid-aligned liquid crystal microlens with a positive dielectric anisotropy are shown in Figures. 1 (a)–(c), where the diameter of the pattern is 250 μm and the thickness of the cell is 50 μm. Figure 1 (a) shows the light intensity profile

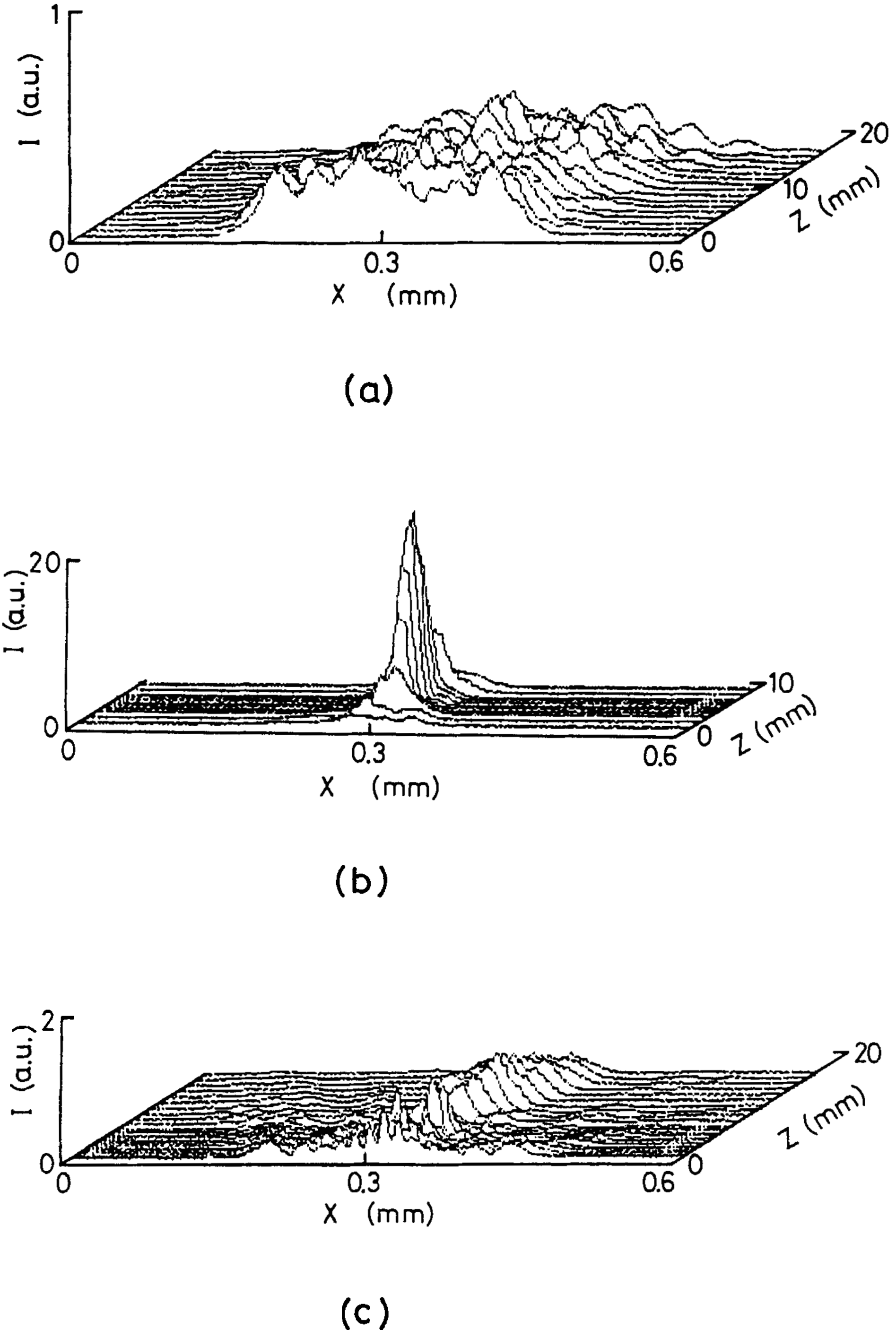


FIGURE 1 Light intensity profiles through the liquid crystal microlens with a positive dielectric anisotropy. The diameter of the hole-pattern is 250 μm and the thickness is 50 μm. (a) V_{LC} = 0 V; (b) V_{LC} = 1 V; (c) V_{LC} = 4 V.

without voltage. The X axis shows the direction of a diameter of the hole-pattern. The Z axis is perpendicular to the surface of the cell and parallel to the direction of light incidence. There are no focusing properties and the incident light passes through the hole-pattern without changing its intensity profile. As shown in Figure 1 (b), converging properties can be obtained with a relatively low applied voltage of 1 V. In this case, focal length is about 6 mm, which is considerably longer than that of the homogeneously aligned microlens with the same diameter, the thickness and the voltage level.[5] The maximum variation of the effective refractive index across the liquid crystal layer in the hybrid-aligned cell is smaller than that of the homogeneously aligned cell, however, very high intensities and sharp focusing properties are obtained comparing with the homogeneous lens cell. The minimum spot size at the focal point was measured as small as one picture element of the CCD sensor. When the applied voltage increases, the cell changes to the concave lens and a diverging property can be obtained as shown in Figure 1 (c), where the applied voltage is 4 V.

Figures 2 (a)–(d) show the fringe patterns produced by an interference of the ordinary and the extraordinary rays in the hybrid-aligned microlens with the diameter of 450 μm and the thickness of 50 μm, where the applied voltages are 0 V, 1 V, 2 V, and 25 V, respectively. Since a He-Ne laser was used as a mono-

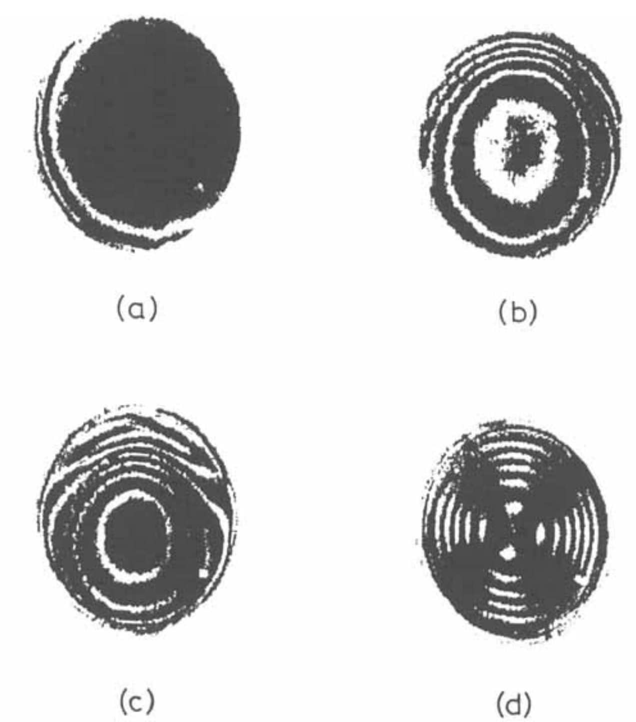


FIGURE 2 Interference fringe patterns for various applied voltages observed by the polarization microscope systems. The diameter of the hole-pattern is 450 μm and the thickness is 50 μm. (a) V_{LC} = 0 V; (b) V_{LC} = 1 V; (c) V_{LC} = 2 V; (d) V_{LC} = 25 V. In this figure, the ratio between the horizontal scale and the vertical scale is 7/8.

chromatic light source, the optical path difference (retardation) according to one fringe is 0.633 μm. The maximum retardation is about the half of the homogeneously aligned cell with the same thickness. When a voltage is applied across the cell, the molecules around the edge of the hole-pattern begin to tilt at first because of the non-uniformity of the electric field. According to this molecular reorientation, a circular fringe pattern appears around the edge of the hole-pattern and its diameter becomes smaller with increasing the voltage, then the next fringe appears. Consequently, concentrically circular patterns can be observed.

The fringe patterns with a voltage of 1 V and 2 V are shown in Figures 2 (b) and (c), respectively. Any disclination lines as being observed in the homogeneously aligned cell are not observed but the center of the fringe patterns shifts from that of the hole-patterned electrode. In the homogeneously aligned microlens, two domains divided by the disclination line with the opposite tilting direction of the molecules are formed when a voltage is applied. On the other hand, the tilt direction is uniform in the hybrid-aligned microlens cell, because the direction tends to be defined by the initial molecular orientation. The strain which generates the disclination line in the homogeneously aligned cell may be released by shifting the center of the axially symmetric molecular orientation. Since there is no disclination line in the hybrid-aligned lens cell, the very sharp focusing property can be obtained with a low voltage as shown in Figure 1 (b).

When the voltage increases and becomes a middle voltage level between the converging property and the diverging property, the fringe patterns become very confused. However, when the applied voltage is sufficiently high, the molecules are forced to align along the electric field almost all over the hole-pattern. Then the concentrically circular fringe patterns without displacement of the center are observed and the radial dark lines according to the direction of the polarizer and analyzer appear as shown in Figure 2 (d). In this case, the molecular orientation profile is axially symmetric and the refractive index becomes smaller as approaching the center; that is, the diverging property can be obtained.

Figures 3 (a)–(c) show a molecular orientation model in a cross section of the cell along the diameter for the hybrid-aligned liquid crystal microlens with a positive dielectric anisotropy. The model is based on the calculated results of the non-uniform electric field and the molecular orientation in this field. Figure 3 (a) shows the molecular orientation model without voltage. The molecules near the ITO glass substrate align parallel to the surface and the tilt angle of the molecules gradually increases until the value of 90° at the upper substrate (hole-patterned electrode).

When the voltage is applied across the electrodes, an axially symmetric electric field can be produced in this asymmetric electrode structure with a hole-pattern and a plane. In the upper half side across the thickness (near the hole-patterned electrode), the intensity of the electric field around the edge of the hole-pattern is maximum and it decreases approaching the center. Similarly, the angle between the electric field and normal direction of the substrate is maximum at the edge of the hole-pattern and it becomes smaller approaching the center. On the other hand, in the lower side across the cell, the direction of the electric field tends to be uniformly perpendicular to the substrate but the intensity decreases approaching the center.

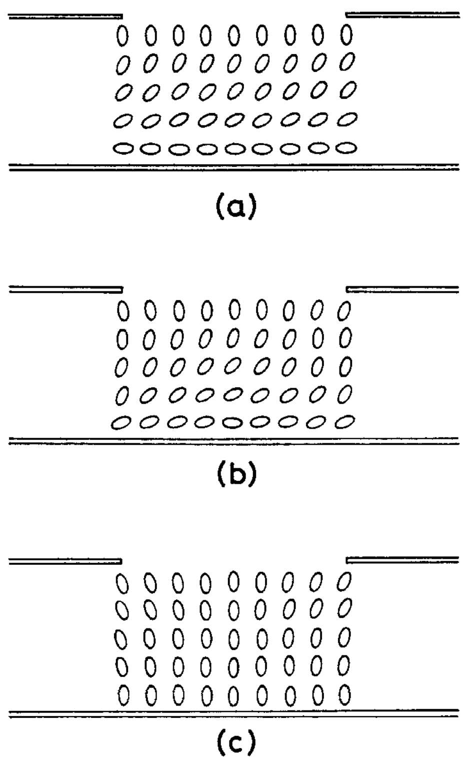


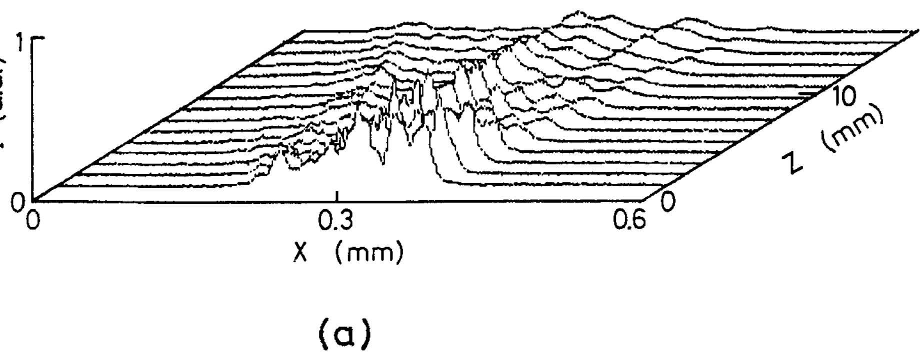
FIGURE 3 A molecular orientation model of the hybrid-aligned microlens with a positive dielectric anisotropy. (a) No applied voltage; (b) relatively low applied voltage; (c) high applied voltage.

A molecular orientation model with a relatively low applied voltage is shown in Figure 3 (b). In the upper side of the cell, only the molecules near the edge of the hole-pattern can be reoriented from the initial perpendicular direction. Therefore only a weak diverging effect can be obtained from this region. On the other hand, in the lower side, the tilt angle of the molecules is varied according to the intensity distribution of the electric field and the converging property can be obtained. As a total effect across the liquid crystal layer, the converging property can be obtained with a low applied voltage as shown in Figure 1 (b). The tilt direction must be uniform because it is determined by the initially treated orientation as shown in Figure 3 (a).

Figure 3 (c) shows a model with a sufficiently high applied voltage. The non-uniform molecular orientation along the axially symmetric electric field can be attained. It is especially obvious in the upper side of the lens cell that the tilt angle is minimum around the edge of the hole-pattern and it becomes larger until the value of 90° as approaching the center, then the spatial distribution of the refractive indices as the diverging lens property can be obtained.

3.2 Liquid Crystal Microlens with Negative Dielectric Anisotropy

Figures 4 (a) and (b) show the light intensity profiles through the hybrid-aligned microlens with liquid crystal materials of a negative dielectric anisotropy, where



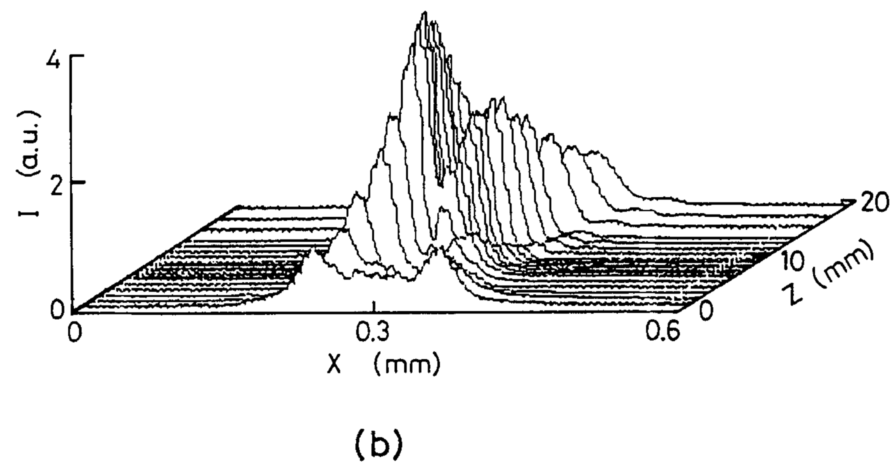


FIGURE 4 Light intensity profiles through the microlens with a negative dielectric anisotropy, where the diameter of the hole-pattern is 250 μm and the thickness of the cell is 50 μm. (a) V_{LC} = 2 V; (b) V_{LC} = 80 V.

the diameter of the hole-pattern is 250 μm and the thickness of the cell is 50 μm. In this case, the long axis of the molecules tends to align perpendicular to the direction of the electric field, therefore, inverse distribution properties of the refractive indices are obtained as compared with the liquid crystal microlens with a positive dielectric anisotropy. The light intensity profile without voltage is almost the same as shown in Figure 1 (a). Figure 4 (a) shows the light intensity profile with the applied voltage of 2 V. It is seen that the diverging property can be obtained with a relatively low applied voltage.

Figure 4 (b) shows the converging property which can be observed with the applied voltage of 80 V. In contrast with the liquid crystal microlens with a positive dielectric anisotropy, the focusing property can be obtained by applying a high voltage and the focusing property is almost saturated. It is easy to select the convex lens property without accurate adjustment of the applied voltage, and fast response time can be obtained.

Figures 5 (a) and (b) show a molecular orientation model for the hybrid-aligned microlens with liquid crystal materials of a negative dielectric anisotropy. Figure

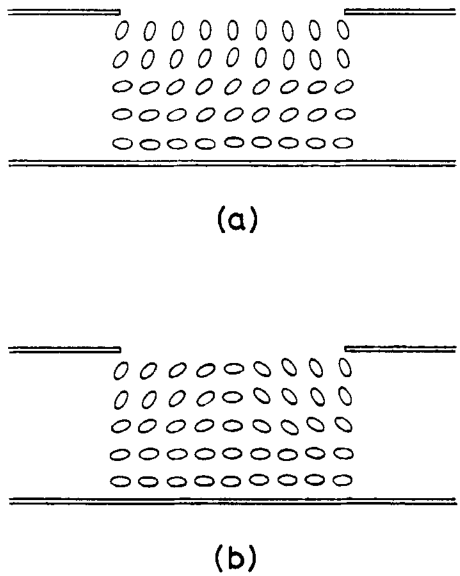


FIGURE 5 A molecular orientation model of the hybrid-aligned microlens with a negative dielectric anisotropy. (a) Low applied voltage; (b) high applied voltage.

5 (a) shows a model with a relatively low applied voltage. Because of the intensity distribution of the electric field, the molecules near the edge of the hole-pattern are reoriented at first and tend to align perpendicular to the electric field. The refractive indices around the edge of the hole-pattern increase and the spatial distribution of the refractive indices as a diverging property can be obtained. In this figure, discontinuous orientation can be observed around the upper right region. Actually, a disclination line along the radius direction which is parallel to the molecular orientation was observed with the voltage application.

Figure 5 (b) shows a model with a very high applied voltage. In the lower side of the cell, the tilt angles of the molecules may not change so much from the initial orientation. On the other hand, in the upper side, almost all the molecules align perpendicular to the electric field and a radial distribution of the refractive indices, that is, the converging property, can be obtained. There may be two axially symmetric molecular orientations: a concentrically circular orientation or a radial orientation. If the molecular orientation is concentrically circular, there is no spatial distribution of the refractive indices as a lens and the focusing property can not be obtained. The converging property observed in Figure 4 (b) confirms the model in Figure 5 (b); that is, the long axes of the molecules align radially with the distribution of tilt angles.

From the measured results of the response and recovery properties, the microlens with a positive dielectric anisotropy with a low applied voltage has a very sharp focusing property but several seconds are necessary as the response time. On the other hand, since the higher voltage levels are necessary to obtain the focusing properties in the microlens with negative dielectric anisotropy, the response time of several tens of milliseconds can be obtained. Response time is usually longer than the recovery time in the liquid crystal microlens with a positive dielectric anisotropy, however, the relation is reversed in the liquid crystal microlens with a negative dielectric anisotropy.

CONCLUSIONS

A hybrid-aligned liquid crystal microlens has been prepared using liquid crystals with a positive or a negative dielectric anisotropy and their optical properties have been investigated.

In the liquid crystal microlens with a positive dielectric anisotropy, any disclination lines which are observed in a homogeneously aligned microlens can not be observed, and a very sharp focusing property can be obtained with a low applied voltage.

The variable range of the effective refractive indices in the hybrid-aligned liquid crystal microlens is smaller than that of the homogeneously aligned microlens, and the focal length of the former lens tends to be longer than that of the latter lens.

The lens property can also be obtained in the liquid crystal microlens with a negative dielectric anisotropy; that is, the diverging property and the converging property were observed with a low and high applied voltage, respectively.

The response of the microlens with a negative dielectric anisotropy in the converging lens property is very fast, because the converging property can be obtained with a very high applied voltage in contrast with the microlens of a positive dielectric anisotropy.

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