In-fiber nematic liquid crystal optical modulator based on in-plane switching with microsecond response time

Bharat R. Acharya,[a] K. W. Baldwin, R. A. MacHarrie, and John A. Rogers[b]
Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974

C. C. Huang
School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455

R. Pindak
National Synchrotron Light Source, Brookhaven National Laboratory, Upton, New York 11973

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We describe a simple method and device design that enables fast in-plane electro-optic modulation in conventional nematic liquid crystal (NLC) devices. When combined with optimized NLC materials, this approach yields rotational speeds of 1°/μs (independent of rotation angle, over a wide range) at a moderately low voltage. The observed rotational dynamics indicate that even these high speeds may not represent fundamental physical limits. We demonstrate these ideas in a compact tunable NLC waveplate that uses microelectrodes patterned directly on the tips of optical fibers. These devices offer fast, continuously tunable optic axis with low insertion loss and good performance in the near infrared. Modulators that use this design have promising potential applications for polarization control and analysis in optical communication systems. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1532532]

Electro-optical devices (such as, attenuators, switches, modulators, filters, etc.) are essential components of high-speed optical communication systems. Devices based on technologies such as microelectromechanical systems,[1] lithium niobate wave guides,[2] microfluidics,[3] liquid crystals (LCs),[4–6] etc. have been demonstrated, and many of these are extensively implemented in optical networks. For certain important applications, LC-based devices may offer some potential advantages: they possess high electro-optic response, nonmechanical operation, low power consumption, easy fabrication, and low cost. In this letter, we report an approach for achieving microsecond, low voltage in-plane rotation of nematic LCs (NLCs). The rotational dynamics indicate that even these high speeds are not limited by the technique itself or by the physics of the liquid crystal. We combine this approach with optimized NLCs and microelectrodes formed on the tips of optical fibers, to demonstrate a compact optical modulator that has many features that are attractive for optical fiber communication systems.

NLCs are materials whose molecules show preference for alignment with their neighboring molecules even though they are in the liquid state with no long-range positional ordering. The local orientation of the NLCs is described by the director (a unit vector along the direction of the average orientation of the molecules), which can be aligned by application of proper boundary conditions to achieve a macroscopic alignment.[7] An aligned layer of NLC behaves like a uniaxial medium; when light passes through an aligned layer of NLC, a phase difference is introduced between the ordinary and extraordinary rays.

To dynamically reorient the liquid crystal director, we use two pairs of thin (300 Å) gold electrodes, as shown in Fig. 1(a), patterned onto two glass substrates. The width of the electrodes was 40 μm and the spacing between them was 50 μm. A thin layer of polyimide SE7511 (Nissan Chemicals) spin cast onto these substrates provides the homeotropic alignment (i.e., the NLC director is perpendicular to the substrates). The electrodes on the top and the bottom substrates were aligned using an optical microscope. A cell with 5.5 μm gap, determined by the diameter of small (~10 μm long) glass spacer rods, was fabricated by pressing these two glass substrates together. The cell was filled with a NLC E7 (Merck Chemicals) in isotropic phase at 70 °C and then was

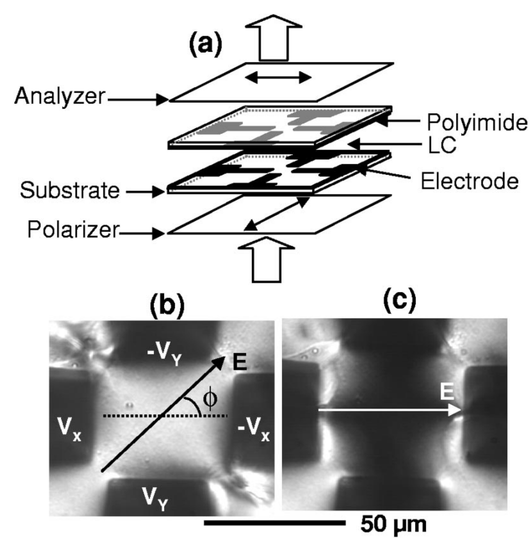

FIG. 1. (a) The geometry of the cell. Corresponding electrodes on the top and the bottom substrates are electrically connected together. The photomicrograph of the cell when the director is aligned at (b) $\phi = 45°$ and (c) $\phi = 0°$. In order to orient the LC director along the azimuthal direction ϕ, potentials $V_x = V_0 \cos\phi$ and $V_y = V_0 \sin\phi$ are applied.

[a]Electronic mail: bacharya@lucent.com
[b]Electronic mail: jarogers@lucent.com

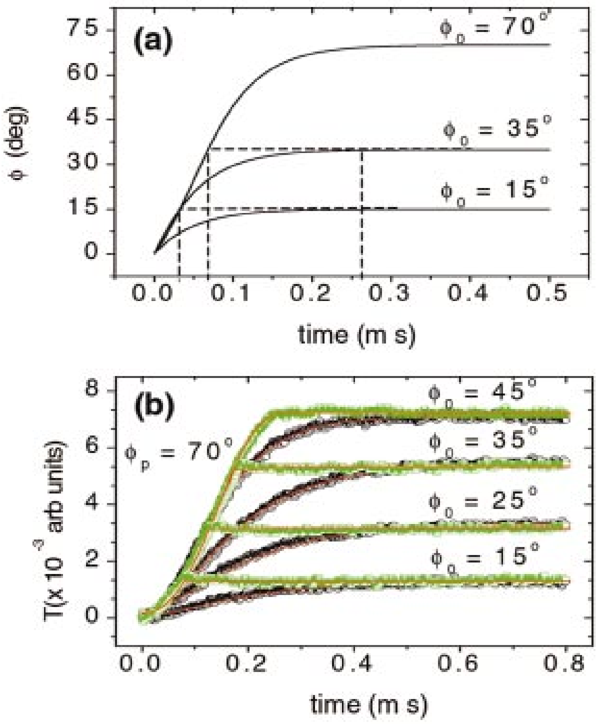

FIG. 2. (Color) (a) Theoretical dependence of the azimuthal orientation of the nematic director as a function of time when the electric field is applied at different angles at $t=0$. The dashed lines are drawn to indicate that the director rotates to 15° or 35° faster if the field is applied along $\phi_p = 70°$ than when it is along respective angles. (b) Variation of the optical transmission (T) for a cell filled with NLC E7 as a function of time with (green) and without (black) the initial triggering pulse along $\phi_p = 70°$. The solid lines are theoretical fits using Eqs. (2) and (3) to the experimental data.

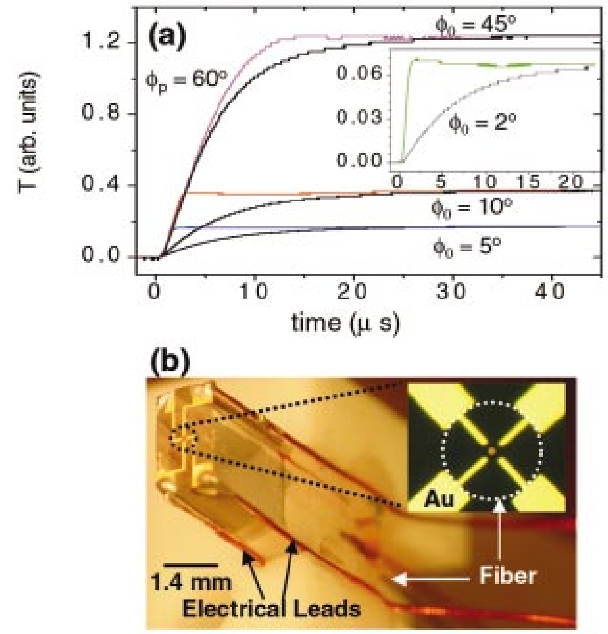

FIG. 3. (Color) (a) Switching characteristics for a cell filled with NLC MLC-14200-000 at 75 °C, with $V_0 = 400V_{pp}$ with and without triggering pulse along $\phi_p = 60°$ for various angular orientations. The inset shows the switching characteristics for 2° rotation. (b) The photomicrograph of the fiber ferrule used for fabrication of in-fiber waveplate. The inset shows the electrode structure at the tip of the ferrule. The circle represents the perimeter of the 125 μm diameter single mode fiber, and the dot at the center represents its core.

slowly cooled down to room temperature. The corresponding electrodes on the top and the bottom substrates were connected together, and a potential $V_i(\phi) = V_0 \cos(\phi + i\pi/2)$ was applied to the ith electrode, where V_0 was a 10 kHz square wave ac voltage. The azimuthal orientation ϕ of the electric field was controlled by adjusting the potential applied to these four electrodes. Numerical solutions of the three-dimensional Laplace equation with appropriate boundary conditions show that the orientation and magnitude of the field is uniform in a central region of 20 μm diameter to within ~5%. The LC cell was placed between two crossed polarizers and was illuminated by white light. A photodiode collected the light transmitted through this central region.

When the applied electric field is greater than a threshold value, the Frederiks transition occurs from the homeotropic to planar orientation. At sufficiently high electric field almost all the NLC molecules are aligned parallel to the substrates and the alignment layer has little effect. The in-plane orientation of the nematic director can then be adjusted by controlling the direction of the electric field (i.e., by adjusting the potentials V_i). When switched from one azimuthal orientation to another, the dynamic response of the NLC director is determined by the torques associated with viscosity, elasticity, and external field; it is also affected by the inertia of the NLC and surface effects. For simplicity, we make the standard assumption that the contribution from the surface, elasticity, and inertial effects are negligible in comparison to that from viscosity.[8,9] Thus, when an external field E is applied along the direction ϕ_0, the Erickson–Leslie equation describing the dynamic behavior of the NLC director becomes:[10]

$$\gamma_1 \frac{d\phi(t)}{dt} = \frac{1}{2} \Delta\varepsilon E^2 \sin 2[\phi_0 - \phi(t)], \tag{1}$$

where, γ_1 and $\Delta\varepsilon$ are the rotational viscosity and the dielectric anisotropy of the NLC material, respectively. The solution of Eq. (1) is given by

$$\phi(t) = \phi_0 - \tan^{-1}[\tan(\phi_0 - \alpha) e^{-t/\tau}], \tag{2}$$

with $\tau = \gamma_1 / \Delta\varepsilon E^2$ the characteristic *response time* of the NLC and α the initial azimuthal orientation of the director.

The rotational speed of the director is determined by the interplay between the viscous and electric torques. For given electric field strength and material parameters, it depends on the orientation of the field relative to the initial orientation of the director. Compared with small angular rotations, the maximum rotational speed is higher for rotations through large angle since the electric torque is also higher at larger angles. Figure 2(a) depicts calculated director profile as a function of time when an electric field is applied at $t=0$ for different orientations. For this calculation we have used $\tau = 50$ μs. It is clear from the figure that the angular speed of the director is not constant; the maximum speed is higher if the electric field is directed at larger angle with respect to the initial director orientation. Thus, the director can be rotated faster through an angle ϕ, if we apply the initial torque to the director as if it were to be rotated through $\phi_0 (> \phi)$. As soon as it rotates through ϕ, the external field is then switched to the value required to hold the director at ϕ. This effect can be exploited to improve the switching speed significantly if the device under consideration requires reorientation of the director through small angles (which is an essential capability for many important applications in optical communications). If a *triggering pulse* of strength E is applied for time t_1 along the direction ϕ_p and then a holding field of the same strength is applied along ϕ_0 at t_1, the solution to Eq. (1) for $t<t_1$ is given by Eq. (2) with ϕ_0 replaced by ϕ_p. For $t>t_1$, it is given by

$$\phi(t)=\phi_0-\tan^{-1}(\tan\{\phi_0-\phi_p+\tan^{-1}\times[\tan(\phi_p-\alpha)e^{-t_1/\tau}]\}e^{-(t-t_1)/\tau}). \quad (3)$$

The optical transmission of the cell between the crossed polarizers is given by $T(t)=\frac{1}{2}\sin^2(\delta/2)\times\sin^2 2\phi(t)$, where δ is the optical retardation of the NLC cell.

We have implemented this approach to achieve fast rotational speeds that are independent of reorientation angle over a wide range. Figure 2(b) shows the optical transmission of the NLC cell for different angles of rotation, with and without a triggering pulse along 70°, when $V_0=300\mathrm{V_{pp}}$ was applied across the electrodes. As soon as the optical transmissions attained a value corresponding to the necessary angular rotation of the director, the triggering pulses were turned off, and electric field needed to hold the transmission at the corresponding value was applied thereafter. Clearly, compared to the conventional driving scheme, the switching time improves significantly when an initial triggering pulse is applied, especially for small angles. Moreover, the NLC director follows the trajectory generated by the triggering pulse in a predictable fashion for all angles. This behavior simplifies the design of the driving electronics. The solid lines are theoretical fits using Eqs. (2) and (3) with $\alpha=0$ to the experimental data. From these fits, a close agreement between the experimental data and theoretical predictions can easily be inferred. Although the time scale associated with inertial and other effects are typically reported[9] to be on the order of microseconds, these effects are not observed in the regime we explored even for small angular rotations, thereby validating the assumptions that led to Eq. (3). The absence of inertial effects, especially for small angle rotations at high speeds with pulsed drive, is an important result.

For a given NLC, the maximum speed with the pulsed driving scheme will be limited ultimately by dielectric breakdown[8] and possible electrochemical instability of the NLC itself. Breakdown can be avoided to a certain extent by specialized electrode designs. Further increases in speed are possible by choosing materials and operating conditions that maximize $\Delta\varepsilon/\gamma_1$. In general, the ratio $\gamma_1/\Delta\varepsilon$ attains the smallest value at a temperature about 20 °C below the nematic-isotropic transition temperature.[11]

To exploit all three different mechanisms for improving the response time, we chose a NLC, MLC-14200-000 (Merck Chemicals), with large optical birefringence, high dielectric anisotropy, and relatively low viscosity ($\Delta n=0.1292$ at $\lambda=589.3$ nm, $\Delta\varepsilon=29.3$, and $\gamma_1=297$ mPas at 20 °C). The nematic–isotropic transition temperature of this material is ~95 °C, which allowed us to raise the operating temperature to ~75 °C. An external electric potential $V_0=400\mathrm{V_{pp}}$ was applied across the electrodes to reorient the nematic director in the plane of the substrates. A triggering pulse of the same V_0 was applied along the direction at 60°. The LC cell was placed in between two crossed polarizers, and a He–Ne laser at $\lambda=632$ nm was used as a source. Figure 3(a) shows the measured response time characteristics of the NLC cell using MLC-14200-000 for different angular orientations with and without the triggering pulse. As seen in the figure, a rotational speed of 1°/μs, even for small rotation angles, can easily be achieved using this device.

Although the electric field strength is not excessively high compared to what has been used for operation of conventional NLC devices, the operating voltage is relatively high because the spacing between the electrodes is much larger than it needs to be for certain applications. Bringing the electrodes closer reduces the operating voltage significantly, at the expense of reducing the area of the uniform electric field, which, in turn, requires high numerical aperture bulk optics for collimating/focusing of light. Nevertheless, small electrode spacing can be used effectively in waveguiding devices that require a uniform electric field over a small ''active area,'' such as in optical fibers, tapered optical fibers, or planar waveguides, where light is confined to ~2–10 μm diameter. In these cases, the electrodes can be brought close to each other, while still maintaining a uniform electric field over the active area. This approach reduces the required voltage to easily accessible ranges, and it yields a compact device that does not require any additional bulk optics.

We fabricated a liquid crystal cell between two single mode optical fibers with core diameters of ~10 μm by microfabricating electrodes in the tips of these fibers. With this arrangement, it was possible to achieve average rotational speeds of 1°/μs with $V_0=200\mathrm{V_{pp}}$ for rotation angles between 1° and 60°. We note that the data contained in the inset of Fig. 3(a) shows that the pulsed driving scheme decreases the switching time by more than 50× compared to the case without pulsing. Figure 3(b) shows a photomicrograph of one of the fiber ferrule assembly and microelectrode patterns on it. This in-fiber design has potential applications in polarization analysis and control systems for optical networking, which require rotation of the optic axis at small angular steps in microsecond time scale. A future publication will describe this device in detail and our implementation of it in ultrahigh capacity wavelength division multiplexed optical communication systems.

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