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Dual frequency cholesteric light shutters

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We developed a dual frequency cholesteric light shutter which utilizes a cholesteric liquid crystal; the dielectric anisotropy of the material changes from positive to negative when the frequency of applied voltage is increased. The shutters are switched to the transparent homeotropic texture by low frequency voltages, and switched to the reflecting planar texture by high frequency voltages. We designed a waveform which reduced the transition time from the homeotropic texture to the planar texture to less than 100 ms. © *1997 American Institute of Physics.* [S0003-6951(97)01006-1]

Liquid crystal light modulators have been studied intensively and have been used in a tremendous number of applications in the last couple of decades. They are not satisfactory, however, for some applications, such as laser-protection goggles, where it is desired that the light modulator have very high transmittance (>90%) in the light-on state and low transmittance (<1%) in the light-off state. There are three major types of liquid crystal light modulators. In the first type, such as twisted nematic liquid crystal (TN),[1,2] the polarization plane of the incident light is rotated by liquid crystals and polarizers are employed. The problem of this modulator is that the transparency of the light-on state is less than 50% because of the polarizers. The second type is the guest/host effect modulator in which dichroic dyes are mixed with liquid crystal.[3] The absorption of the dye depends on the relative orientation of the direction of the electric field of the light and the direction of the dye molecules, which is aligned along the liquid crystal director. The transparency of the light-on state is still low because the orientational order of the dye molecules is not perfect. The third type is polymer dispersed liquid crystals (PDLC) in which light scattering is caused by spatial refractive indices variation.[4–6] This type of modulator has very high transparency in the light-on state; however, in the light-off state, light is scattering in the forward direction, making it not suitable for laser-protection goggles.

Cholesteric liquid crystals can also be used to make a light modulator. A cholesteric liquid crystal with pitch P_0, in the planar state, Bragg reflects light peaked at wavelength $\lambda = nP_0$ with band width $\Delta\lambda = \Delta n P_0$, where n and Δn are the average refractive index and birefringence, respectively.[7] The reflected light is circularly polarized. If the incident light is unpolarized, then the maximum reflectance of a one layer cholesteric liquid crystal is 50%. When one layer of left-handed cholesteric liquid crystal and one layer of right-handed cholesteric liquid crystal are stacked together, then the unpolarized light is reflected completely. When an external electric field higher than the critical value $E_c = (\pi^2/P_0) \times (K_{22}/\varepsilon_0 \Delta\varepsilon)^{1/2}$ is applied to the material ($\Delta\varepsilon > 0$), it is switched to the homeotropic texture and becomes transparent. When the field is turned off, it relaxes back to the planar texture, and becomes reflecting (nontransparent).

Response times (turn-on and turn-off times) are the major problem when conventional cholesteric liquid crystals are used. When a cholesteric liquid crystal relaxes from the homeotropic texture to the planar texture, the transition takes place in two steps.[8,9] It first transforms to a transient planar texture with a pitch around $2P_0$ in a short time (~few ms). Then it transforms from the transient planar texture to the stable planar texture with the intrinsic pitch P_0. The second transition is a nucleation process and defects are involved. The turn-off time (the relaxation from the homeotropic texture to the planar texture) is typically a few seconds, and is too slow for many applications.

We developed a dual frequency cholesteric light shutter which has much faster turn-off time. For a dual frequency liquid crystal, when a low frequency voltage is applied, the liquid crystal has a positive dielectric anisotropy, and it is aligned along the field; when a high frequency voltage is applied, the dielectric anisotropy is negative, and it is aligned perpendicular to the field.[10] This phenomenon was utilized in nematic liquid crystal displays and phase-change quest-host liquid crystal displays.[11,12] In our dual frequency cholesteric light shutter, we apply low frequency voltage to switch the cholesteric material to the homeotropic texture and apply high frequency voltage to make the material relax back to the planar texture faster.

The material used was a mixture of nematic liquid crystal DF-05XX (Chisso Chemical), E48 (EMerck), EK11650 (Kodak), and chiral agent MLC-6247 (left-handed) and MLC-6248 (right-handed). The dielectric anisotropy of the nematic material of the mixture is shown in Fig. 1. The chiral dopants have a small dielectric anisotropy and addition of them does not significantly change the dielectric anisotropy

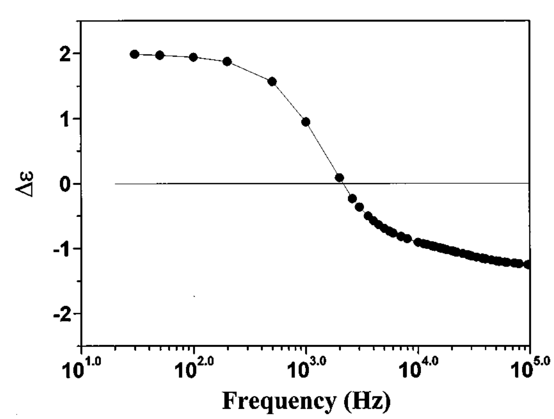

FIG. 1. Frequency dispersion of the dielectric anisotropy of the nematic constituents of the cholesteric mixture.

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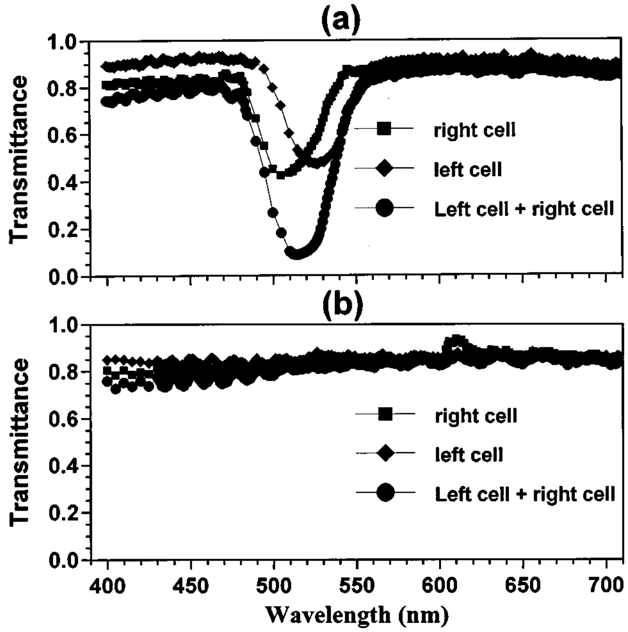

FIG. 2. Transmission spectra of the cells. (a): planar texture, (b): homeotropic texture.

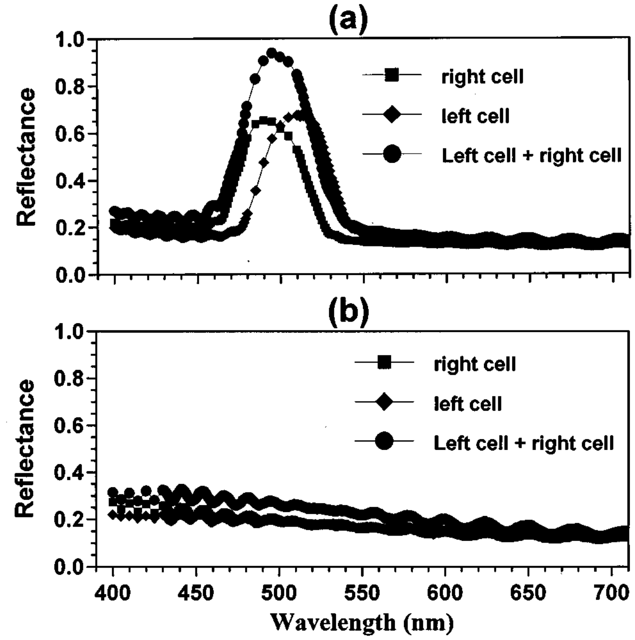

FIG. 3. Reflection spectra of the cells: (a) planar texture, (b): homeotropic texture.

of the mixture. The cells used were 5 microns thick and had rubbed polyimide alignment layers. In the transmission measurement, the detector was placed behind the cell with the collection angle of 21°. In the reflection measurement, the collection angle is 65°. The incident and detection angle were 22.5°. White light produced by an arc lamp was used. All spectra were normalized to that of the incident light intensity.

The transmission spectra of the material in the planar texture (nontransparent state) and the homeotropic texture (transparent state) are shown in Figs. 2(a) and 2(b), respectively. The incident light was perpendicular to the cells. The minimum transmittance of the stack of left and right cells in the planar texture is 8%. This minimum transmittance can be reduced if thicker cells are used or liquid crystals with higher birefringence are used. The transmittance of the stack in the homeotropic texture is 80%. The light loss is mainly caused by the reflection from glass-air interfaces. The reflection spectra of the material is shown in Fig. 3. The reflection peaks of the right- and left-cell are not at the same wavelength because the cells have slightly different thickness and the pitch is quantized to match the boundary condition. For the left and right cell, the peak reflectance is 60% with about 40% from the liquid crystal and 20% from the glass-air interfaces. This glass-air reflection is high because the light was incident at 22.5° instead of normal. The peak reflectance of the stack of the left and right cells is 95%.

We studied the response times of the cells under various voltage waveforms. When we applied a 200 ms voltage pulse of 125 V and 100 Hz as shown by waveform 1 in Fig. 4, the transmittance of the stack is shown in Fig. 5. The turn-on time is about 10 ms. The turn off consists of two steps: first the transmittance decreases quickly to 20% in about 10 ms; it then decreases slowly with a transition time longer than 10 s as shown by the inset in Fig. 5. The reflectance of the stack is shown in Fig. 6. The turn-on time is about 10 ms. The turn-off time is longer than 10 s as shown by the inset in Fig. 6. We observed the cells under a polarizing optical microscope. After the voltage was turned off, the liquid crystal was in a polydomain structure with many defects. The defects scatter light but do not reflect light. Both reflection and scattering reduce the transmittance. The scattering, however, does not contribute to the reflection. The defects were produced quickly but disappeared slowly. Therefore when the voltage is turned off, the transmittance decreases quickly while the reflectance increases slowly. This explains the difference between the turn-off times measured under transmission and reflection.

A high-frequency field makes the liquid crystal align perpendicular to it, and therefore can make the material transform from the homeotropic texture to the planar texture faster. After the low frequency voltage, we applied a high frequency voltage to the cell (as shown by waveform 2 in Fig. 4), the transmittance of the stack is shown in Fig. 5. The

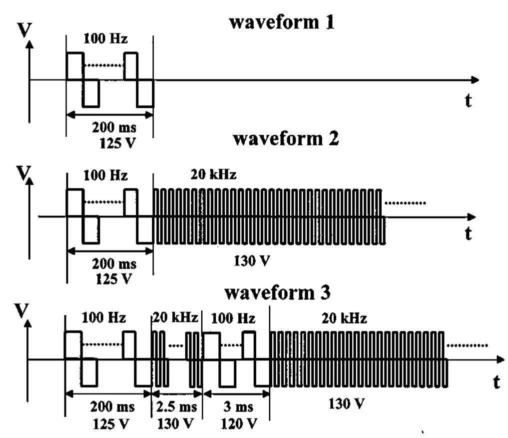

FIG. 4. Schematic diagram of the voltage waveforms used to switch the cholesteric light shutter.

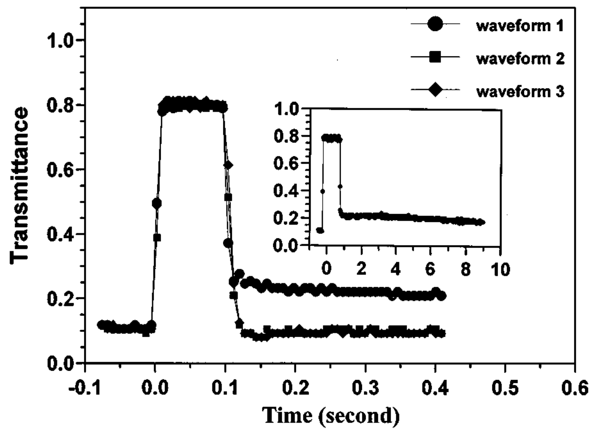

FIG. 5. The transmittance of the stack of the left and right cell vs time under various voltage waveforms.

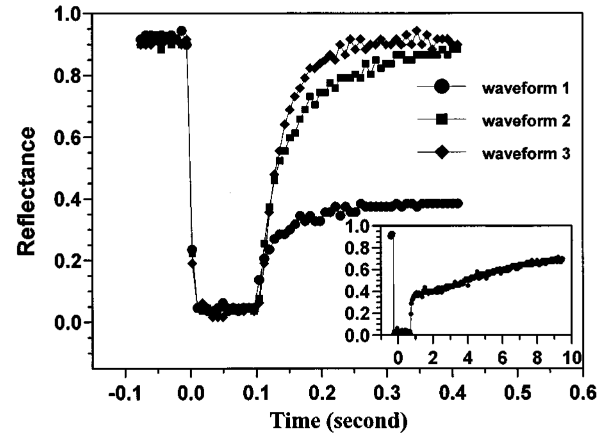

FIG. 6. The reflectance of the stack of the left and right cell vs time under various voltage waveforms.

turn-off time is reduced to 15 ms. The reflectance of the stack of the cell is shown in Fig. 6. The turn-off time is reduced to 200 ms. The high frequency field helped greatly to eliminate the defects and restore the material to the planar texture.

When the liquid crystal relaxes from the transient planar texture to the stable planar texture, the molecules have to tilt back to the cell normal direction. Under high frequency field, this tilting is difficult. If a low frequency voltage is applied at some time in the transition, the transition can be sped up. Therefore, we designed a waveform as shown by waveform 3 in Fig. 4. After the low frequency voltage is turned off, a high frequency voltage is applied for a short time, and then a low frequency voltage is applied again for a short time, and then a high frequency voltage is applied. Under this waveform, the transmittance of the stack is shown in Fig. 5. The turn-off time is around 15 ms, similar to that under waveform 2. The reflectance of the stack is shown in Fig. 6. The turn-off time is reduced to 100 ms. The time intervals of the short high frequency voltage pulse and short low frequency voltage pulse are critical, and have to be optimized for each cholesteric liquid crystal. We have studied the effects of the time intervals of the pulses and the results will be published soon.

We developed dual frequency cholesteric light shutters. In the transparent state, the transmittance of the shutters is higher than 80%, and can be increased if antireflection coating on the cell is used. In the nontransparent state, the incident light is Bragg reflected. The turn-off time (from the transparent state to the nontransparent state) is reduced to 200 ms by application of high frequency voltage. We designed a waveform which reduces the transition time further to 100 ms. Using a chiral dopant with low viscosity, we have made a shutter whose turn-off time is shorter than 40 ms. This shutter is suitable for laser-protection goggle.

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