

© 1989 American Institute of Physics.

This article may be downloaded for personal use only. Any other use requires prior permission of the author and the American Institute of Physics.

The following article appeared in Applied Physics Letters vol. 54 and may be found at <http://link.aip.org/link/?APL/54/1394/1>.

# Electro-optic switching using total internal reflection by a ferroelectric liquid crystal

M. R. Meadows, M. A. Handschy, and N. A. Clark  
*Displaytech, Inc., 2200 Central Avenue, Boulder, Colorado 80301*

(Received 2 December 1988; accepted for publication 30 January 1989)

An electro-optic switch using total internal reflection by a ferroelectric liquid crystal is reported. The device has rise and fall times of about 150  $\mu$ s, and causes the optical power in the output beam to be attenuated by a factor of 500 000 in the off state. It does not employ polarizers, and its operation is nearly independent of wavelength. The measurements here cover the 400–1600 nm band.

Ferroelectric liquid crystals (FLCs) have a unique combination of electro-optic properties which complement those found in the more traditional solid and liquid electro-optic materials. Like the commonplace nematic liquid crystals, FLCs exhibit very large birefringence and require low levels of voltage and power to drive. Unlike the nematics, FLCs are capable of submicrosecond switching times. This difference opens a wide range of potential applications to FLCs, e.g., fiber optic switches, waveguide switches, and optical interconnects as well as traditional shuttering, chopping, and beam switching functions.

In the most commonly used configuration, FLCs are fabricated into a thin, optically uniaxial film. An applied dc electric field of around 10 V/ $\mu$ m of film thickness selects between two optic axis orientations, both lying nearly parallel to the plane of the film, but differing in direction by up to 90°. The polarity of the applied field determines which orientation is selected. Details of FLC physics which account for this behavior have been reviewed elsewhere.<sup>1–3</sup>

Optical switches using nematic liquid crystals in a total internal reflection (TIR) configuration were introduced by Kashnow and Stein.<sup>4</sup> Soref<sup>5–7</sup> showed how to extend the principle to unpolarized light and described and built several novel fiber optic switches.

A FLC can also be used to make a TIR switch as shown in Fig. 1. The FLC film is fabricated between glass prisms whose surfaces are coated with a transparent electrode. In the fabrication process, one of the two optic axis directions is made perpendicular to the plane of incidence of the light to be switched. The other optic axis direction is still in the plane of the film but is rotated by the angle  $\psi$ .

Suppose that the applied field selects the perpendicular direction. When  $\hat{s}$  linearly polarized light falls on the film, its electric field is parallel to the optic axis, so the light becomes an extraordinary ray which sees the principal refractive index  $n_e$  of the FLC. If the prisms have the refractive index  $n_g = n_e$ , then the light will cross the FLC film. This is the on state.

If the optic axis is switched to the second direction, the light is decomposed into an ordinary ray which sees the principal refractive index  $n_o$  and an extraordinary ray which sees the refractive index

$$n_e = \sqrt{n_e^2 [1 - (n_e^2 - n_o^2)/n_o^2 \sin^2 \psi \sin^2 \theta]},$$

where  $\theta$  is the angle of incidence. Common FLCs are positive

uniaxial with  $n_e \gg n_o > n_g$ , so it is possible to choose  $\theta$  to be beyond the critical angle for both rays. This requires

$$\theta > \arcsin [n_o^2 / (n_e^2 \sin^2 \psi + n_o^2 \cos^2 \psi)]^{1/2},$$

and causes the incident light to experience TIR. This is the off state.

When  $\hat{p}$  polarized light is incident, the electric field is perpendicular to the optic axis in the on state: the light experiences the index  $n_o$  and TIR. In the off state, the light gives rise to the same two rays as does the  $\hat{s}$  light, and also experiences TIR. Thus,  $\hat{p}$  light is reflected in both states.

The resulting device should switch the  $\hat{s}$  component of the incident light between transmission and reflection while always reflecting the  $\hat{p}$  component. The switching mechanism should, moreover, be independent of wavelength.

Our prisms were made of Schott SF2 optical glass. The refractive index of this glass is 1.646 at 633 nm. The 1.8-in.-long rectangular face of each prism was coated with about 150 Å of indium tin oxide (ITO) to make the transparent electrode. The entrance and exit faces of the prisms were 0.5 in. square and were at an angle of 78° from the plane of the FLC film. Thus autocollimation provided a known angle of incidence at the FLC film which was then fine tuned to optimize the performance.

The FLC material was a commercially available mixture.<sup>8</sup> Its birefringence  $n_e - n_o$  is about 0.15 at 633 nm with an extraordinary refractive index of about 1.65, and its optic axis moves through approximately 42° between the two field-selected states. The critical angle inside the glass is thus approximately 72°, so the 78° angle of incidence reduces the penetration of the evanescent wave in the off state while al-

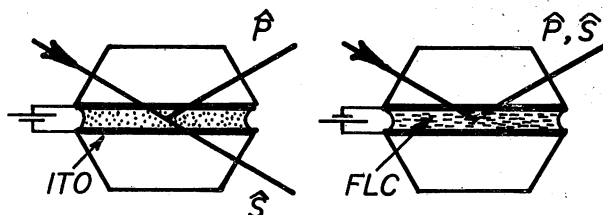


FIG. 1. TIR switch made by sandwiching a FLC film between a pair of glass prisms whose opposing surfaces carry an electrically conductive, optically transparent electrode. By appropriately aligning the film, it can be made to transmit linearly polarized light when a voltage is applied, while reversing the polarity will cause the light to be reflected. The left side shows the switch in the on state, while the off state is on the right.

TABLE I. These data characterize the performance of the FLC over the visible and near-infrared portions of the spectrum. The efficiency of the FLC film is described by the fraction of incident power transmitted in the on state,  $T_{on}$ . The ability to turn off is shown as the ratio of the transmittances in the off state and the on state. The data have been corrected for Fresnel losses at the air/glass interfaces.

$\lambda$ (nm)	$T_{on}$	$10^5 \frac{T_{off}}{T_{on}}$
450	0.61	1.1
550	0.76	1.9
650	0.87	2.1
750	0.82	2.2
850	0.90	2.0
950	0.83	1.2
1050	0.89	1.1
1150	0.87	1.6
1250	0.89	1.1
1350	0.85	1.4
1450	0.86	1.1
1550	0.77	2.2

lowing some tolerance in the alignment of the incident beam.

A polymer edge spacer with  $3.4 \mu\text{m}$  thickness was applied to one of the mating prisms. A second polymer was spun onto each prism to provide a layer of about  $100 \text{ \AA}$  thickness. These were then rubbed to force the FLC to align with one of its optic axis states perpendicular to the long edge of the prisms. Finally, the two prisms were assembled and the  $3.4 \mu\text{m}$  gap was vacuum filled with the FLC.

Each finished switch was inspected with a polarizing microscope. With 30 V applied between the electrodes, the FLC films always consisted of large featureless domains which showed reasonably good extinction when the optic axis was parallel to either polarizer axis. The domains were separated by a FLC defect called zig-zag walls. The alignment of the smectic layers changes discontinuously across a zig-zag wall,<sup>9,10</sup> producing a small refractive index discontinuity. The optic axis in the on state was perpendicular to the long edge of the prism to within  $2^\circ$ .

When a switch was placed in the linearly polarized beam of a He-Ne laser and autocollimated off the entrance face, the intersection of the beam with the FLC was an ellipse whose axes are about  $2 \times 10 \text{ mm}$ . When this ellipse was within a single domain, neither the reflected nor transmitted beams showed any apparent loss of beam quality. When the ellipse fell onto a region with zig-zag walls, the transmitted and reflected intensity patterns both acquired two narrow lobes of scattered light radiating out on opposite sides of the central beam. The angle between the plane of incidence and the plane of this scattering was about  $5^\circ$ .

Static measurements, which characterize the two states as a function of wavelength, were made with 30 V dc across the switch and with light from a tungsten-halogen lamp which was passed through a monochromator. The light was collimated to within a few degrees and linearly polarized to be perpendicular to the plane of incidence at the FLC film. A silicon photodiode was the detector in the 400–1000 nm spectral range, and a germanium photodiode was used for the 850–1600 nm range.

The static measurements for a typical device are shown in Table I. The middle column contains the fraction of incident optical power which crosses the FLC film in the on state. The Fresnel losses at the prism/air interfaces were removed by normalizing the measured transmittance of the entire switch with the value measured when the switch was replaced with a plain prism. These values have errors of about  $\pm 0.03$ , as estimated by repeated measurements and by comparing the values measured with the two detectors in the range they both cover. The lost light is removed from the beam by scattering, absorption, and by reflection from the electrodes. The transmission spectrum is expected to be modulated by interference between the two electrodes, but the effect is submerged below the precision of the data. One could obtain still better transmittance at the expense of spectral range by applying antireflection coatings to the ITO.

The rightmost column of the table is the contrast of the switched beam, defined as the ratio of the transmittance in the off state to that of the on state. Unpolarized input light was used for these measurements, and a mechanical chopper and lock-in amplifier were employed. The data show that very little power is transmitted in the off state. These data do not characterize the true situation, however: it is very easy to see with the eye that the transmitted power being measured comes from zig-zag wall imperfections in the FLC film which cannot be entirely avoided. With a He-Ne laser beam, however, data taken from a single FLC domain have shown contrast of  $2 \times 10^{-6}$ , and even these results represent the noise level of the measurement rather than the intrinsic device characteristic. It thus appears possible that in a well-aligned FLC film the extinction will be determined solely by tunneling of the evanescent wave.

The dynamic measurements, which characterize the switching behavior, were made with a linearly polarized, 5 mW, He-Ne laser. The detector was a Si photodiode which was attached to a broadband amplifier. The switch was driven with 30 V at 200 Hz, and the drive signal and the optical response were shown together on an oscilloscope. Typical rise and fall waveforms are shown in Fig. 2 where the horizontal sweep is  $100 \mu\text{s}/\text{div}$ . In all cases, the optical response was extremely stable and exhibited no detectable jitter relative to the drive signal. The 10-to-90 rise and the 90-to-10 fall times are both about  $150 \mu\text{s}$ , which are the same values we observe for this material's switching times at similar applied fields in a shutter made from a half-wave thick film between crossed polarizers. However, the switching dynamics of the TIR device are distinguished from those of the shutter by the

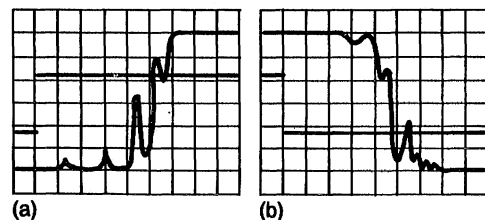


FIG. 2. (a) shows the optical rise of the transmitted beam, while (b) shows its fall. The featureless square wave is the 200 Hz driving signal, and the horizontal sweep is  $100 \mu\text{s}/\text{div}$ . The peaks during the rise and fall are due to multiple-beam interference.

appearance of the intensity peaks and dips preceding the saturation of the optical response. We explain these as follows.

The refractive index profile of the steady-state device has the thin, fixed ITO electrodes ( $n \approx 2$ ) and alignment polymer ( $n \approx 1.5$ ) outside the FLC film which has more or less uniform refractive index (off state  $n \approx 1.56$ , on state  $n \approx 1.65$ ). Calculations of the reflectance and transmittance of this profile predict a switch with some on-state efficiency loss due to reflections and an essentially perfect off state with no detectable tunneling. These characteristics are consistent with the observations summarized in Table I. During switching though, numerical calculations of FLC dynamics<sup>2,11</sup> show that the FLC optic axis direction becomes non-uniform shortly after an applied field reversal. The reorientation of the axis starts in the film's center and eventually grows out to the surfaces. The exact calculation of both the resulting refractive index profile and its optical properties is difficult. We have made calculations based on a simplified FLC profile, with thin, homogeneous outer layers having the refractive index of the unswitched FLC, and a homogeneous core of refractive index varying in time between the initial and final FLC refractive indices. The multiple-beam interference of this model produces peaks and dips much like those we observe, if not exactly identical in width, height, and time of occurrence. Welford *et al.*<sup>12</sup> have observed very similar phenomena in a device comprising a nematic liquid crystal film between partially silvered plates, where the optic axis distortion was produced statically by varying the drive voltage.

To summarize, we have demonstrated an electro-optic switch using total internal reflection by a ferroelectric liquid

crystal. The device provides fast switching, exceptional extinction, and high efficiency for light spanning the visible and near-infrared portions of the spectrum. The efficiency could be made still higher for a narrow band by applying antireflection coatings to the electrodes. Its contrast is better than 40 000:1 over the entire spectral range, and 500 000:1 at 633 nm for a selected FLC domain. With better FLC alignment it should be limited only by tunneling of the evanescent wave.

The present switch is useful as a broadband chopper or low-speed modulator. With improvements in the FLC alignment and application of an antireflection coating to the electrodes, the very high extinction could be exploited in  $1 \times N$  and  $N \times N$  switches and arrays for fiber optic, optical interconnect, and signal processing applications.

This work was supported by U.S. Air Force Systems Command under contract F19628-85-C-0087.

<sup>1</sup>N. A. Clark, M. A. Handschy, and S. T. Lagerwall, *Mol. Cryst. Liq. Cryst.* **94**, 213 (1983).

<sup>2</sup>M. A. Handschy and N. A. Clark, *Ferroelectrics* **59**, 69 (1984).

<sup>3</sup>N. A. Clark and S. T. Lagerwall, *Ferroelectrics* **59**, 25 (1984).

<sup>4</sup>R. A. Kashnow and C. R. Stein, *Appl. Opt.* **12**, 2309 (1973).

<sup>5</sup>R. A. Soref, *Opt. Lett.* **4**, 155 (1979).

<sup>6</sup>R. A. Soref and D. H. McMahon, *Opt. Lett.* **5**, 147 (1980).

<sup>7</sup>Richard A. Soref, *Appl. Opt.* **21**, 1386 (1982).

<sup>8</sup>The FLC mixture is designated LIXON CS-1014 and was obtained from Chisso Corporation, Tokyo, Japan.

<sup>9</sup>T. P. Rieker, N. A. Clark, G. S. Smith, D. S. Parmar, E. B. Sirota, and C. R. Safina, *Phys. Rev. Lett.* **59**, 2658 (1987).

<sup>10</sup>N. A. Clark and T. P. Rieker, *Phys. Rev. A* **37**, 1053 (1988).

<sup>11</sup>Yoshihiro Ishibashi, Hiroshi Orihara, Kohji Nakamura, and Yuichiro Yamada, *Jpn. J. Appl. Phys.* **26**, Suppl. 26-2, 107 (1987).

<sup>12</sup>K. R. Welford, J. R. Sambles, and M. G. Clark, *Liq. Cryst.* **1**, 91 (1987).