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Surface-stabilized ferroelectric liquid-crystal electro-optic waveguide switch

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We demonstrate control of the optical coupling between a pair of planar waveguides by application of voltage to surface-stabilized ferroelectric liquid-crystal films between them. A prototype switch exhibited a response time of 200 μs and a 40:1 switching ratio.

Ferroelectric liquid crystals (FLCs) in the surface-stabilized (SSFLC) geometry[1] exhibit electro-optic effects having strong optical interaction (birefringence $\Delta n \sim 0.1$–0.2) combined with response times in the microsecond regime, operation at low voltage and energy dissipation, and ease of fabrication. The large birefringence of FLCs suggests using them to make electro-optic devices that depend on changes in the optical properties of an interface between the FLC and another material,[2] such as total-internal-reflection (TIR) beam switches[3] and integrated optical devices. In this letter we report the demonstration of SSFLC-mediated control of the optical coupling of planar waveguides, a basic function required for many potential SSFLC-integrated optical devices.

In our waveguide switch prototype, shown schematically in Fig. 1, the FLC film, $\sim 2\ \mu$m thick, is sandwiched between a pair of glass plates having optical waveguide layers on their facing surfaces. HeNe (633 nm) laser light polarized parallel to the waveguide plane (TE mode) is launched into one of the guides. The FLC is oriented so that the wave of this TE mode evanescent into the FLC sees a large refractive index for one sign of voltage applied to the FLC, and a small index for the other. TE light incident in the first waveguide remains in that waveguide for the small-index FLC state, but is radiated out and coupled into the other waveguide for the large-index FLC state.

Given this basic geometry of a waveguiding layer between bulk glass and FLC, the index of the guiding layer must be higher than the glass, but lie between the highest and lowest indices available in the FLC. The combination of the FLC mixture Chisso CS-1014,[4] which is optically quite typical of available FLC materials, and K-Ag ion-diffused waveguides in standard microscope cover slips proved to be useful.

The FLC is sandwiched between a pair of glass plates each 150 μm in thickness. The liquid crystal in the ferroelectric smectic phase is approximately optically uniaxial, with the optic axis along the molecular director $\hat{n}$, and with ordinary refractive index $n_o = 1.50$ and extraordinary index $n_e = 1.65$. In the aligned SSFLC geometry the smectic layers are planar and approximately normal to the planar surface of the bounding glass plates, intersecting the glass along straight lines normal to $\hat{s}$, a selected direction in the FLC-glass interface plane. In an applied electric field the preferred state of $\hat{n}$ is nearly parallel to the plates, at an angle $\pm\psi$ to $\hat{s}$, the sign depending on the sign of the applied field. Thus, reversing the applied field effectively rotates $\hat{n}$ through twice the smectic C tilt angle ψ; CS-1014 has $\psi = 22°$ at room temperature. The glass (bulk refractive index $n_g = 1.50$) was treated by ion diffusion to have a higher index surface layer ($n_s \sim 1.60$) of thickness sufficient to waveguide HeNe laser light. Ion diffusion was carried out by immersion of the glass in a $AgNO_3$-KNO_3 eutectic melt at 150 °C, according to the procedure of Jackel.[5] Excellent low-loss guides, single-mode or multimode depending on the immersion time, were made this way, and were prism coupled to a focused HeNe laser beam. Care was taken in these experiments to make the two waveguides in a given device identical.

Since voltage reversal produces a net reorientation of

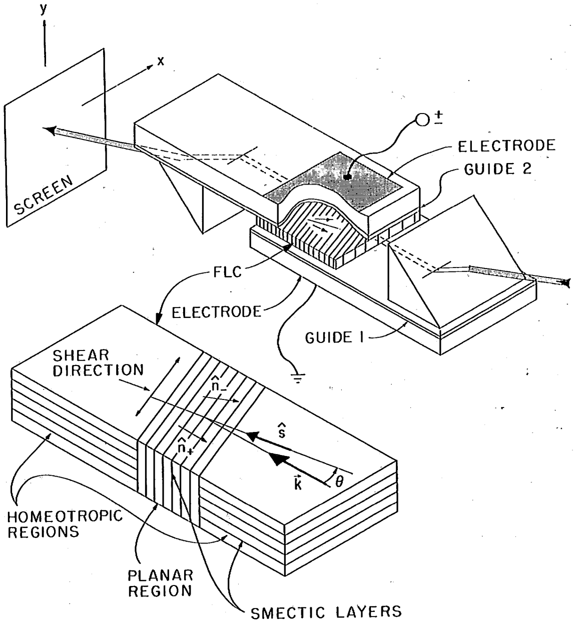

FIG. 1. Prototype FLC optical waveguide switch. Two glass cover slips (thickness of each about 150 μm) with indiffused waveguides on their inner surfaces bound a FLC film a few microns thick. Light is prism coupled into one waveguide and out of the other. Electric fields produced by voltages applied to electrodes on the outer surfaces of the glass sheets reorient the optic axis $\hat{n}$ of the FLC, thereby controlling the refractive index seen by light propagating in the guides. The FLC smectic layer normal direction $\hat{s}$ is chosen to make an angle θ to the light propagation direction $\hat{k}$. Then the FLC optic axis direction $\hat{n}_+$ selected by positive applied voltage lies parallel to $\hat{k}$, while the optic axis direction $\hat{n}_-$ selected by negative applied voltage makes a substantial angle to $\hat{k}$. When the TE mode sees a low refractive index ($\hat{n}_+$) it remains confined to the guide it was originally coupled into, whereas when it sees a high refractive index ($\hat{n}_-$) it is coupled across the FLC into the facing waveguide. The FLC film comprises a mosaic of homeotropic regions, which act as passive low index decoupling layers, and SSFLC regions in the form of narrow (10–20 μm wide) strips.

the FLC optic axis *in* the waveguide plane, the principal electro-optic effects will be for TE modes. In order to optimize response speed and alignment, the SSFLC thickness is best kept in the 1–3 μm range. As a result, to optically decouple the two waveguides the apparent refractive index of the FLC layer needs to be as low as possible in one state, which is achieved by orienting the smectic layering ($\hat{s}$) to give the minimum effective SSFLC refractive index n_o for one sign of applied voltage. An angle $\theta = \psi$ between $\hat{s}$ and $\hat{k}$, the optical propagation direction, results in propagation along the FLCs optic axis for one sign of applied voltage (optic axis state $\hat{n}_+$), giving the desired lowest refractive index n_o. With 3-μm-thick waveguides separated by a 3 μm FLC film of this effective index, the optical coupling length depends greatly on how close the chosen waveguide mode is to cutoff, varying from ~100 μm for a high-order mode near cutoff to much longer than the sample dimensions for the low-order modes which are well confined to the ion-diffused layer.[6] Upon voltage reversal $\hat{n}$ reorients to be 44° away from $\hat{k}$, making the effective refractive index of the FLC layer increase to 1.57, as calculated from the usual expression for uniaxial materials.[7] Depending on the guide thickness, this effective index change can be large enough to switch the mode below cut off, providing a strong coupling of light into the FLC layer and the other guide. Significant coupling can be achieved in a few microns of propagation.

Initial experimentation with electrode placement revealed that an indium-tin-oxide (ITO) layer deposited on the glass over the waveguide absorbed light excessively, necessitating placement of the electrode on a buffer layer outside of the waveguide-FLC-waveguide sandwich to remove the ITO from the optical evanescent field. For the present experiments the 150-μm-thick glass was simply used as the buffer, although in practical application much thinner layers would be desirable and feasible. With the glass buffer a ±1 kV applied voltage produced a ±3 V/μm capacitively coupled effective field in the FLC, sufficient to produce complete switching upon sign reversal. Polystyrene sphere spacers determined the thickness of the FLC-filled gap. The FLC was introduced into the gap in its isotropic phase by capillary suction and cooled into the smectic *A* phase, where layer alignment was achieved by shearing the plates relative to each other. The shearing produces either SSFLC alignment with the layers along the shear direction and nearly normal to the plate or rotates the layers into the homeotropic orientation with the layers parallel to the plates. The result was a mosaic structure with the FLC almost entirely homeotropic except for SSFLC in a few narrow strips of 10–20 μm in width. This structure proved to be useful to confine the region where coupling occurs to selected areas in the waveguide. In the homeotropic regions $\hat{n}$ is within 22° of being normal to the optical electric field ($n < 1.52$), providing decoupling of the guides.

Guides propagating 4 or 5 TE modes were used, and the incident beam was translated in the FLC layer until a SSFLC region of appropriate width was encountered and switching observed. High-contrast clean switching could be found at various places in the sample; Figs. 2 and 3 show typical results. Contrast of 40:1 was observed for switching of a chosen mode. The response times are comparable to those found in the half wave plate or TIR switch[3] geometries.

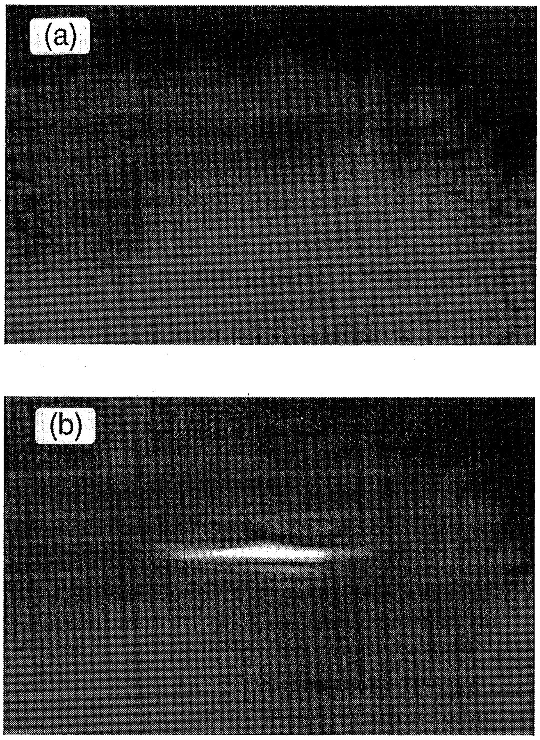

FIG. 2. Output light mode pattern for the opposite applied voltages. (a) The low refractive index FLC state; (b) the high refractive index FLC state showing the transmitted mode pattern on the screen (Fig. 1).

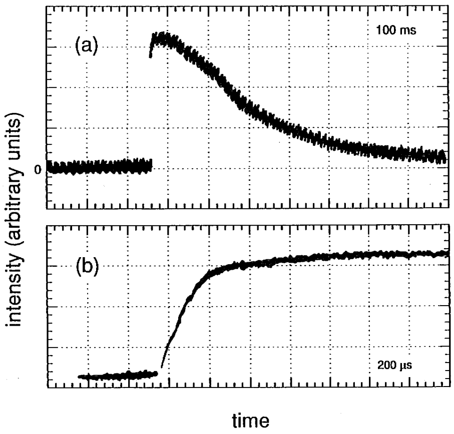

FIG. 3. Detector voltage proportional to light intensity passing through a slit-shaped aperture about the exit mode shown in Fig. 2 vs time during switching with a square wave voltage applied. The top trace shows a switching event beginning at the left with a very small amount of light coupled into the output (OFF state); sweep is 100 ms/div. The noise on the trace comes from the detector. When the applied voltage is reversed, the light output increases sharply (ON state), and then falls slowly due to the capacitive decay of the electric field in the FLC. The ratio of the peak transmitted intensity to the initial intensity is about 40:1. The bottom trace shows the rise time of the switched light intensity; sweep is 200 μs/div, giving 200 μs response time.

To conclude, we have demonstrated the control of the optical coupling between two planar waveguides by SSFLC electro-optic switching. The results suggest that by exploiting the short interaction length and low power dissipation of SSFLCs one could make dense, compact arrays of electro-optic waveguide switches. This work was supported by contract DAAH01-87-C-1041 from the Defense Advanced Research Projects Agency.

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