

# Integrated liquid crystal optical switch based on total internal reflection

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An optical switch structure which combines a planar lightwave circuit and liquid crystal is proposed and experimentally demonstrated. The switching is realized by inducing total internal reflection through controlling the refractive index of the liquid crystal. The principle and the design of the integrated optical switch are described. Experimental results suggest that anchoring of the liquid crystal molecules on nonplanar structures is very crucial in affecting the switching performance.

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In recent years, integrated optical switches utilizing total internal reflection (TIR) effects have aroused considerable interest for their wavelength insensitivity and easy integration to achieve a large matrix. Controlling the refractive index of waveguides at the intersection of an optical switch based on two crossing waveguides presents one method of realizing the switch function. Different physical mechanisms can be used to control the refractive index, such as plasma dispersion effect<sup>1</sup> and thermo-optic effect.<sup>2</sup> Limited by the index changes in most materials, the branch angle between the two intersecting waveguides is usually only 1° or 2°. Large branch angles, however, can be realized by using a matching oil or bubble.<sup>3–5</sup> A key part of the bubble-type optical switch is the bubble movement control, which is often achieved by an inconvenient process of temperature change.

As a type of optical material, liquid crystals (LCs) are very attractive because of their large birefringence, low power consumption, and low drive voltage. LCs have already been proposed in bulk optical switches based on the TIR effect.<sup>6,7</sup> But their volume is still quite large and they are not easy to integrate.<sup>8</sup> On the other hand, LC waveguides provide a means to miniaturize devices.<sup>9</sup> Optical switches based on LC waveguides with different structures have been proposed.<sup>10–13</sup> Yet, the large propagation loss of LC remains a problem.<sup>14</sup> In this letter, an integrated LC optical switch utilizing the TIR effect is proposed. The integrated optical switch combines a LC with an integrated lightwave circuit composed of waveguides to reduce the switch volume. The resultant optical switch can be fabricated into a matrix network which can support a large number of ports and enhance the switch flexibility and stability.

The optical switch structure is shown in Fig. 1. Two optical channel waveguides intersect at a certain angle. At the intersection, a groove is etched down into the wafer to make room for a sufficiently large pocket, which is to be filled with a LC. One face of the etched groove serves to reflect the light beam propagating inside the input waveguide upon the right conditions. The refractive index of the LC can be adjusted by controlling its molecular orientation through an external electric field.

In the following analysis, the field mismatch between the waveguide mode and the reflected light is neglected. The ray theory can then be applied to describe the operation of the device. Let the index of the waveguide core be  $n_c$  and the incidence angle be  $\theta$ . When one polarization of light coming from Port A experiences the extraordinary index,  $n_e$ , of a suitable LC, an appropriate incidence angle can be found such that  $n_e(\theta) = n_c$ . In such a case, the incident light will pass through the intersection and exit from Port D. When the refractive index seen by the incident light at the intersection is changed to  $n_o$ , which is chosen to be smaller than the critical index ( $n_o < n_c \sin \theta$ ), then, the light will be totally reflected to exit from Port C due to the TIR effect.

LCs are often aligned into the three states as shown in Fig. 2. Assume the incident light beam has two polarizations:

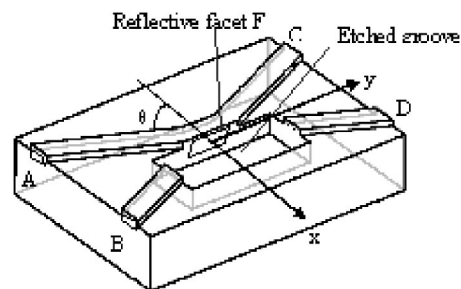


FIG. 1. Optical switch structure based on total internal reflection.

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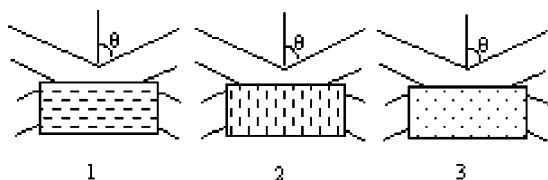


FIG. 2. LC molecular orientation.

*s* polarization [transverse magnetic (TM) mode], which is vertical to the incidence plane, and *p* polarization [transverse electric (TE) mode], which is parallel to the incidence plane. A summary of the three alignment states and switching behavior is listed in Table I. When the LC is aligned in State 1, both the TM and TE modes from Port A will be totally reflected to Port C by the TIR effect. When the LC is aligned in State 2, the TM mode will be reflected to Port C and the TE mode will pass through to Port D. When the LC is aligned in State 3, the TM mode will pass through to Port D while the TE mode will be reflected to Port C. By controlling the LC to switch between States 2 and 3, both the TM and TE modes will be switched from one port to the other. When the incident light contains both TE and TM modes, this device will work as a controllable polarization beam splitter. If the incident light has only one polarization, this device will work as a routing-type optical switch. In the experimental results reported in this letter, the LC is first aligned in State 2 and a vertical electric field is applied to drive the LC molecules into State 3.

The integrated optical switch structure is fabricated with silicon oxynitride on a silicon wafer, as shown in Fig. 3. The incidence angle  $\theta$  is about  $70^\circ$ . The refractive index of the waveguide core layer is 1.515 at 1550 nm. After the switch structure is fabricated, the wafer is cleaved and the switch is characterized. The waveguide properties of the structure are reported elsewhere.<sup>15</sup> Incident light from Port A is observed to be reflected to Port C before the pocket is filled with a LC, while no light can be observed at Port D. Then, a layer of silicon monoxide (about 20 nm) is evaporated at an oblique angle on both the silicon wafer with the switch structure and a piece of glass with indium tin oxide (ITO) in order to align the LC molecules. An evaporation angle of about  $80^\circ$  is selected and the LC molecular direction is estimated to be anchored as shown in State 2 of Fig. 2. The LC molecular orientation will be controlled by an external electrical field which is perpendicular to the waveguide plane. The lower electrode is an aluminum film which has been deposited on the silicon wafer before the waveguide fabrication. The upper electrode is the ITO film on the covering glass.

TABLE I. The switching behavior of the three LC orientation states.

Orientation state	Incident light polarization	Incidence angle	Refractive index	Switch direction
State 1	TM mode	Any angle	$n_o$	A → C
	TE mode	Large	$\sim n_o$	A → C
State 2	TM mode	Any angle	$n_o$	A → C
	TE mode	Large	$\sim n_e$	A → D
State 3	TM mode	Any angle	$n_e$	A → D
	TE mode	Any angle	$n_o$	A → C

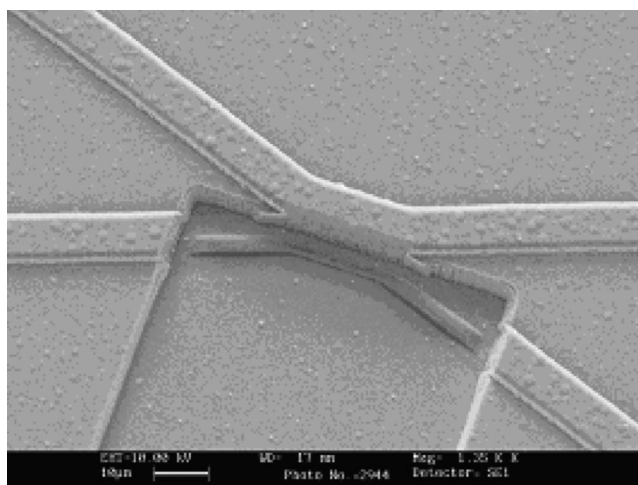


FIG. 3. Scanning electron micrograph of the fabricated switch structure.

The pocket is then filled with a LC. The switching response of the integrated LC optical switch is measured at the driving frequency of 60 Hz using a laser source at the wavelength of 1550 nm. The detected power versus the driving voltage is shown in Fig. 4. Before applying any voltage, a high output power is measured at Port D while a low output power is obtained at Port C. When the external electric field is applied, the optical power at Port C increases and the optical power at Port D decreases. The change of optical power at port C is smaller than that at Port D, which is presumably caused by the far-from-ideal properties of the reflection surface due to its roughness and deviation from the vertical plane. The roughness of the surface is visible in Fig. 3. From Fig. 4, we can see that there is a threshold voltage of about 2 V for the switch to start to respond. The peak output at Port D near the threshold can be explained as follows. When the voltage is smaller than the threshold, the LC molecules possess some fluctuations from the alignment direction, hence producing a scattering loss. When the voltage exceeds the threshold, the fluctuations are much reduced and the scattering loss is similarly reduced, thus creating the peak output.

A simulation result of the output power at Ports C and D by the beam propagation method is shown in Fig. 5 for the proposed integrated switch when the refractive index of the LC is reduced from 1.5 to 1.4, which corresponds to the values of the LC adopted in our experiments, assuming there

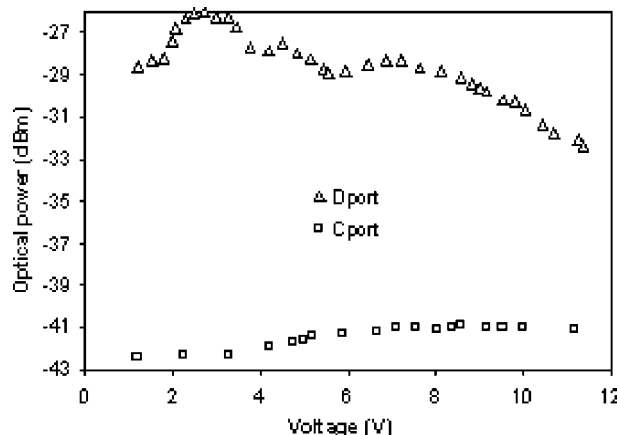


FIG. 4. Switch performance of the integrated LC optical switch.

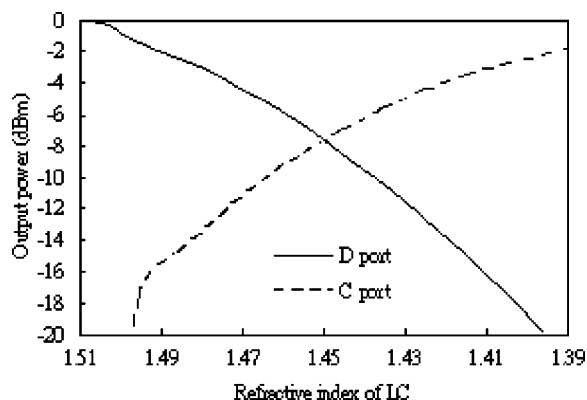


FIG. 5. Beam propagation method simulation of the output power vs the LC refractive index change.

is no degradation of the reflection facet, and the waveguide index is 1.515. The input power is taken to be 0 dBm. The power in both output ports is observed to change by more than 20 dB, which contrasts sharply with the experimental results. In order to explain the difference, we also include the nonideal properties of the reflection surface into our simulation. Although the changes in power at Port C are reduced by this inclusion, they are still much larger than our experimental results. Hence, it is suspected that the achieved change in the refractive index by applying an external field may be far less than what we initially anticipate from the bulk LC, which is 0.1 in our selected LC.

From Fig. 4, the output power at port C becomes saturated at 10 V, suggesting that the refractive index of the LC cannot be reduced further. If this is the case, then the small overall refractive index change obtained is not caused by a low drive voltage, but most probably by the complicated anchoring condition for the LC in the etched groove around corners and in close proximity to the boundary transition region near the waveguide and an insufficient birefringence of the LC. It is difficult to align the LC molecules on an uneven surface as is the case in our experiment, because the LC molecules near the corner are affected not only by the orientation layer at the bottom surface but also by that on the sidewall. Moreover, there exists a boundary transition region in the LC adjacent to the waveguide which may not respond to an external field as does the bulk LC. Consequently, the overall refractive index change of the LC inside the groove is reduced significantly when an applied field attempts to

change the LC orientation from that shown in State 2 to that of State 3 in Fig. 2. In order to achieve a switch performance comparable to that shown in Fig. 5 in our proposed integrated switch structure, the anchoring of LC molecules in the etched groove needs to be investigated in detail and a LC with a larger birefringence should be used.

In summary, an integrated LC optical switch has been fabricated in silicon oxynitride waveguides grown on Si wafers. The switching properties of the optical switch have been characterized, which clearly demonstrate a limited switching behavior. Comparing the actual switching performance with the simulation result, it can be inferred that the achieved refractive index change of the LC in our experiment is too small. The complex anchoring condition in the etched groove and the small birefringence of the LC may be the cause of such a small refractive index change. It is believed that the switching performance can be improved by choosing a LC with a larger birefringence and by correctly anchoring the LC inside the etched groove of the switch structure.

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