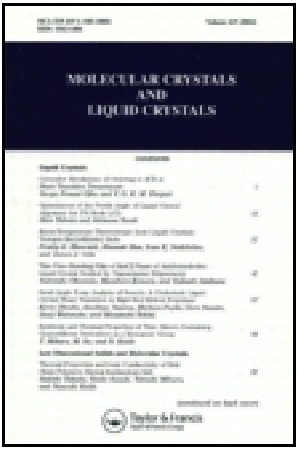

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A new precise control scheme of the liquid crystal (LC) molecular orientation state in the nonuniform electric field is discussed. An extra controlling electrode is introduced outside of the conventional driving electrode in the LC cylinder lens and LC microlens, and the molecular orientation effects and related optical properties are investigated for various experimental conditions. The behavior of disclination lines is very important in this case as is in other LC cells which are utilizing the nonuniform electric field for the molecular orientation, and it strongly depends upon the rubbing direction and the driving condition. The degradation of lens properties, which is usually followed by a variable action such as variable focusing and/or beam steering, becomes very slow because the reduction of the effective lens aperture is restricted. Consequently, the variable range can be extended by the extra controlling electrode structure.

Keywords: nonuniform electric field; LC microlens; LC cylinder lens; disclination line

INTRODUCTION

Graded index type liquid crystal (LC) lenses are obtained by utilizing a molecular orientation effects in the nonuniform electric filed which is produced by the slit-patterned and/or circular hole-patterned electrode structure [1-5]. The LC cylinder lens and LC microlens have a potential application to the novel optical controlling devices with variable focusing and beam steering [6]. However, the spatially distributed molecular orientation state is closely related with a creation of disclination lines which sometimes show a unique behavior but usually deteriorate the optical properties in the LC devices [7]. The investigation of the disclination line behavior is always indispensable in the LC devices which is utilizing the molecular orientation effects in the nonuniform electric filed.

In the conventional type LC microlens, excellent lens properties of which focusing spot size is close to the diffraction limit can be obtained under optimum conditions [3]. The beam steering properties can also be obtained by introducing the divided electrode structure [6]. However, the lens quality tends to decrease sharply as the various parameters of the LC cell and/or driving conditions are deviated from the optimum conditions. These phenomena become conspicuous if we intend to utilize their light wave controlling functions as active optical devices.

In this work, an extra controlling electrode is introduced to the conventional LC cylinder lens and LC microlens outside of the driving electrode in a planar structure. The molecular orientation properties with and without a disclination line are observed under various driving conditions and rubbing directions, and their refractive index distribution properties obtained with the new electrode structure are investigated. Their variable focusing and beam steering properties are compared with the conventional electrode structure, and a possibility as a novel precise control scheme of the LC molecular orientation in the nonuniform electric field is discussed.

EXPERIMENTAL

Fig.1 (a) and (b) show the electrode structures of the LC cylinder lens and LC microlens which have the extra controlling electrode structure used in

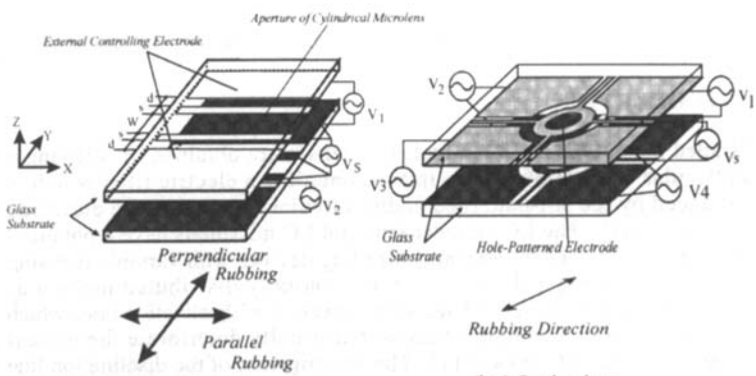


Fig.1 Structures of the the LC cell with an extra controlling electrode structure. (a) LC cylinder lens and (b) LC microlens.

this work, respectively. Two narrow slit patterns ***d*** are fabricated on both sides of the driving electrode ***s*** in the LC cylinder lens, where the width ***s*** and ***d*** are 100 μ m. The lens aperture is varied from 200 μ m to 400 μ m and the thickness of the cell is 100 μ m. Two exactly same electrode patterns are assembled precisely, and both surfaces of the electrodes are treated with PVA coating and rubbing to give a homogeneous alignment. The rubbing direction is set along the direction parallel or perpendicular to the slit pattern.

In the LC microlens, 4 separated extra controlling electrodes are fabricated on the LC cell and are driven by 4 different voltages for the arbitrary directional beam steering functions. Diameter of the lens aperture is 300 μ m and the cell thickness is 100 μ m. The ring shaped driving electrode has a 4 long arms for contacting outer driving source considering with the symmetry of the electric field distribution. The rubbing direction is basically set to be 45 degrees from the elongated arms to eliminate the appearance of the disclination line in the outer narrow slit patterned region where the rubbing direction is perpendicular to the slit direction.

LC CYLINDER LENS

Fig.2 shows the interference fringe patterns observed in the LC cylinder lens of which rubbing direction is perpendicular to the slit pattern, where the voltage is applied only to the inner driving electrode and the voltage of both extra controlling electrodes are fixed to 0V. In this case, since the molecular tilt directions of upper and lower regions within the lens aperture are conflicted, a disclination line appears in the middle of the slit pattern at higher applied voltage.

The optical path difference distribution; that is, the refractive index

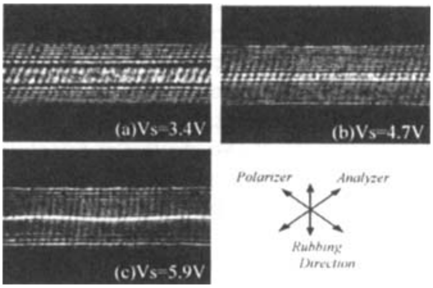


Fig.2 Interference fringe patterns observed in the LC cylinder lens of which rubbing direction is perpendicular to the slit pattern. (w=200 μ m)

distribution profiles are plotted from the interference fringe data as shown in Fig.3 (a). It is seen that the distribution properties are almost linear and symmetrical between left and right regions. The slope of the disclination is almost constant in any applying voltages; that is, the distribution profile is very different from that of the lens properties, and the prism like optical properties are obtained as observed previously in the LC cylinder lens with the asymmetric electrode structure [2].

When the voltage is applied to both extra controlling electrodes and inner driving electrodes, no disclination lines appear and the cylinder lens properties which have ideal quadratic distribution properties are obtained as shown in Fig.3 (b). A constant voltage of 3V is applied to the extra controlling electrode and the inner electrode is driven by the voltage from

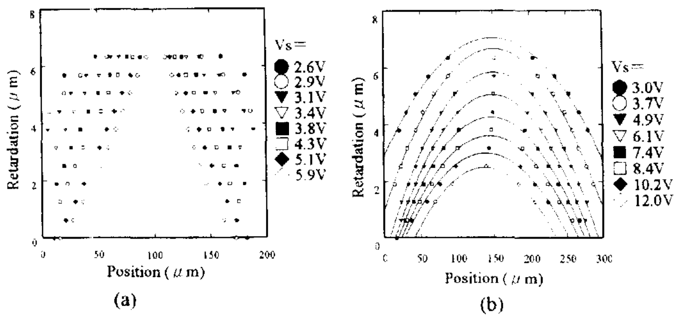


Fig.3 Voltage dependence of the retardation properties in the LC cylinder lens for various driving conditions (a) V1=V2=0V and (b)V1=V2=3V.

3V to 12 V. In this case, the refractive index distribution properties decrease greatly by increasing the applying voltages, however, the curvature of the distribution profiles do not change so much. That means the focal length of the LC cylinder lens doesn't change widely by the driving voltage of Vs. It is also seen that the center of the refractive index distribution tends to shift to the left side as the applied voltage increases. It is interesting that we can select two molecular orientation states with or without the disclination line by changing the driving method, however, the excellent lens quality may not be expected in the LC cylinder lens of which rubbing direction is perpendicular to the slit pattern.

When the rubbing direction is parallel to the slit pattern in the LC cylinder lens, any disclination lines don't appear and the number of the fringes tends to decrease with increasing the voltage unlike with the case in Fig.2. The refractive index distribution properties are plotted as shown in

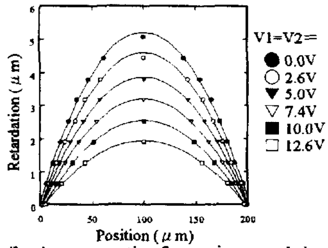


Fig.4 Retardation distribution properties for various applying voltage on the extra controlling electrodes.

Fig.4, where the inner driving voltage is fixed to the optimum value where the excellent lens properties can be obtained without voltage on the extra controlling electrodes, and then they are driven by the various voltages. In any applied voltage levels, ideal refractive index distribution properties which are almost on the quadratic curves; that is, the high quality of lens properties can be obtained. The decrease of the lens aperture depending upon the driving voltage is one of the principal factors of degradation of lens quality related with the variable focusing actions in the conventional LC lens [1]. However, it is seen that the effective lens width doesn't change with increasing the voltage. The center of the distribution doesn't change either for any applying voltage in this case.

Beam steering properties are investigated by applying the different voltages on the extra driving electrodes as shown in Fig.5, where the voltage on the driving electrode Vs is fixed to be 3.66V and V_1 is changed from 0V to 20V. The shifting distance of the focusing line from the initial position and the peak light intensity are plotted by closed and open circles in this figure, respectively. The focal position gradually moves to the lower applying voltage side as observed in the conventional type lenses [6].

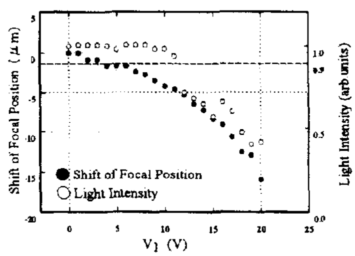
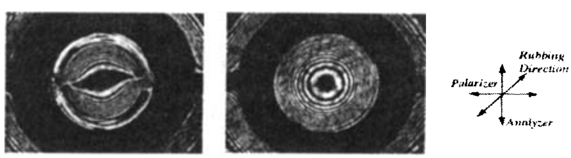


Fig.5 Beam steering properties in the LC cylinder microlens.

However, the degradation of the light intensity related with the moving action is very mild with increasing the applying voltage. Consequently, the actual beam steering range can be extended comparing with the conventional type ones. In this case, the high lens quality is maintained up to 10V for both shifting directions and the shifting distance about 5 μm for either side can be obtained without any serious degradation of lens quality.

LC MICROLENS

Fig.6 shows the interference fringe patterns appearing in the LC microlens with the extra controlling electrodes. When the voltage is applied only to the inner driving electrode (Fig.6(a)) and the voltage of extra controlling electrodes V_1 through V_4 is 0V, it is seen that a disclination line tends to appear in the middle of the lens aperture similarly observed in Fig.2. If the extra and the inner electrodes are driven at the same time, there seems to exist no disclination lines for any driving conditions in the lens aperture as shown in Fig.6 (b). It is seen that concentrically circular and perfect refractive index distribution properties can be obtained, and there is no lens center deviation from the electrode pattern.



(a) (b)

Fig.6 Interference fringe patterns in the LC microlens for various driving methods.

Change of the focal length and the focusing spot light intensity properties are shown in Fig.7 as a function of the applying voltage on the extra controlling electrodes. The focal length increases gradually with increasing the applying voltage as observed in the conventional LC microlens, and the light intensity tends to decrease with the change of the focal length from the initial value.

The refractive index distribution properties for various applying voltages for extra driving electrode are shown in Fig.8, where the voltage of V_s is fixed to 4.5V. Effective lens aperture is almost constant for considerably lower applying voltage region similarly with the LC cylinder lens. It is seen that the aperture tends to increase under high voltage application, and

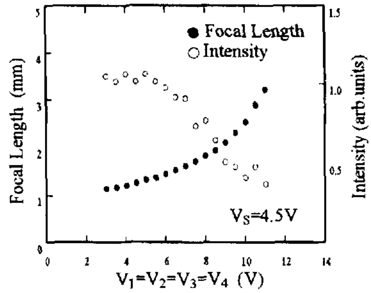


Fig.7 Focal length and focusing spot light intensity properties in the LC microlens with the extra controlling electrodes.

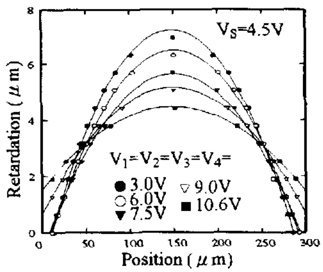
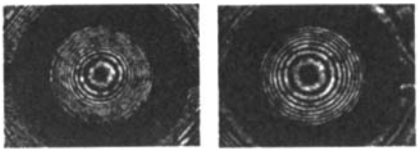


Fig.8 Retardation distribution properties for various applying voltages on the extra controlling electrodes.

a disclination line is observed outside of the aperture which influences to the lens quality. Consequently, the variable range of the focal length is comparable with the conventional ones. However, there are some remaining experimental conditions which should be optimized for the better performance.

Fig.9 (a) and (b) show the interference fringe patterns before and after the beam steering action. In the initial state (a), the fringe patterns are concentrically circular and the excellent lens properties can be obtained. When the voltage on the extra controlling electrode is changed from the symmetric condition, we can see the shift of the refractive index distribution properties as shown in Fig.9 (b). In this case, the distribution profile is still on the ideal one and the degradation of the peak light intensity at the focusing spot is within 10% from the initial state. More than 15 μm shift of the focal point can be obtained and the value is improved comparing with the conventional type of LC microlens [6]. The



(a) $V_1 \sim V_4$=3.0V (b) V_1=V_3=9.0V V_2=3.0V, V_4=18V

Fig.9 Interference fringe patterns in the LC microlens for various driving voltages.

advantage of the molecular orientation effects by using the extra driving electrode becomes more clear under the experimental condition deviated from the optimum ones.

CONCLUSIONS

Liquid crystal molecular orientations and their optical properties are investigated using the LC cylinder lens and LC microlens which have an extra controlling electrode structure outside of the conventional driving electrode. A disclination line appears under some conditions related with the directions between the rubbing treatment and electrode pattern, but the disclination free state can be obtained by proper driving method. The LC cylinder lens of which rubbing direction is parallel to the slit pattern shows excellent lens properties and the variable range can be improved by the effects of the extra controlling electrode. In the case of the LC microlens, although the improving effects is not so large comparing with the cylinder lens, it is obvious that the variable range is extended especially in the deviated state from the optimum condition.

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