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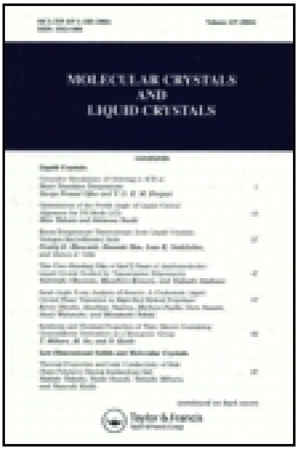

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New Method of Voltage Application for Improving Response Time of a Liquid Crystal Lens

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New Method of Voltage Application for Improving Response Time of a Liquid Crystal Lens

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A new method of rapid driving of a liquid crystal lens is proposed. High external voltages are initially applied to the liquid crystal cell accompanied with an in-plane electric field. The occurring of disclination lines is prevented and the response of the lens becomes more than two times faster.

Keywords: liquid crystal lens; response time; voltage application

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INTRODUCTION

Liquid crystals (LCs) have large electrical and optical anisotropies, and their optical properties can be easily changed by external electric fields. Optical devices such as optical waveguides, optical switch, and light deflection devices made of LC materials have optical properties that are electrically controllable. LC lenses are optical lenses made of LC materials with appropriate electrode structures, and they have focal lengths tunable with external electric fields. They are promising devices that can replace traditional variable-focus lenses in many applications such as optical imaging, optical inter-connection, and data reading in optical drivers. The LC lens has attracted much research interest and various lens structures have been reported [1–15]. The thickness of the LC layer in an LC lens usually exceeds

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100 μm and therefore the operation of an LC lens is generally very slow. It is possible to decrease the recovery time of an LC lens to merely several milliseconds by application of an in-plane electric field [16], but the response time of an LC lens is usually in the order of several tens of seconds, and there is not yet an effective method to decrease it. One possible method to speed up the response of the LC directors in an LC cell to external electric fields is to apply a high initial voltage. Strong fields in the LC layer nevertheless usually results in the occurring of disclination lines. Recently we have proposed a technique to drive an LC lens without disclination occurring by applying an in-plane electric field in the LC layer [17]. Here we report a method to decrease the response time of an LC lens by application of high voltages, using the new technique of preventing the occurring of the disclination lines with an in-plane electric field. The operation speed of the LC lens becomes more than two times higher.

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STRUCTURE OF LC CELL

The structure of the LC lens is shown in Figure 1. A thin layer of LC (E44 of Merck) is sandwiched between two glass substrates. The lower substrate is coated with a transparent electrode and the electrodes face the LC layer. The upper substrate is coated with aluminum (Al) as another electrode and there is a round hole in the center of the coating. The surface without the Al coating faces the LC layer. The surfaces of the substrates contacting the LC are covered with polyimide and are rubbed uniformly in one direction, so that the LC is aligned homogenously. The directors have a pretilt angle θ_0 of approximately 2.5° in the absence of an applied voltage. The diameter of the hole, the thickness of the glass substrate between the Al electrode and the LC layer, and the thickness of the LC are, respectively, 7.0 mm, 1.3 mm, and 130 μm. The bottom electrode is prepared by sputtering ZnO powder mixed with a small amount of In_2O_3 powder. The prepared electrode is transparent and of high resistance. Two Al subelectrodes A and B are coated on the surface of the transparent electrode. The resistance and the distance between the two subelectrodes are about 7 kΩ and 10 mm, respectively.

RESPONSE TIME

For a planar LC cell with planer electrodes, the rise time is $t_{\text{rise}} = \tau/[(V/V_c)^2 - 1]$, where V is the voltage across the LC layer, V_c

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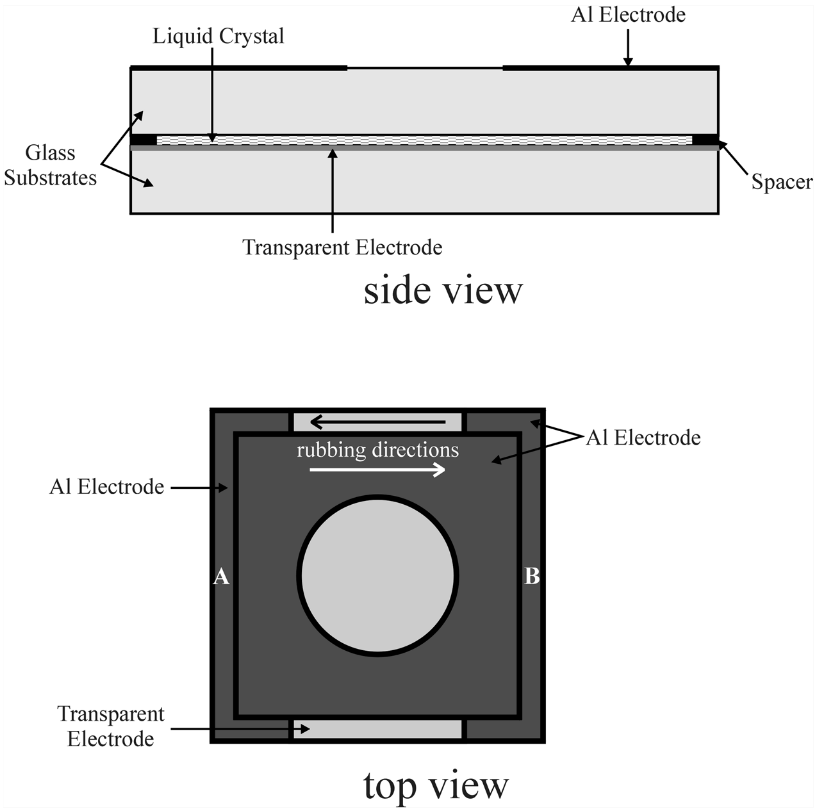

FIGURE 1 Cell structure.

the critical voltage for the Freedericksz transition, and τ the time constant of the LC cell. The critical voltage $V_c = \pi(4\pi K_{11}/\Delta\varepsilon)^{1/2}$ and the time constant $\tau = \gamma_1 d^2/(K_{11}\pi^2)$, where d is the thickness of the LC layer, γ_1 and K_{11} the viscosity and one of the elastic coefficients of the LC material, respectively [18].

The time constant τ is proportional to d^2. It is therefore possible to accelerate the response of an LC device by using a thin LC layer. However, to use a thin LC layer in an LC lens will lose the lens power.

The time constant τ of an LC device decreases with the increase of the applied voltage, so it is also possible to accelerate the response of an LC lens without the sacrificing of the lens power by driving the cell initially with a high voltage for a short time interval before the desired voltage is applied.

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VOLTAGE APPLICATION WITHOUT DISCLINATION OCCURING

When a high voltage is applied directly on the LC cell, however, disclination lines often occur. The electric field $\boldsymbol{E}$ in the LC layer is nonuniform. Near the lower transparent electrode, the field is perpendicular to the electrode surface, but at positions having distance from the electrode, the field at the two sides in the rubbing direction tilts to opposite side. The angle α between the electric field and the LC directors therefore differs with location. The electric torque acting on the LC directors is $\Delta\varepsilon \boldsymbol{E}^2 \sin(2\alpha)/(8\pi)$. The sign of the torque when α is acute is opposite to that when it is obtuse. The angle α is acute for most of the LC directors, but for a small potion of the LC directors it is obtuse. As shown in Figure 2(a), α of some directors at the right side is obtuse. So if a voltage, particular a high voltage, is applied, some LC directors at the right side tend to rotate in the direction opposite to the direction in which the other LC directors rotate, as shown by the arrows in the figure. As a result, there appear two domains of reverse tilt. The boundary of the two domains forms a disclination line.

To prevent the occurring of the disclination line, we apply different potentials at the two subelectrodes. Let the potential of the top electrode be 0. The required voltage V is applied to the cell at one of the two subelectrodes on the bottom electrode. Meanwhile, a portion of

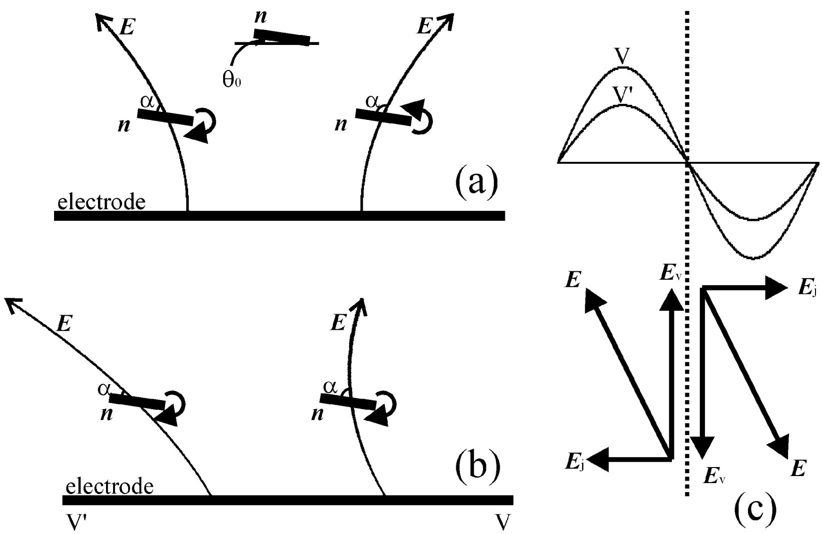

FIGURE 2 Electric field and LC directors.

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the voltage, that is, V', is shared by the other subelectrode for a short time interval Δt, following that the potential is switched to V. There is then a potential difference across the two subelectrodes during Δt, and a current in the rubbing direction alternating in phase with the applied voltage flows in the ITO electrode between the two subelectrodes. Then there appears an electric field in the bottom electrode parallel to the current. The electric field $\boldsymbol{E}_J = \boldsymbol{J}/\sigma$, where $\boldsymbol{J}$ is the current density and σ the conductivity of the electrode. As the current alternates in a very low frequency, the effect of the magnetic field is negligible. Therefore, $\nabla \times \boldsymbol{E}_J \approx 0$, implying that in the LC, there is also an in-plane electric field parallel and nearly equal to the electric field in the electrode. We denote the electric field induced by the voltage, that is, the usual drive voltage for the LC cell, across the top and the bottom electrodes by $\boldsymbol{E}_V$, and that by the current in the bottom electrode by $\boldsymbol{E}_J$, and the total field by $\boldsymbol{E}$. The directions of the field components and the total field during the first and the latter halves of one period are illustrated in Figure 2(c). It can be seen that the total electric field $\boldsymbol{E}$ is tilted to one side, as shown in Figure 2(b). If the inclination of the electric lines is sufficient, the angle α between the electric field and the directors in most locations in the LC may become acute, and all the directors will finally tend to rotate in the same direction. The disclination line then will not occur [17].

EXPERIMENTAL METHOD AND RESULTS

The method of voltage application described in the previous section makes it possible to apply high voltages to the LC cell without the appearing of the disclination lines. Before the application of the desired voltage V_0, we first apply different high voltages V_h and V'_h on subelectrodes B and A, respectively, in a short time interval Δt, as shown in Figure 3, where $V'_\mathrm{h} < V_\mathrm{h}$. The LC directors are rapidly rotated by the high voltages. In the time interval Δt, an in-plane electric field occurs in the LC layer due to the potential difference between A and B, and the total field is tilted to one side, and therefore the occurring of disclination lines is prevented. Owing to the high voltages, the response of the cell is speeded up.

In the experiment, $V_\mathrm{h} = 270\,\mathrm{V_{rms}}$, $V'_\mathrm{h} = 210\,\mathrm{V_{rms}}$, and $V_0 = 80\,\mathrm{V_{rms}}$. We adjust Δt and observe the change of the lens properties with time. The properties of the LC lens are observed by the interference method described in ref. 13. Figure 4 shows the temporal evolutions of the interference patterns after the voltages are applied for $\Delta t \approx 2s$ and $\Delta t \approx 0$. In the case of $\Delta t \approx 2s$, that is, the high voltages last for about 2 seconds, the response of the LC lens is apparently speeded up. The

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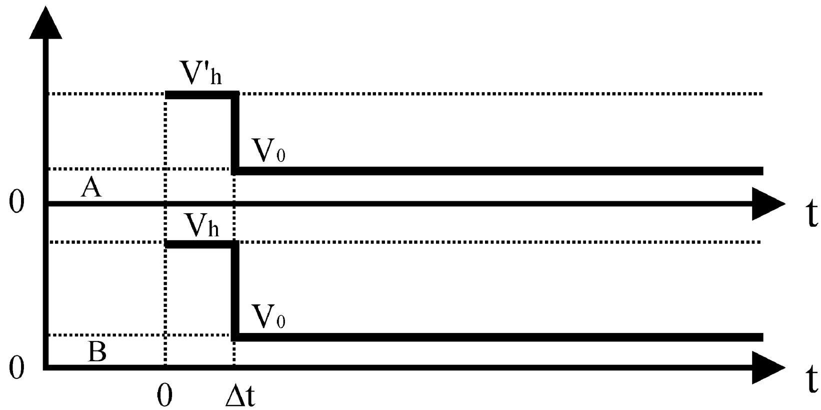

FIGURE 3 Voltages applied on subelectrodes A and B.

temporal evolution of the LC lens differs with the time interval Δt during which the high voltages are applied.

Figure 5 shows the intensity of the focus changes with time at various Δt. The intensity grows with time and finally reaches to a saturated value. The speed of the intensity growth varies with Δt. The response time t_{rise} of the LC lens is defined here as the time elapsed after the application of the voltages to reach to the 90% of the saturated value.

The rise time t_{rise} dependents on Δt. It is shown in Figure 6 as a function of Δt. When $\Delta t = 2\,s$, t_{rise} becomes the smallest and is about $20\,s$. In the case of conventional method of direct voltage application ($\Delta t \approx 0$), t_{rise} is about $50\,s$. The new method is very effective in speeding up the response of the LC lens.

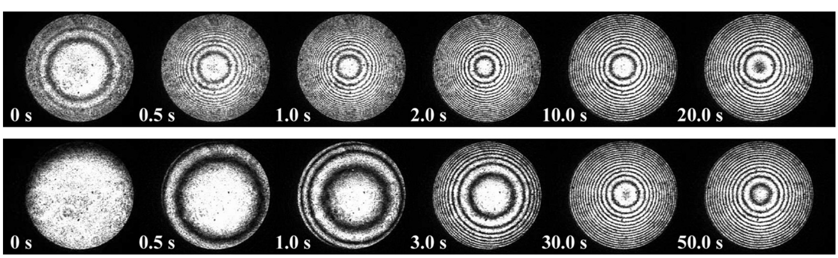

FIGURE 4 Temporal evolutions of interference patterns when $\Delta t \approx 2s$ (above) and $\Delta t \approx 0s$ (below).

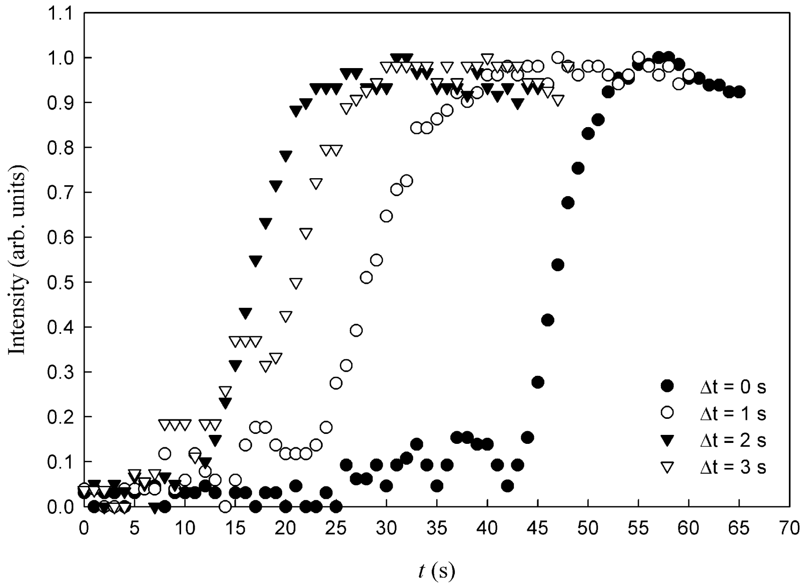

FIGURE 5 Intensity of focus changes with time at various Δt.

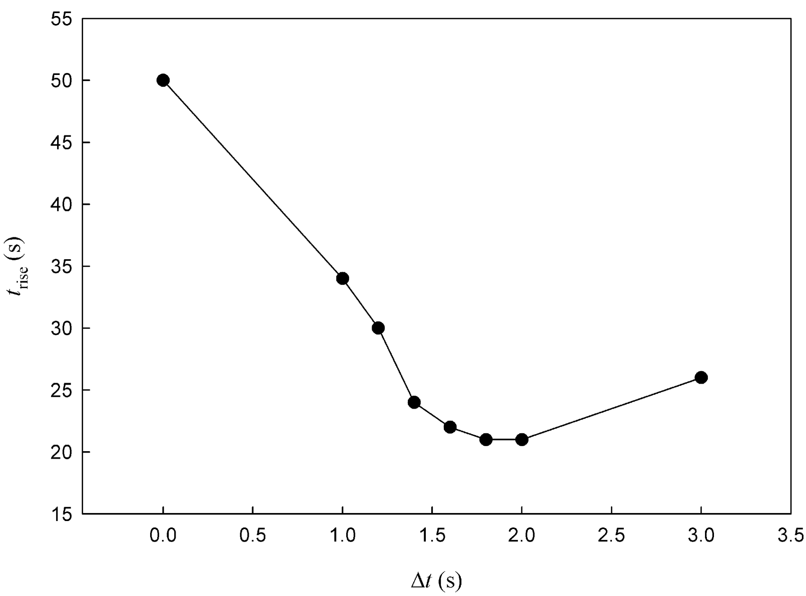

FIGURE 6 Response time as function of Δt.

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CONCLUSION

A method of voltage application to an LC lens to decrease the response time is proposed. Before the application of the desired voltage V_0, two different high voltages V_h and V'_h are applied in a short time interval. The response of the LC lens is accelerated by the high voltages. An in-plane electric field is introduced due to the potential difference and occurring of disclination line in the LC layer is prevented. The response time is decreased from about 50 s to about 20 s.

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