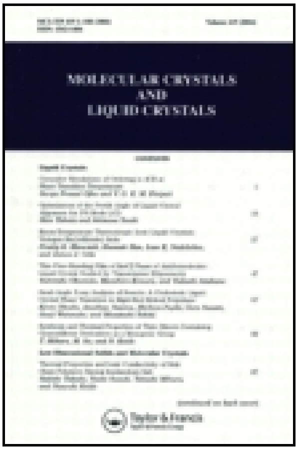


Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl16

The pi-Cell: A Fast Liquid-Crystal Optical-Switching Device

Philip J. Bos [a] & K. Rickey Koehler/beran [a]
[a] Tektronix, Inc., P.O. Box 500, Beaverton, Oregon, 97077, USA

Version of record first published: 17 Oct 2011.

To cite this article: Philip J. Bos & K. Rickey Koehler/beran (1984): The pi-Cell: A Fast Liquid-Crystal Optical-Switching Device, Molecular Crystals and Liquid Crystals, 113:1, 329-339

To link to this article: http://dx.doi.org/10.1080/00268948408071693

Mol. Cryst. Liq. Cryst., 1984, Vol. 113, pp. 329-339
0026-8941/84/1134-0329/$20.00/0

THE pi-CELL: A FAST LIQUID-CRYSTAL OPTICAL-SWITCHING DEVICE

PHILIP J. BOS and K. RICKEY KOEHLER/BERAN
Tektronix, Inc., P.O. Box 500, Beaverton, Oregon 97077, USA

Abstract A new approach is given for obtaining fast electro-optical response and good angular-viewing characteristics in a liquid-crystal variable-retardation device. The improved characteristics make the new device well suited for use in field-sequential color systems.

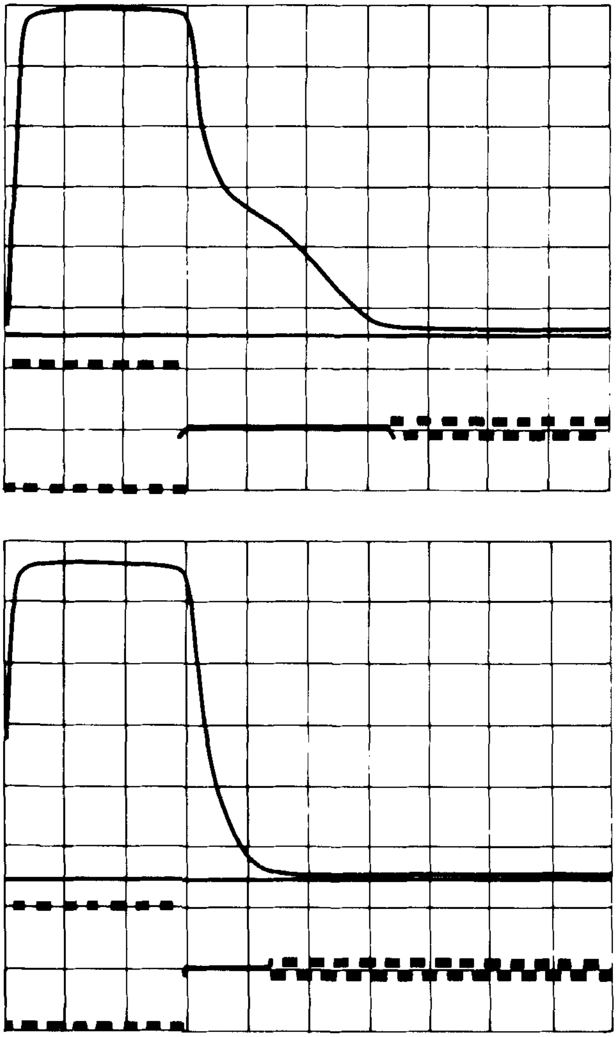
INTRODUCTION

This paper describes a new approach to making a fast liquid-crystal optical-switching device that also has low power consumption and a large cone of view. The approach is compared with some previously reported fast liquid-crystal devices.

CONSTRUCTING A LIQUID-CRYSTAL DEVICE FOR FAST RESPONSE (BACKGROUND)

For some applications, such as a field-sequential color display,[1] the relaxation time of a liquid-crystal device must be less than a few milliseconds. The relaxation times of conventional twisted nematic devices to their twisted state are much longer than this, primarily because of the backflow-induced alignment phenomenon.[2,3,4] In an earlier paper, we show that a twisted nematic device having a $-3\pi/2$ radian twist can be built in which the flow alignment is not a problem and, consequently, the device relaxes much faster.[5] Another technique for obtaining fast response is to use "two-frequency" twisted nematic devices.[6] This technique, however, requires the use of drivers that must deliver a high-frequency signal into a large capacitive load. Other problems are the limited temperature range of the devices and the difficulty in getting cells to switch uniformly over large areas.[7]

Another approach to making a fast cell is to start with a variable-retardation device[8,9,10] having homogeneous alignment. A speed advantage might be expected over twisted devices because the director is required to rotate through a smaller angle between the ON and OFF states. The director in the untwisted device need tip only about 30° in a cell whose thickness is $2\,\lambda/\Delta n$, while it must tip about 40° in a $\pi/2$ cell of the same thickness[11] and about 55° in a $-3\pi/2$ cell.[12] So except for flow-alignment effects, the untwisted device should be the fastest. Figure 1(a) shows the optical response ($\lambda = 545$ nm) of a $5.2 \pm 0.4\,\mu m$ untwisted cell filled with 1132 (Ref. 13). The



(a)

(b)

Figure 1. Electro-optical response of a uniform cell (a), and a π-cell (b). The light transmission ($\lambda = 0.545$ μm) was measured for the cells placed between parallel polarizers aligned at 45° to the liquid crystal surface alignment direction. Both cells are filled with the compound 1565 and are around 5.3 μm thick. A small holding voltage (around 2 V) was applied to arrest the cell's relaxation when the optical retardation was a half wave. (Horizontal scale: 2 msec/div).

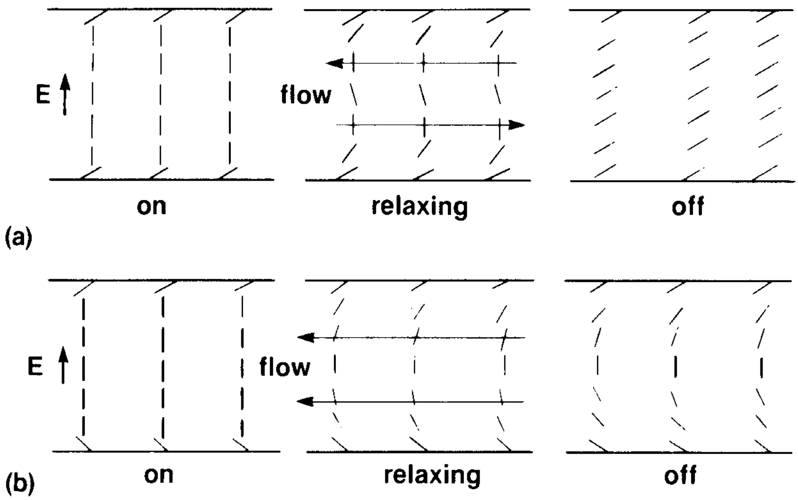


Figure 2(a). Material flow that takes place in a relaxing, uniformly aligned cell. A result of this flow is to apply a "backwards" torque on the local directors near the center of the cell. This shows the cell's relaxation to the OFF state. (b) The material flow that takes place in a relaxing π-cell. No torque is applied to the local directors near the center of the cell, and the cell relaxes quickly to its OFF state.

relaxation time (100%-10%) is 5.5 msec. The tilt is in opposite directions on the two surfaces to produce a uniformly aligned cell as shown in Fig. 2(a). The cell was placed between parallel polarizers with the alignment at 45° to the polarizer axis. The optical response shows the same backflow-induced "optical bounce" problem seen in a $\pi/2$ twist cell.[3] Making the cell as thin as possible ($d = \lambda/2\Delta n$) speeds the relaxation of the cell, as would be expected.[14] A cell constructed the same as the previous one but $2.0 \pm 0.4\ \mu$m thick showed a relaxation time of 3.5 msec (100%-10%) with $\lambda = 545$ nm. It is interesting that speed improvement over the cell whose response is shown in Fig. 1(a) can also be obtained by making the cell thicker. By making the thickness $8.8 \pm 0.4\ \mu$m, the relaxation time can be reduced to 1.9 msec. Part of the speed improvement results from the lack of a noticeable "bounce." That thick variable-retardation cells can exhibit rapid relaxation has been previously noted and explained as an uncoupling of the surfaces.[15] A problem with this approach is the limited cone of view.

THE π-CELL

This paper describes an alternative way—eliminating the adverse effects of flow alignment—to speed up a variable-retardation device. The approach is to provide a surface alignment that will cause the flow patterns set up within the relaxing cell to produce no "backwards" torque on the director near the center of the cell. Figure 2(a) shows the direction of material flow in a uniformly aligned cell. As described by VanDoorn,[2] the flow causes a "backwards" torque to be exerted on the local directors near the center of the cell and slows the cell relaxation. In the π-cell, the surfaces are treated so that the pretilt direction is the same on both surfaces, so the flow causes no torque to be applied to the central directors. A cell having this type of alignment would be expected to relax, after the aligning field is removed, through a state as shown in Fig. 2(b), in which the directors throughout the cell are roughly co-planar. This is the intended OFF state of the device. The thickness of the cell is chosen so that the retardation in this planar configuration is a half wave.

If the cell were allowed to further relax, it would adopt a π-radian twist [Fig. 3(a)] that would, over a period of minutes, convert to a splayed configuration [Fig. 3(b)]. Boyd, *et al.*[16] previously studied the transition between the splayed and twisted states in a similar cell. Here, however, we are primarily interested in the relaxation from the electric-field aligned state to the planar configuration shown in Fig. 2(b) because, in our application, the cell is switched ON again before the relaxation proceeds further.

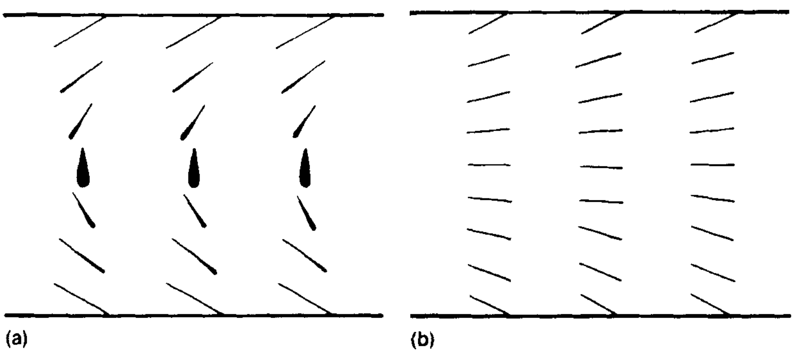


Figure 3. Relaxed director configurations in cell where the tilt direction is the same on both surfaces: (a) the π-radian twist configuration; (b) the splayed configuration.

CHARACTERISTICS OF THE π-CELL

The electro-optical response of a 5.4 ± 0.4 μm π-cell filled with 1132 is shown in Fig. 1(b). The cell's two glass plates were coated with an alignment layer that causes the director to tilt in the same direction on both suıfaces. The relaxation time is 1.7 msec.

Another nice feature of this device is that the angle of view is quite large. This is because of the optically self-compensating nature of the director configuration. Figure 4 shows that for normally incident light, the cell has an effective birefringence (Δn) and thickness (d) such that $\Delta nd/\lambda = 1/2$. For the obliquely incident light ray shown in the figure, the ray will be more nearly parallel to the optic axes in the bottom half of the cell than for the case of normal incidence but, in the top half, the ray will be at a greater angle to the optic axes than in the case of normal incidence. So light passing through the cell at an angle will see a lower effective birefringence than normally incident light in one half of the cell but a higher effective birefringence in the other half. This compensation improves the off-state angle of view considerably over that obtained in a uniformly aligned cell of the same thickness. To demonstrate this, two nearly identical cells were built. Each was filled with 1565 (Ref. 13) and were approximately 4.6 μm thick. The cells were different only in that, in one the director tilt direction on the two surfaces was the same (π-cell), and in the other they were opposed (uniform cell). Data was recorded at the point where each cell was a half-wave retarder for normally incident light ($\lambda = 0.545$ μm). Figure 5 shows the transmitted light intensity for each cell between parallel polarizers. The light was incident at 40° from the cell normal and was recorded for azimuthal angles ranging from 0° to 360°. The radial axis is the percent of light transmitted relative to the maximum amount of light possible to be transmitted through the cell with the two polarizers at normal incidence (roughly the ON state intensity between parallel polarizers). For a perfect angle of view, the intensity would be zero at all azimuthal angles.

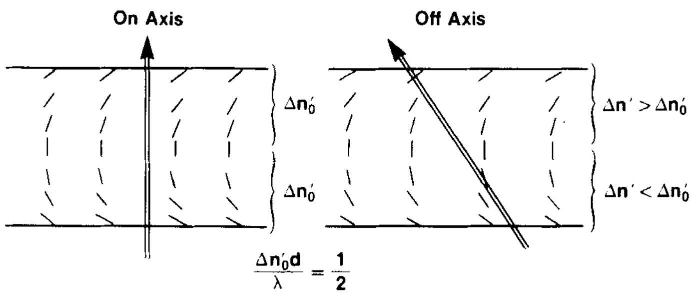


Figure 4. Off-axis optical self compensation of the off-state.

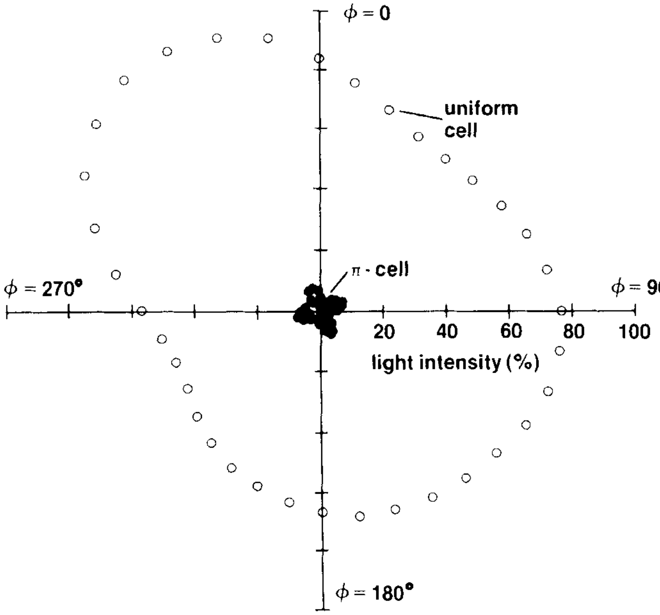


Figure 5. Transmitted light intensity through a π-cell (solid curve) and a uniform cell (dots) placed between parallel polarizers. The light ($\lambda = 0.545$ μm) was incident at 40° to the cell normal. Both cells were in a state of half-wave retardation for normally incident light.

THE OFF-STATE DIRECTOR CONFIGURATION

When one observes the optical response of a π-cell on a longer time scale, the relaxation of the director configuration through the transient OFF state to the π-radian twisted configuration is evident. As the directors are in the process of twisting, the effective retardation of the cell can decrease.[11] The effect of this can be seen in Fig. 6; the optical response for trace (b) is noted to have three transmission minima. Our explanation is that the directors initially relax in a plane to the point where the optical retardation is slightly greater than a half wave; then as the director field twists, the retardation is lowered to somewhat less than a half wave; and finally, when the twisting is complete and the molecules complete their relaxation to be roughly parallel with the cell surface, the retardation again increases to a final value of slightly greater than a half wave. So the first hump and the final rise in Fig. 6(a) are the result of the retardation being slightly greater than a half wave, but the middle hump is where the retardation is less than a half wave. Consistent with this explanation is the observation that if the cell is made thicker

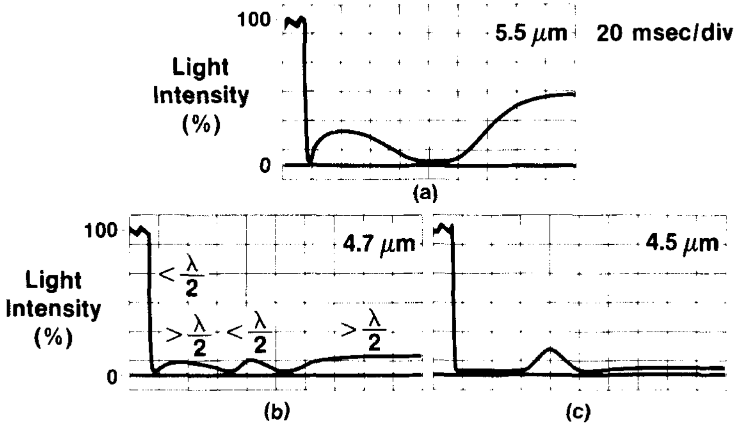


Figure 6. Electro-optical response of a π-cell using the material 1132. The cell thickness for trace (a) is 5.5 μm, for trace (b) is 4.7 μm, and for trace (c) is 4.5 μm. The wavelength of light was 0.545 μm. The horizontal scale is 20 msec/division. A 30-V drive voltage was applied to the cell for 12 msec.

[Fig. 6(a)], the first hump and the final rise grow in intensity and, if it is made thinner [Fig. 6(c)], the middle hump grows.

In applications where we have used cell thicknesses (with 1132) close to 4.5 μm, the retardation of the device remains near a half wave in excess of 20 msec. Alternatively, if the cell is made thick enough so that there is little tendency for the director field to twist at the point where it passes through a half-wave retardation, then a small voltage can be applied to arrest the cell's relaxation at a half-wave retardation and to hold it there for several tens of milliseconds. In cells using the compound 1132, this condition was found to be met when the first hump in Fig. 6(a) has an intensity greater than 10% (cell thickness > 5.3 μm).

As mentioned previously, it is our intent to operate the device with the "OFF" state director configuration being roughly co-planar. To more accurately know what the director configuration is in the "OFF" state, the approach was taken of comparing the angle-of-view data with that calculated for a particular configuration. The problem was simplified by noting that the cone-of-view data for a cell held in its half-wave state by a holding voltage is the same as that for the same cell as it passes through its transient half-wave state. So rather than trying to find the director configuration of the dynamic off state, it is necessary only to consider the static case of a cell in the presence of a small electric field. If the cell can be held in its half-wave state without twisting, the surfaces must be fairly uncoupled. So the angle that the director makes with respect to the cell normal as a function of the distance from the surface will be similar to that for the case of a semi-infinitely thick cell. So we can say:[17]

$$\Theta = 2\tan^{-1}\exp(-z/\varepsilon) \quad \text{for } z=0 \text{ to } d/2$$
$$= 2\tan^{-1}\exp[-(d-z)/\varepsilon] \quad \text{for } z=d/z \text{ to } z$$

where $\varepsilon = \frac{1}{E}\sqrt{\frac{4\pi K}{\Delta\varepsilon}}$

By using the holding voltage necessary to hold the cell in its half-wave state (1.8 V) with $K = 10 \times 10^{-7}$ dynes and $\Delta\varepsilon = 6$ for the material 1565, we calculated a coherence length of 1.2 μm. The model cell was divided into nine layers, each having uniform director alignment. The director orientation in layers one through four and in nine through six was taken from the above equations, with layer five forced to have the director along the cell normal. The optical retardation for normally incident light on the modeled cell was calculated to be very close to a half wave.

To see how this modeled director configuration agrees with the actual configuration, cone-of-view data was first acquired for a π-cell in its transient half-wave state. A 5.3 μm π-cell filled with the material 1565 was placed between polarizers aligned at 45° to the alignment direction. Data was taken for light ($\lambda = 0.545$ μm) incident on the cell at an angle of 40° to the cell normal for azimuthal angles ranging from 0° to 360°. The data is shown in Fig. 7 for the case of parallel and crossed polarizers. Light intensity is shown on the radial axis as a percent of the maximum intensity possible to be transmitted through the package at normal incidence. The light intensity through a π-cell between polarizers was calculated using a simple optical-modeling algorithm that took into account the angular dependence of the birefringence of the cell, the absorption of the polarizers, and the reflections at the air-glass interfaces of the cell and polarizers.

The results are plotted along with the data in Fig. 7. The only input to the modeling process was Δn, K, and $\Delta\varepsilon$ of the liquid crystal; the thickness of the cell; the voltage required to hold the cell in a half-wave state; the absorption of the polarizers; and the wavelength of the light used. Because no adjustable parameters were used, the match between the calculated intensities and the data is a good indication that the director configuration calculated is very nearly correct.

SOME MATERIALS CONSIDERATIONS

Some materials considerations are that: the clearing point be high to minimize the effect of the variation of Δn caused by variations in the nematic order parameter within the temperature region of interest; the birefringence be low so that cells can be made thick without being optically thick to minimize the effect of thickness variations while maintaining a large cone of view; and the turn-off time be short. Because π-cells made with different materials will be desired to have the same optical thickness, the expression for the turn-off time given in Ref. 14 can be expressed in terms of material parameters as:

$$t_{off} = \frac{\eta}{K(\Delta n)^2}$$

Figure 8 shows the turn-off times of several commercially available materials versus a number proportional to the above expression. The deviations from the straight line are probably due to the over simplification of the one elastic constant approximation and to the possible differences in the anchoring energies for the various materials.

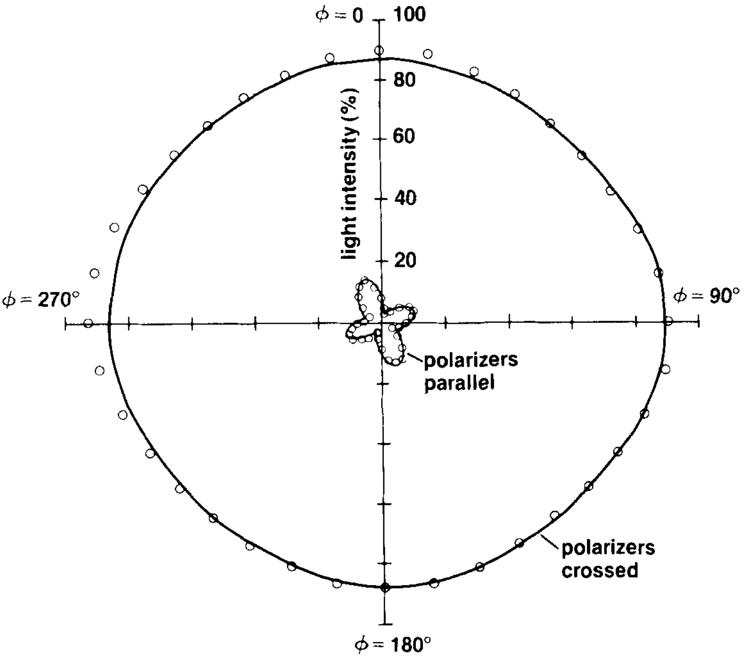


Figure 7. Calculated transmitted light intensity (solid curves) for a π-cell between polarizers, and data (dots). The data cell was 5.3 μm thick and filled with the material 1565. The light had a wavelength of 0.545 μm and was incident at 40° to the cell normal.

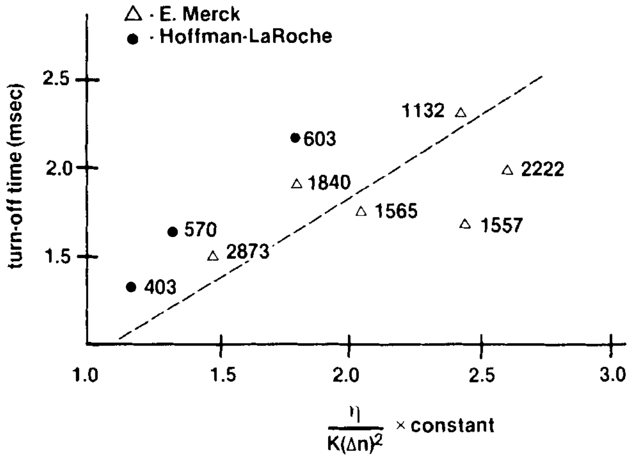


Figure 8. Turn-off time for π-cells using several commercially available liquid-crystal materials. The thickness of each cell was 1.25 $\lambda/\Delta n$. ($\lambda = 0.545$ μm).

CONCLUSION

A variable-retardation device aligned so that the director tilt is in the same direction on both surfaces has been shown to have a fast relaxation time and a relatively large cone of view. It does not have the problems of the "two-frequency" twisted nematic cell previously used in applications requiring a fast switching liquid-crystal cell. The characteristics of the new device make it well suited for use in field-sequential color systems, as well as for other applications in which a high-speed optical shutter is needed.

REFERENCES

1. R. Vatne, *et al.*, *SID Digest of Technical Papers* (1983).
2. C.Z. van Doorn, *J. Physique,* **34,** 9 (1973) 18.
3. C.Z. van Doorn, *J. Appl. Phys.,* **46,** 9 (1975) 3738.
4. D.W. Berreman, *J. Appl. Phys.,* **46,** 9 (1975) 3746.
5. R.L. Hubbard and P.J. Bos, *IEEE Trans. Electron Devices,* **28,** 6 (1981) 723.
6. E.P. Raynes and I.A. Shanks, *Electronics Letters,* 4 (April 1974) p. 114, and I.A. Shanks, *AGARD Conf. Proc.* (published by NATO, Neuilly-sur-Seine, France), **167,** pp. 18.1-18.11.
7. M.G. Clark and I.A. Shanks, *SID Digest of Technical Papers,* (1982) p. 172.

8. J.L. Fergason, T.R. Taylor, and T. Harsch, *Electro-Technology,* (January 1970).
9. F.J. Kahn, *Appl. Phys. Lett.,* **20** (1972).
10. R.A. Soref and M.J. Rafuse, *J. Appl. Phys.,* **43,** 5 (1972) 2029.
11. McIntyre [*J. Opt. Soc. Am.,* **68,** 6 (1978) 869] gives the values of $(\Delta n_{eff} d)/\lambda$ (where $\Delta n_{eff} \approx \Delta n \sin^2\Theta$, Δn is the birefringence of the liquid crystalline material, and Θ is the angle between the surface normal and the director) for the first transmission minimum of twisted liquid-crystal devices between parallel polarizers.
12. Assumes uniform director alignment.
13. E.M. Laboratories, Inc.
14. E. Jakeman and E.P. Raynes, *Phys. Lett.,* **39A** (1972) 69.
15. J.L. Fergason, *Conf. Record of 1980 Biennial Display Research Conf.*, p. 177.
16. C.D. Boyd, J. Cheng, and P.T. Ngo, *Appl. Phys. Lett.,* **36** (1980) 556.
17. *Introduction to Liquid Crystals,* (ed. E.B. Priestly, *et al.*) Plenum Press (1975) 114.