Optical switching of a metal-clad waveguide with a ferroelectric liquid crystal

Masaya Mitsuishi, Shinzaburo Ito, Masahide Yamamoto, Thomas Fischer, and Wolfgang Knoll

Optical switching based on waveguide optics with a ferroelectric liquid crystal (FLC) is reported. The FLC cell was prepared as a prism coupler on which the liquid-crystal layer was sandwiched between two gold cladding layers. The role of the gold layer was examined, and the optimum thickness of the top gold layer for obtaining high contrast was determined by use of the Fresnel equation. Various optical modulations of reflectivity were predicted on the basis of theoretical calculation, taking into account the molecular reorientation of the FLC, and examined at an appropriate angle of incidence and rotational angle of the FLC cell with respect to the plane of incidence. © 1997 Optical Society of America

Key words: Optical switching, ferroelectric liquid crystal, waveguide, metal cladding.

Ferroelectric liquid crystals (FLC’s) have been found to have unique electro-optic effects since Clark and Lagerwall reported them in 1980. FLC’s have been applied to electro-optic devices such as displays, spatial light modulators, and light valves. Recently we elucidated the dynamic behavior of a FLC, 4(2S,3S)-[2-chloro-3-methylpentanoyloxy]-4’-octyloxybiphenyl (3M2CPOOB) by means of time-resolved optical waveguide spectroscopy. Under an alternating high electric field, as illustrated in Fig. 1(a), the 3M2CPOOB molecules took on a chevronlike structure during the reorientation from one bookshelf structure to the other. We designed a high-contrast optical switching cell on the basis of theoretical predictions with respect to a three-dimensional dielectric tensor profile of the FLC. Here we report a novel, to our knowledge, optical switching device based on the electro-optic effect of the FLC in waveguide optics.

Figure 1(b) shows the device we fabricated. The glass substrate (BK-7, n = 1.515) was covered with a gold layer in a vacuum chamber at 2.0 × 10⁻⁶ Torr. This gold layer has an important role as an electrode, as well as being a low-refractive-index cladding. Polyimide was spin coated onto the gold surface and rubbed in one direction to induce the planar orientation of 3M2CPOOB (Iso–SmA–SmC*–crystal), at temperatures of 65 °C for Iso, 55 °C for SmA, and 49 °C for SmC*, in the SmA phase. The 3M2CPOOB was injected carefully into the isotropic phase to maintain the uniform cell spacing by means of monitoring an optical interference between the two gold layers. A right-angle glass prism (BK-7) was placed on the top of the cell with index-matching oil.

As a probe beam, a linearly polarized light from a He–Ne laser (632.8 nm) impinged on the prism coupler at an incident angle δ₁₄, as shown in Fig. 1(b). The time response of the reflected light was recorded in transient memory through a photodiode. This attenuated-total-reflection method is different from the method by which the guided light itself is monitored. The details of this apparatus were published previously. The apparatus has a nanosecond time resolution.

Figure 2 shows waveguide mode patterns calculated with the Fresnel equation for the symmetrical layer structures illustrated in Fig. 1(b). Only the thickness of the top gold layer was changed in the range of 5 to 100 nm; the other optical parameters were fixed as listed in Table 1. In Fig. 2, the dips appearing at particular angles of incidence imply that the incident light, normally reflected at the in-
The interface between the top gold layer and the glass substrate, can propagate in the FLC layer in a guided optical mode. The depth of the dips is influenced markedly by the thickness of the top gold layer. At a thickness $d = 5$ nm, the light can propagate in the waveguide medium, but it couples out again through the prism, resulting in the broad and shallow dips of the reflectivity. On the other hand, when the thickness exceeds 100 nm, light cannot penetrate the top gold layer because of absorption by the gold. This means that the light is almost completely reflected at the interface and that excitation of the guided waves is impossible with a greater than 100-nm-thick top gold layer.

The thicknesses of the top and bottom gold layers were adjusted by vapor deposition to yield effective depletion of the reflectivity at the resonance angle on the basis of the preliminary simulation described above. In the present case, the top and bottom gold

![Diagram](image1)

**Fig. 1.** (a) Reorientational model of 3M2CPOOB molecules under high, alternating electric fields. (b) Schematic illustration of the Kretschmann-type waveguide cell used in the current study. PI, polyimide.

<table>
<thead>
<tr>
<th>Layer</th>
<th>$\varepsilon^a$</th>
<th>$\varepsilon^b$</th>
<th>$d$(nm)$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BK-7</td>
<td>2.296</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Gold (top)</td>
<td>-12.5</td>
<td>1.25</td>
<td>5–100</td>
</tr>
<tr>
<td>Gold (bottom)</td>
<td>-12.5</td>
<td>1.25</td>
<td>40</td>
</tr>
<tr>
<td>3M2CPOOB</td>
<td>2.300</td>
<td>0</td>
<td>5000</td>
</tr>
</tbody>
</table>

$^a$The real part of the optic dielectric constant.
$^b$The imaginary part of the optic dielectric constants.
$^c$The thickness of each layer.

![Diagram](image2)

**Fig. 2.** Waveguide mode patterns calculated by use of the Fresnel equation. The optical parameters used for the calculation are listed in Table 1.
layers were 32 and 42 nm, respectively. Actual thicknesses were determined by surface-plasmon measurements before immersion of the 3M2CPOOB between the two substrates.

One advantage of our optical arrangement is that the prism was coupled with the FLC cell by use of index-matching oil, providing the freedom to choose an appropriate rotational angle for the cell with respect to the plane of incidence of the laser light; the angle is defined as \( \beta \), as shown in Figs. 3~a and 3~b. For example, two waveguide mode patterns at \( \beta = 90^\circ \) are shown in Fig. 3~c. Since the electric vector of \( p \)-polarized light is located just in the plane of symmetry of the molecular rotation, as shown in Figs. 3~a and 3~b, there is no difference between the two waveguide mode patterns even if the polarity of the electric field is changed.\(^8\) It is obvious that one cannot obtain an effective optical contrast with this arrangement. A more suitable position is discussed below.

The cone angle \( \theta \) of 3M2CPOOB was estimated to be approximately 25° at \( T = 50 \) °C by means of polarized microscopic observation. Thus, we used a direction of the incident beam, \( \beta = 25^\circ \), for which the electric vector of the incident \( p \)-polarized light was fitted to the plane along two principal axes (the molecular long axis and the axis perpendicular to it) of birefringence for one of the bistable states of the FLC, as shown in Figs. 3~d and 3~e. Two waveguide mode patterns [Fig. 3(f)] were recorded with an electric field of positive or negative polarity applied to the optical cell at \( T = 50 \) °C. Initially, the director aligns itself in the plane of light propagation [solid curve in Fig. 3(f)], and after changing the polarity of the electric field it is tilted away from the incident plane around 50° [dashed curve in Fig. 3(f)].

As for the two waveguide mode patterns, there exist large changes in the positions of the coupling angles. For example, at \( \delta_{ex} = 53.8^\circ \), one pattern shows a sharp dip with low reflectivity caused by the coupling of light with the guided mode, whereas the other pattern has high reflectivity because of the off-resonance condition under the tilted orientation. Figure 4~a shows the contrast given by the difference between the reflectivities, i.e., \( R(-E) - R(+E) \). This figure shows that several optical modulations are available if an appropriate angle of incidence is chosen. The maximum contrast was approximately 80% against the intensity of the incident light. The contrast could be increased to approximately 90% for this waveguide cell by use of an improved fabrication technique.

More interesting is the time evolution of the reflectivity \( R(t) \) shown in Fig. 4~b. The open circles represent the observed time profile of the reflectivity at the moment of polarity inversion from \(-30 \) V to +30

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![Fig. 3. (a), (b), (d), and (e) Geometrical arrangements of the optical cell and molecular orientation under an alternating electric field. (c) Waveguide mode patterns for \( p \)-polarized light at \( \beta = 90^\circ \). The solid and dashed curves correspond to the geometries in (a) and (b), respectively. (f) Waveguide mode patterns for \( p \)-polarized light at \( \beta = 25^\circ \). The solid and dashed curves correspond to the geometries in (d) and (f), respectively.](image-url)
V. The abscissa denotes the time after switching of the electric polarity. The switching time required for reorientation from one direction to the other on the smectic cone was determined from these data to be 25 μs. The reflectivity $R(t)$ changes with a slight complexity, showing a shallow depletion at 20.0 μs. This could be predicted theoretically by use of a model for the rotational reorientation of the FLC. In short, $p$-polarized light impinged on the sample, and we observed mainly the $p$-polarization mode, giving rise to sharp dips at 53.8° for $-E$ and at 54.3° for $+E$ [Fig. 3(f)]. However, on the way to switching between these states, another $s$-polarization mode appears through $p \rightarrow s$ polarization coupling, where $p$-polarized light excites $s$-polarization mode guided waves in the birefringence induced by the transient orientation of molecules. This causes a shallow dip of $R(t)$ at 20.0 μs, as shown in Fig. 4(b). The solid curve in Fig. 4(b) is the theoretical curve calculated with the modified Berreman $4 \times 4$ matrix method with the following parameters: optical dielectric diagonals $\varepsilon_{xx}$, $\varepsilon_{yy}$, $\varepsilon_{zz}$ of 3M2CPOOB of $2.620 + 0.0005i$, $2.235 + 0.0005i$, and $2.235 + 0.0005i$, respectively; a thickness of the 3M2CPOOB layer of $d = 7.354 \mu m$; and a cone angle of $\theta = 25^\circ$.10

When the direction of the incident light was set at $\beta = 90^\circ$, the direction was symmetric with respect to the molecular motion and no contrast was obtained, as mentioned above [Figs. 3(a) and 3(b)]. However, as shown in Fig. 4(b) (filled circles), the light intensity changed during the reorientation of the FLC molecules. This is also a unique property of optical switching in a metal-cladded FLC optical waveguide. The dashed curve was obtained by analysis similar to that at $\beta = 90^\circ$ by use of the reorientation model shown in Fig. 1(a).

In conclusion, an optical switching device that uses guided optical waves in a FLC medium was prepared. Guided optical waves propagate at specific angles of incidence between low-refractive-index metal-cladding layers, the proper thickness of which is approximately 40 nm. This device gives high-contrast light modulation: 80% in the microsecond range. In contrast to other conventional systems, such as a FLC cell sandwiched between polarizers, this type of switching device can be installed directly in an optical integrated circuit. Furthermore, choosing an appropriate angle of incidence allows several types of light modulation to be used. Optical switching depends on the molecular rotation around the cone between two bookshelf structures of FLC’s under a high electric field.

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References and Notes

8. Actually, there is a slight difference between 32° and 38°. This is due to experimental error when setting the direction of the incident light. In the present study, we tried to set β to be 90°, but the actual angle β was 90.5°. For details, see Ref. 2.
10. For the calculation, we changed the optic tensor and the smectic-layer tilt angle slightly but effectively to obtain the best fit to the transient experimental data.