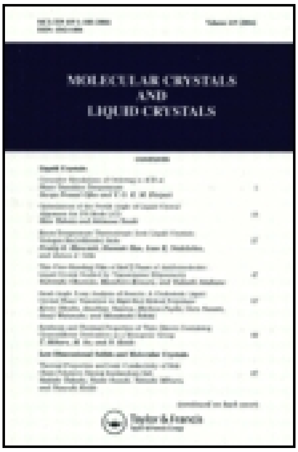


Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl18

High Speed Nematic Liquid Crystal Modulators

Shin-Tson Wu [a] & Chiung-Sheng Wu [a]

[a] Hughes Research Laboratories, 3011 Malibu Canyon Road Malibu, California, 90265

Version of record first published: 24 Sep 2006.

To cite this article: Shin-Tson Wu & Chiung-Sheng Wu (1991): High Speed Nematic Liquid Crystal Modulators, Molecular Crystals and Liquid Crystals, 207:1, 1-15

To link to this article: http://dx.doi.org/10.1080/10587259108032083

Mol. Cryst. Liq. Cryst., 1991, Vol. 207, pp. 1–15
Reprints available directly from the publisher
Photocopying permitted by license only

Printed in the United States of America

HIGH SPEED NEMATIC LIQUID CRYSTAL MODULATORS

SHIN-TSON WU and CHIUNG-SHENG WU
Hughes Research Laboratories, 3011 Malibu Canyon Road
Malibu, California 90265

Abstract Nematic liquid crystal modulators with fast response time, high contrast ratio and low operation voltage are demonstrated. The transient nematic effect, together with reflective mode operation, is responsible for the observed fast response times. The use of a tunable liquid crystal phase compensator results in excellent contrast at a reasonably low operation voltage.

1. INTRODUCTION

Nematic liquid crystals (LCs) have been used widely for displays, light modulators, tunable phase retardation plates and so on. In display application, perpendicular alignment[1] in which the LC directors are aligned to be nearly perpendicular to the substrate surfaces offers an excellent contrast ratio at the normal incident angle. Its dark state is independent of wavelength, as demonstrated in Fig.1. Fig.1 shows the voltage dependent optical transmission of a 4-μm-thick, perpendicular aligned ZLI-4330 in reflective mode operation. In addition to the excellent dark state, the first transmission peak is not sensitive to wavelength. This feature is particularly important for obtaining true color display. A drawback associated with perpendicular alignment is in its relatively slow response time. Normally, the device is operated between a dark state (with a bias voltage V_b below the Fredeerisckz transition threshold, V_{th}) and the first transmission maximum. Under this operation condition, the LC director's decay time (τ_d) is related to V_b as:[2]

$$\tau_d = \tau_o / \left| (V_b/V_{th})^2 - 1 \right| \tag{1a}$$

and

$$\tau_o = \gamma_1 d^2 / K_{33}\pi^2 \tag{1b}$$

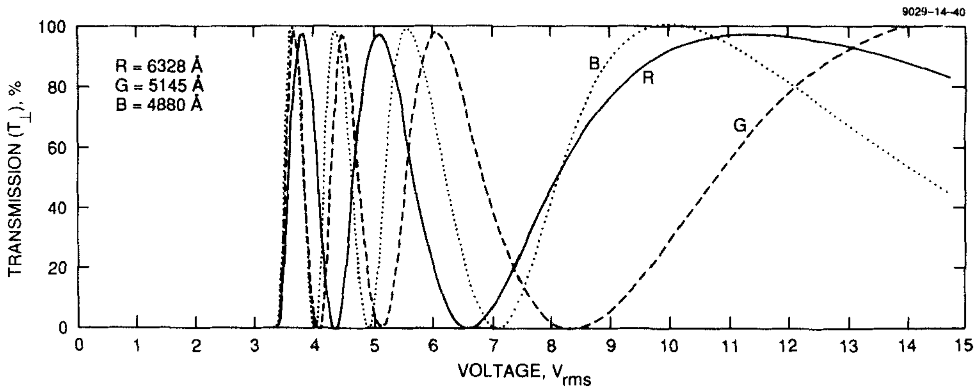


FIGURE 1. Voltage-dependent transmission of a perpendicular-aligned, 4-μm-thick, ZLI-4330 LC cell at T=23°C. The experimental apparatus is similar to that shown in Fig. 3 except no LC compensator. The frequency of the applied voltage is 10KHz sinusoidal waves. The V_{th} is 3.35 V_{rms}.

is the free relaxation time of the LC directors where γ_1 is the rotational viscosity, d is the LC layer thickness and K_{33} is the bend elastic constant. If V_b is close to V_{th}, the rise time is fast but a prolonged decay time is observed. Lowering the bias voltage improves the decay time; however, an undesirable delay time appears in the turn-on process. A typical value of τ_d is about 20-40 ms for a 4-μm-thick LC layer. This relatively slow response is owing to the use of the central layers of a LC cell. The dynamic response of central layers can be described by the lowest order Fourier component which has slower response time than the higher order modes.[3]

A twist alignment[4,5] has been widely employed in active-matrix type LC displays. When the Mauguin's criterion is satisfied:

$$d\Delta n/\lambda >> 1 \tag{2}$$

where Δn is the birefringence and λ is wavelength, the incoming linearly polarized light follows closely the twist of the LC directors. Two thresholds exist in a twist LC cell: 1. the Freederiskz transition threshold, where LC directors start to reorient, and 2. the optical threshold, where the waveguiding effect begins to fail and light

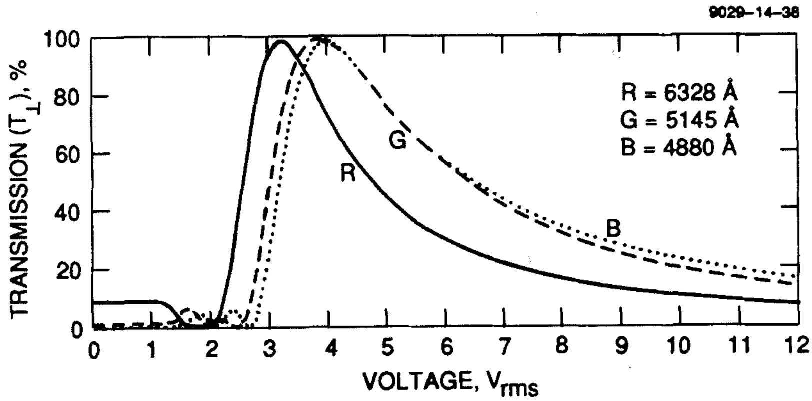


FIGURE 2 Similar to Fig.1 except the LC cell is a 4-μm-thick, 45°-aligned E-7. The directors of the front surface are parallel to the polarization axis of the incoming light.

leaks through the analyzer. An example is shown in Fig. 2 for a 4-μm-thick, 45° twist E-7 LC cell operated at the reflective mode The Freedericksz transition threshold voltage of the cell at T = 23°C is calculated to be 0.93 V_{rms}, independent of wavelength. However, the optical threshold is sensitive to wavelength. As λ increases, the optical threshold decreases. This is because for a given LC thickness, the Mauguin's criterion is more difficult to satisfy by a longer λ. For a longer wavelength, $\Delta n/\lambda$ decreases. Generally, Δn declines with increasing wavelength in the visible spectral region and gradually saturates in the infrared region.[6] As a result, the waveguiding effect of the LC fails at an earlier stage for a longer λ and light leaks at a lower voltage, as shown in Fig. 2. Thus for a twist cell, a high contrast can only be achieved by a narrow band light source. The V_b for a twist cell is usually set at the last minimum right before the major transmission starts. Its magnitude is about two times higher than V_{th}, as shown in Fig. 2. Thus, its decay time is about three times faster than the corresponding free relaxation time, as described in Eq. 1 (here, K_{33} is replaced by K_{22} for a twist cell). A typical response time of a 4-μm-thick E-7 cell is about 10-20 ms.

To achieve a sub-millisecond response time, we have to utilize the higher order Fourier components — for instance, to operate a parallel-aligned LC cell at its last transmission cycle. To overcome the poor contrast as encountered in a parallel-aligned cell, a tunable LC phase retardation plate[7] is added to work as a phase compensator. In Sec. 2, the physical mechanisms and unique features of the transient nematic effect are briefly reviewed. In Sec. 3, molecular parameters affecting the response times of a LC modulator are analyzed. The operation of the transient nematic effect in a Fabry-Perot cell is described. Finally, in Sec. 4 the idea of using a liquid crystal cell as a tunable phase compensator is introduced and experimental results are presented.

2. TRANSIENT NEMATIC EFFECT

Parallel alignment is a preferred alignment for demonstrating the transient nematic effect.[8-10] The experimental apparatus is depicted in Fig. 3 for the reflective mode operation. We first discuss the configura-

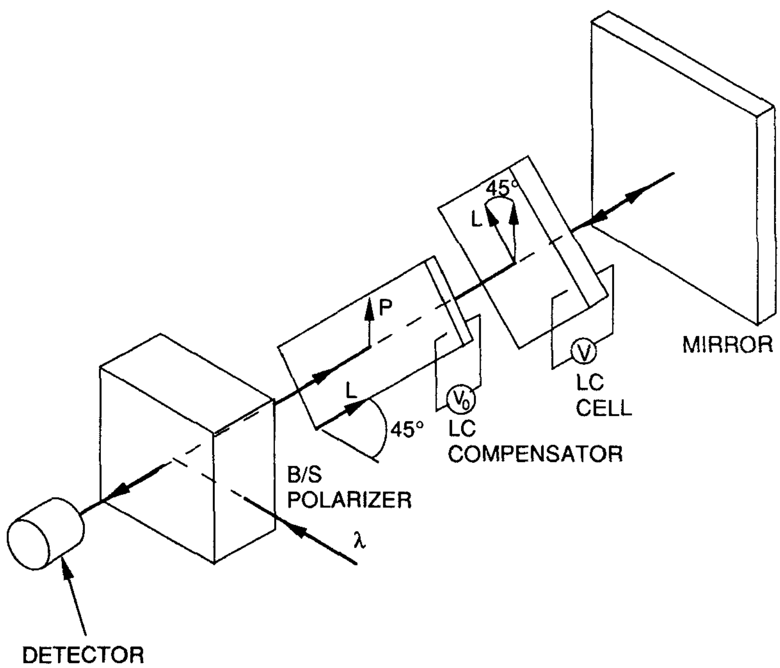


FIGURE 3 Experimental apparatus for demonstrating high speed, high-contrast and low operation voltage LC modulators. B/S represents beam splitting polarizer. The laser beam is normal to both LC compensator, cell and mirror.

tion without a compensator. The LC cell is oriented at 45° to the incoming linearly polarized light in order to obtain the maximum birefringence effect. The voltage-dependent transmission of a parallel-aligned, 4-μm-thick ZLI-1780-000 LC cell without a phase compensator is shown in Fig. 4. Please note that the choice of ZLI-1780-000 is arbitrary; there are many high performance commercial LC mixtures available. As voltage exceeds the threshold, transmission oscillates for several cycles and finally decreases to zero in the high voltage regime. Due to the LC birefringence dispersion, these transmission curves are generally very sensitive to wavelength in the low voltage regime as shown in Fig.4.

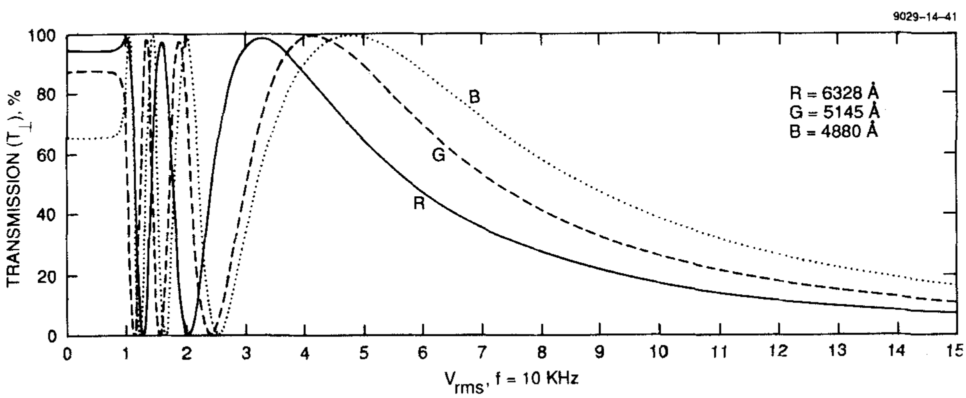


FIGURE 4 Voltage dependent optical transmission of a parallel-aligned LC cell situated as shown in Fig.3 except no LC compensator. The LC used for this illustration is 4-μm-thick ZLI-1780-000. V_{th}=0.9 V_{rms} at f = 10KHz and T = 23°C.

A. Physical Mechanisms

The transient nematic effect operates at the last transmission cycle, as shown in Fig.4. The LC directors are initially driven to nearly perpendicular to surfaces (except boundary layers) by the root-mean-square voltage of the applied voltage bursts. During the relaxation period, the applied voltage is in its null state for a short period of time so that the maximum restoring torque is achieved. Once the bright state is reached, the LC directors are reactivated by the next voltage burst to their dark state. The dynamic response of the LC directors under this operation condition is calculated numerically, using the Ericksen-Leslie equation, by neglecting the back-flow and inertia effects:

$$\frac{\partial}{\partial z}\left[\left(K_{11}\cos^2\phi+K_{33}\sin^2\phi\right)\frac{\partial\phi}{\partial z}\right]-(K_{33}-K_{11})\sin\phi\cos\phi\left(\frac{\partial\phi}{\partial z}\right)^2$$
$$+\left(\alpha_2\sin^2\phi-\alpha_3\cos^2\phi\right)\frac{\partial v}{\partial z}+\varepsilon_a E^2\sin\phi\cos\phi=\gamma_1\frac{\partial\phi}{\partial t}+I\frac{\partial^2\phi}{\partial t^2} \quad (3)$$

where ϕ is the deformation angle of the LC directors, K_{11} and K_{33} represent the splay and bend elastic constants, $\varepsilon_a\left(=\varepsilon_{\parallel}-\varepsilon_{\perp}\right)$ is the dielectric anisotropy, $E(z)=D_z/\left[\varepsilon_{\parallel}\sin^2\phi+\varepsilon_{\perp}\cos^2\phi\right]$ is the electric field in the LC medium, D_z is the z component of the electric displacement, v is the flow velocity, α_2 and α_3 are the Leslie viscosity coefficients, $\gamma_1 = \alpha_2 - \alpha_3$ is the rotational viscosity, and I is the inertia of the LC director, which is so small that it can be neglected.

Results on the LC director's spatial distribution are shown in Fig. 5. The example illustrated in Fig. 5 is a parallel-aligned, 15.5-μm-thick E-7 LC cell driven at $V/V_{th} = 14$. The total phase change of this cell at $T = 23°C$ and $\lambda = 632.8$ nm is 11π for a single pass. However the required voltage for obtaining the full amount of phase change is very high, because the boundary layers are strongly anchored with surfaces and difficult to reorient by the electric field. At $V/V_{th}=14$, the achievable phase change is 10.6π. Fig. 5 shows the director's redistribution corresponding to a phase change from 10.6 to 10π. Two cases on 10π are possible, depending on whether a constant bias voltage is present or not. These two cases result in slightly different director configurations. From our computer simulations, the one with a constant bias voltage (bias voltage effect) involves more bulk LC layers (dotted line) than the transient nematic effect (solid line). A constantly present bias voltage leads to a long relaxation tail and a slower response time.[10] In the transient nematic effect, only the surface LC layers (or high order Fourier components) are involved in the dynamic response; the bulk remains basically unchanged. The higher order Fourier components exhibit faster response times than the corresponding lower orders.[3] As a result, fast response times are achieved.

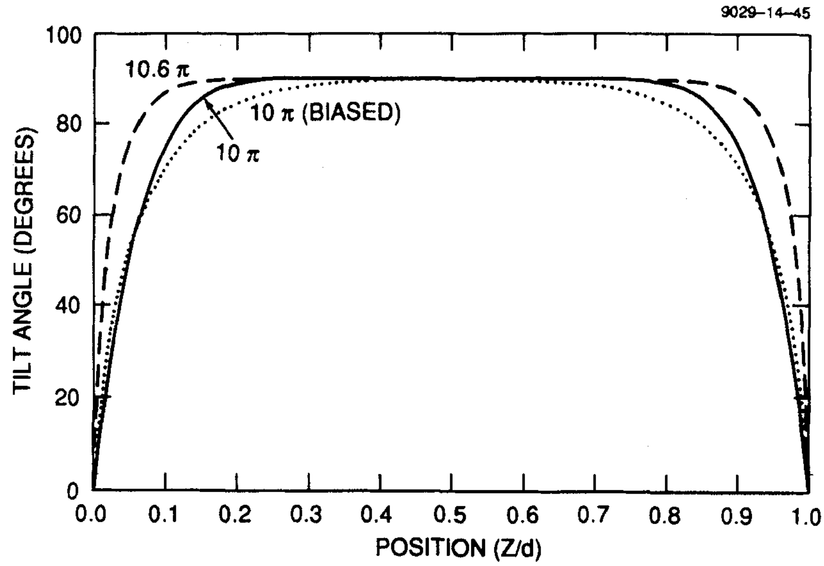


FIGURE 5 Dynamic response of LC directors under transient nematic effect and bias voltage effect. The LC cell used for this study is a 15.5-μm-thick, parallel-aligned E-7. $\lambda = 632.8$ nm. $T = 23°C$. The switching ratio (V/V_{th}) is 14 and the total phase change is 10.6π. The director's distribution before the voltage is removed is shown as the dashed lines. The solid line and dotted lines are computer results corresponding to $\delta = 10\pi$ without and with a constant bias voltage, respectively.

B. Unique Features

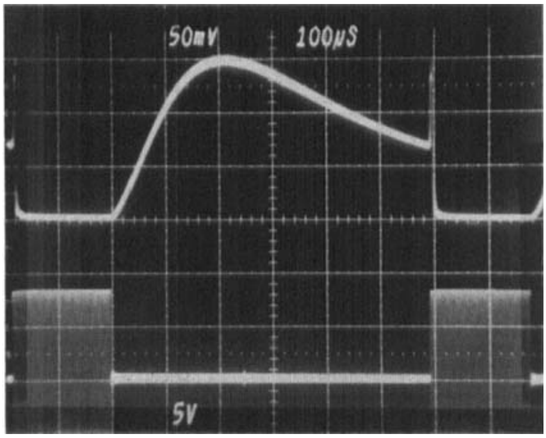
The optical decay time, t_o, (from a bright state to 0%) of the transient nematic effect has been derived as follows:[9]

$$t_o \cong \left(\frac{\Delta/\pi}{2\pi}\right)^2 \frac{1}{\left(1-\beta V_{th}/V\right)^2} \frac{\gamma_1\lambda^2}{K_{11}\Delta n^2} \tag{4}$$

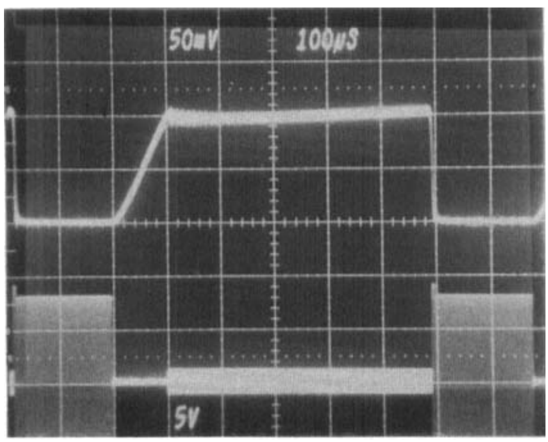
where Δ is the phase change between the light ON and OFF states, β is a material constant (e.g., $\beta \cong 0.6$ for E-7 at $T = 23°C$), and V ($V \gg V_{th}$) is the rms voltage applied to the cell.

From Eq.(4), the transient nematic effect exhibits several interesting features: (1) decay time t_o is insensitive to LC layer thickness provided that the total phase δ of the cell is much greater than 1π. Nevertheless, the use of a thicker LC layer would result in a higher operation voltage, which is undesirable. At a given wavelength, the required voltage is linearly proportional to the LC layer thickness. A typical thickness for realizing the transient nematic effect is about 5 μm for the reflective mode operation. At this thickness, the back-flow takes place at a much later time than the transient nematic effect and does not interfere with the optical signal. (2) t_0 is insensitive to the applied voltage in the $V >> V_{th}$ regime; but from the standpoint of lowering the operation voltage, LCs with low V_{th} are highly desirable. (3) t_0 is inversely proportional to $K_{11}\Delta n^2/\gamma_1\lambda^2$, which are intrinsic LC material parameters. This merit factor is dependent on temperature, because each parameter is temperature sensitive; in particular, the viscosity decreases exponentially with increasing temperature. High temperature operation makes a significant improvement in the response time of a LC modulator. A 30μs frame time nematic LC modulator has been demonstrated at ~ 100°C using a commercial LC.[11] For a given LC, this merit factor exhibits a maximum at an optimal operation temperature[12] which is about 20 degrees below the clearing point. (4) t_0 is proportional to Δ^2, which indicates the reflective mode operation is four times faster than the transmissive mode, at the expense of about two times higher operation voltage.

The controllability of the durations of the ON and OFF states of a LC modulator is an important issue. In the transient nematic effect, the light OFF state is manipulated by the pulse width of the activating voltage, as demonstrated in Fig.6(a) for a 5-μm E-44 LC cell operated at reflective mode and $\lambda = 514.5$ nm. Although the measurement was performed at room temperature, the actual cell temperature reached 40°C after a few minutes operation due to the dielectric heating effect of E-44 through the applied high frequency (50 KHz sinusoidal waves) electric field. If the voltage-off state is too long, the optical signal climbs over the first maximum and approaches the next minimum (Fig.6a), causing a non-uniform intensity output. One way to maintain a constant output is to apply a holding voltage at a pre-determined time after the free relaxation starts, as shown in Fig.(6b). This small holding voltage serves three purposes:[13] 1) It controls the duration of the light ON state; 2) it leads to a constant optical output, and 3) it



(a)



(b)

FIGURE 6 (a). Response times of a 5-μm-thick, E-44 LC cell configured as shown in Fig. 3 except no compensator. λ = 514.5 nm. T = 23°C, but the cell was heated up to 40°C after ~10 minutes operation due to the dielectric heating effect. The voltage scale is 50V/div. (b). A small holding voltage is applied to maintain the output at a constant level and shorten the response time. The transmission shown here is truncated at ~ 66% due to the early application of the holding voltage.

shortens the response time, at the price of sacrificing some transmission efficiency, when the holding voltage is applied at an earlier time (Fig.6b) before the optical signal reaches its maximum.

3. HIGH SPEED LC MODULATORS

From Eq. (4), the response time of a LC modulator employing the transient nematic effect is determined by the visco-elastic coefficient, birefringence and wavelength. Moreover, from Fig. 4, sharpening the transmission curve of the last cycle would reduce the operation voltage and response time. In this section, molecular parameters affecting the performance of the LC modulators are briefly analyzed. The combination of the transient nematic effect and the Fabry-Perot effect to steepen the transmission curve is discussed.

A. Molecular Tailoring

LCs with high birefringence and small visco-elastic coefficient are essential for achieving fast response times. Based on the phenomenological birefringence dispersion theories,[6,14] a LC molecule with long resonance absorption wavelength, large oscillator strength and large dichroic ratio would exhibit a large birefringence. Also, from the statistical viscosity theories,[15,16] LCs with linear shape, low activation energy, low molecular association or no dimer formation, small inertia moment and elevated temperature operation would exhibit small rotational viscosity.

A highly conjugated but linear LC molecule would satisfy most of the above mentioned criteria. For example, diphenyl-diacetylenic LCs are not only highly conjugated but rather linear along the principal molecular axis. Thus, the homologues of diacetylenes should be very useful. Indeed, these LC molecules are found to exhibit both high Δn and reasonably low viscosity.[17] However, some problems associated with these LCs are found: (1) These LCs are symmetric in shape, so their dielectric anisotropy is relatively small. As a result, the required operation voltage is too high. Asymmetric diacetylenic LCs should have a large dielectric anisotropy, but they are harder to synthesize; (2) The melting points for highly conjugated LCs are usually high; and (3) The photo-stability of highly conjugated LCs is a concern when they are exposed to UV irradiation due to their long absorption wavelengths and strong absorption.[18] Using a HRL-formulated LC mixture, a nematic LC modulator with a frame time of about 50 μs has been demonstrated at room temperature and λ = 514.5 nm.[13]

B. Fabry-Perot Effect

To demonstrate the transient nematic effect in a Fabry-Perot cell, we use the transmissive mode operation. The LC director's axis is oriented to be parallel to the polarization of the incoming light. No analyzer is needed because the Fabry-Perot effect is based on the phase modulation. The reflectivity of each substrate is about 90% throughout the visible spectral region by depositing a two-pair Si/SiO_2 dielectric mirror onto the substrates. After the mirror deposition, a thin SiO_x alignment layer was evaporated to produce a good LC alignment. Voltage dependent transmission of a 6-μm, parallel-aligned E-44 LC cell at λ = 632.8 nm and T = 23°C is shown in Fig. 7.

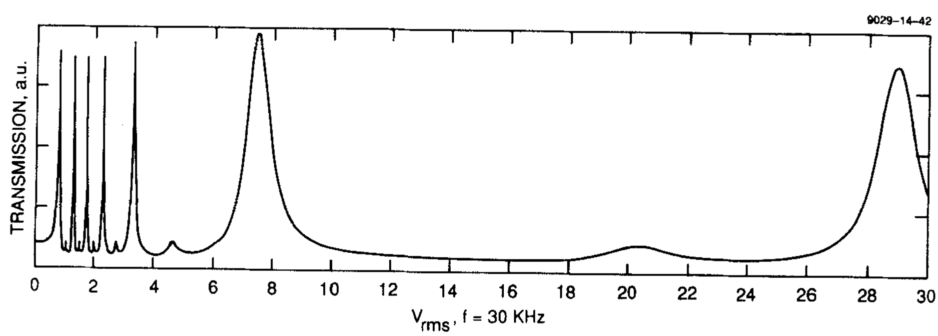


FIGURE 7 Voltage-dependent optical transmission of a Fabry-Perot LC cell in a single pass. The director's axis is parallel to the incoming light polarization. No analyzer is needed. The LC used is a 6 μm E-44. λ = 632.8nm. The reflectivity of each surface is ~ 90% at visible wavelengths.

Indeed, each transmission cycle is much sharper than a normal parallel-aligned cell. The optical response of such a LC cell is shown in Fig. 8 for the last cycle operation. If the second last cycle is selected, the response times are somewhat slower but the required voltage is also lower. Rectangular (30KHz frequency) voltage bursts as shown in the lower traces of Fig. 8 were used. The upper traces are the corresponding optical responses. Compared to a 6-μm-thick E-44 cell at the normal transmission mode and at the same wavelength, the response time of the Fabry-Perot cell is about 5 times improved. However, a common drawback for the Fabry-Perot LC cell is in its low contrast. The overcoated alignment layer on the mirror may degrade the finesse of the cavity and result in poor contrast.

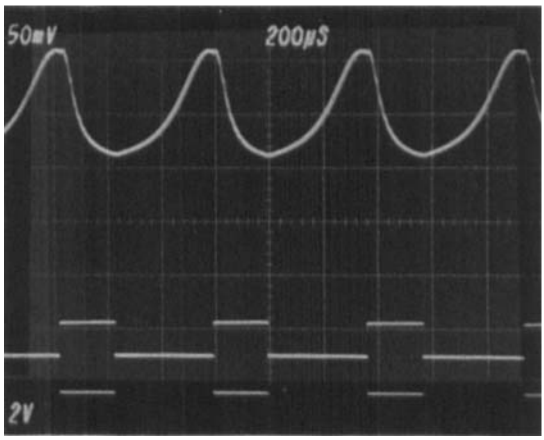


FIGURE 8 Response times of the 6-μm E-44 Fabry-Perot cell operated at the last transmission cycle as shown in Fig.7. Square voltage bursts with 30 KHz frequency are used to drive the cell.

4. TRANSIENT NEMATIC WITH A COMPENSATOR

The idea of adding a fixed phase compensator for lowering the operation voltage and improving contrast was discussed previously.[19,20] Here, we use a tunable phase compensator which is made from a LC cell. This LC compensator is made as identical as possible to the LC cell used for measurement. The experimental configuration is shown in Fig. 3. The planes of the LC compensator and the cell are parallel. The axis of the compensator is oriented at 45° to the incoming light polarization. The directors of the LC compensator and the cell are orthogonal so that the phase change experienced by the ordinary and extraordinary rays after propagating through these two cells compensates each other. By adjusting the voltage of the LC compensator, an excellent dark state was obtained at $V = 15\ V_{rms}$, as shown in Fig. 9. This dark state is insensitive to wavelength in a quite broad voltage region. Furthermore, this dark state can be manipulated by the voltage of the compensator. Evidence is shown in Fig. 10. The only difference between Figs. 9 and 10 is in the applied voltage of the compensator; the compensator voltages for Figs. 9 and 10 are $V_0 \cong 9$ and $8.5\ V_{rms}$, respectively.

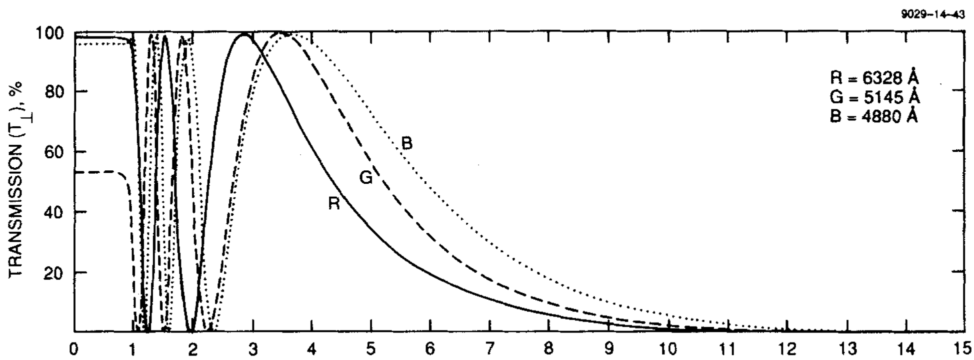


FIGURE 9 Same as Fig.4 except the LC compensator is inserted as shown in Fig.3. The compensator is nearly identical to the LC cell. The voltage applied to the compensator is ~ $9.0\ V_{rms}$.

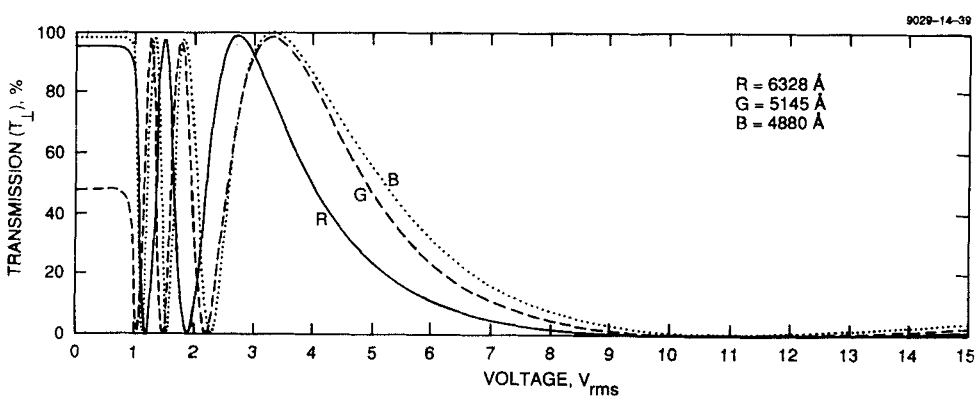


FIGURE 10 Same as Fig. 9 except the compensator's voltage is reduced to ~ $8.5\ V_{rms}$.

Two features in the compensator-LC cell system are noticed: (1) An excellent contrast is obtained at a relatively low voltage. The contrast ratio was measured to be about 1000 at HeNe laser wavelength, λ = 632.8 nm and spot size of 2 mm diameter. Without this compensator, a modest contrast can only be obtained at the price of very high voltage. (2) The voltages corresponding to the last transmission peaks of each wavelength decrease, resulting in a slightly slower response time.

5. CONCLUSION

A LC modulator with fast response time, high contrast ratio and low operation voltage employing the transient nematic effect was demonstrated. The response time using a commercial LC mixture is comparable to that of a typical ferroelectric LC modulator. The operation voltage is reduced and contrast ratio improved significantly by adding a tunable LC compensator in the system. Potential applications of these LC modulators are foreseeable.

REFERENCES:

1. J.Grinberg, W.P.Bleha, A.D.Jacobson, A.M.Lackner, G.D.Myer,L.J.Miller, J.D.Margerum, L.M.Fraas, and D.D.Boswell, IEEE Trans. Electron Devices, ED-22, 775 (1975).
2. S.T.Wu, Appl.Opt.28, 48 (1989).
3. F.Brochard, P.Pieranski, and E.Guyon, J.Phys.(Paris) 34,35 (1973).
4. M.Schadt and W.Helfrich, Appl.Phys.Lett. 18, 27 (1971).
5. J.Grinberg, A.Jacobson, W.P.Bleha, L.Miller, L.Fraas, D.Boswell, and G.Myer, Opt. Eng. 14, 217 (1975).
6. S.T.Wu, Phys.Rev.A33, 1270 (1986).
7. S.T.Wu, U.Efron and L.D.Hess, Appl.Opt. 23, 3911 (1984).
8. A.E.Perregaux, U.S.Patent 4,595,259 (1986); also, SID International Symposium Digest, 360 (1987).
9. S.T.Wu and C.S.Wu, Appl.Phys.Lett. 53, 1794 (1988).
10. S.T.Wu and C.S.Wu, J.Appl.Phys. 65, 527 (1989).
11. S.T.Wu and C.S.Wu, Mol.Cryst.Liq.Cryst.Lett. 7, 7 (1990).
12. S.T.Wu, A.M.Lackner and U.Efron, Appl.Opt. 26, 3441 (1987).
13. S.T.Wu, Appl.Phys.Lett. 57, 986 (1990).
14. S.T.Wu and C.S.Wu, J.Appl.Phys. 66, 5297 (1989).
15. M.Osipov and E.Terentjev, Z.Naturforsch.A44, 785 (1989).
16. S.T.Wu and C.S.Wu, Phys. Rev.A 42, 2219 (1990).

17. S.T.Wu, U.Finkenzeller and V.Reiffenrath, J.Appl.Phys. 65, 4372 (1989).
18. S.T.Wu, E.Ramos and U.Finkenzeller, J.Appl.Phys. 68, 78 (1990).
19. G.A.Dir and A.E.Perregaux, U.S.Patent, 4,767,190 (1988).
20. S.K.Hark and V.J.Hull, Conference Record of the International Display Research Conference (1988), Oct.4-6, San Diego, CA, p.170.