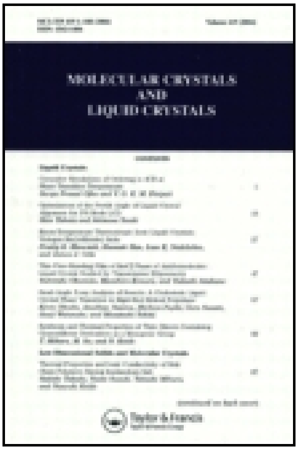

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Surface Anchoring Effect on LC-Covered Planar Lightwave Modulator

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Liquid crystal (LC) waveguide claddings with different boundary couplings have been electrically switched. It is observed that the cut-off voltage of guided modes significantly decreases with decreasing the azimuthal surface anchoring energy of the LCs. An LC-covered planar lightwave modulator with low driving voltage of 12 volts is demonstrated by controlling the surface azimuthal anchoring energy of LC claddings.

Keywords: Waveguide; liquid crystal; photo-alignment; azimuthal anchoring energy; linear polarized UV light

1. INTRODUCTION

Silica-based planar lightwave circuits (PLCs) have been extensively studied for constructing wavelength-division multiplexing and a fiber-to-the-home system. The add/drop multiplexer and the Mach-Zehnder interferometer are very important circuit devices among PLCs [1, 2]. In these devices, thin-film heaters were used for controlling or adjusting the optical phase of guided modes. On the other hand, although the higher propagation loss in liquid crystal (LC) materials hinders them from serving as the waveguide film, it has been common that LCs exhibiting a large optical anisotropy and an electrically controllable molecular alignment are applied to the investigation

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of slab waveguide cut-off switching as an active medium. For instance, the synapse neuron waveguide modulators and the waveguide switch with high contrast used the electrically-controllable liquid crystal cladding [3–6]. An effective alignment way to obtain uniform LC orientation on these waveguide devices was polyimide (PI) buffing, and these devices needed tens of volts of the driving voltages due to the strong surface anchoring nature of the PI alignment films. An LC covered optical waveguide modulator with a photo-alignment film showing a weak surface anchoring energy has been reported [7]. The surface anchoring energy of the LC alignment on the film is rather weak and can be controlled by changing the UV exposure dosage from 10^{-7} to $10^{-5}\,\mathrm{J/m^2}$ [8].

In this paper, we report the surface anchoring effect of LCs cladding on a channel waveguide modulator. By using an optical fiber and a photomultiplier measurement system, the optical output power of an LC-covered optical waveguide modulator is measured as a function of the surface anchoring energy varied by changing alignment condition. The results are also compared with the conventional PI buffing samples.

2. PRINCIPLE

LCs are aligned uniformly along a multimode channel waveguide and are electrically tunable by a lateral electric field through a pair of film electrodes separated beside the channel waveguide, as shown in Figure 1. For switching the channel waveguide, the switching behavior of a surface liquid crystal layer near a polymer/LC interface (an evanescent region) is of great importance, where the switching behavior of LCs is strongly influenced by the surface anchoring.

2.1. LC Cladding

LC molecules are homogeneously aligned with the director of

$$\mathbf{n} = (\sin\phi(x,y), 0, \cos\phi(x,y)), \tag{1}$$

where $\phi(x, y)$ is the tilt angle from the z axis (Fig. 2). The free energy in LC cladding can be written as

$$F = \int_0^d (f_d + f_e)dxdy, \tag{2}$$

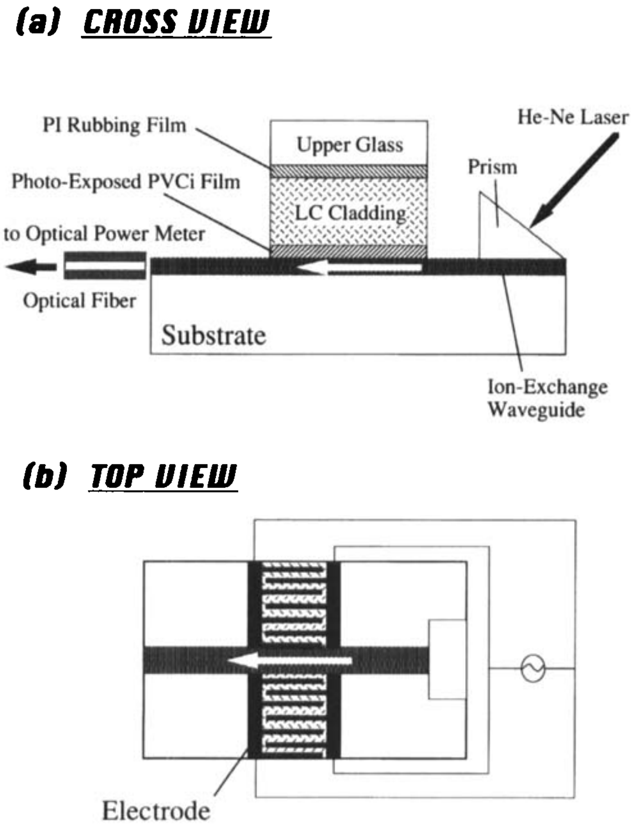

FIGURE 1 Schematic illustration of a liquid crystal covered PLC modulator, where LCs are aligned uniformly along a multimode channel waveguide and are electrically tunable by a lateral electric field through a pair of film electrodes separated beside the channel waveguide. (a) Cross view; (b) Top view.

where the distortion f_d and electrical f_e components of the free energy density can be written as follows

$$f_d = \frac{1}{2}K_1(\nabla \cdot \mathbf{n})^2 + \frac{1}{2}K_2(\mathbf{n} \cdot \nabla \times \mathbf{n})^2 + \frac{1}{2}K_3|\mathbf{n} \times \nabla \times \mathbf{n}|^2, \qquad (3a)$$

$$f_e = -\frac{1}{2}\varepsilon_0 \Delta\varepsilon(\mathbf{n} \cdot \mathbf{E})^2, \qquad (3b)$$

where K_1, K_2, K_3 are splay, twist and bend elastic constants of an LC material, respectively. An applied lateral electric field is given by $E = Ei_y$. Thus by using the Euler-Lagrange Equation with the assumption of

$K_1 \approx K_2$, we can obtain

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\varepsilon_0\Delta\varepsilon}{K_2}E^2\sin\phi\cos\phi = 0, \tag{4a}$$

for the bulk LC alignment distribution with the boundary condition of

$$\left.\frac{\partial\phi}{\partial x}\right|_{x=0} = \frac{A_\phi}{K_2}\sin\phi(0,y)\cos\phi(0,y) = 0, \tag{4b}$$

where A_ϕ is the azimuthal anchoring energy at the interface just above the waveguide.

With applying the electric field, the LC medium is deformed and the guided TE modes sees the effective refractive index n_{LC} represented by

$$n_{LC} = \frac{n_{\|}n_{\perp}}{\sqrt{n_{\perp}^2\sin^2\phi + n_{\|}^2\cos^2\phi}}. \tag{5}$$

here n_e and n_0 are refractive indices for extraordinary and ordinary lights, respectively.

2.2. Optical Modulation

Considering a thin enough LC alignment film, a guided mode in the film may be neglected in the present theoretical model. An incident lightwave

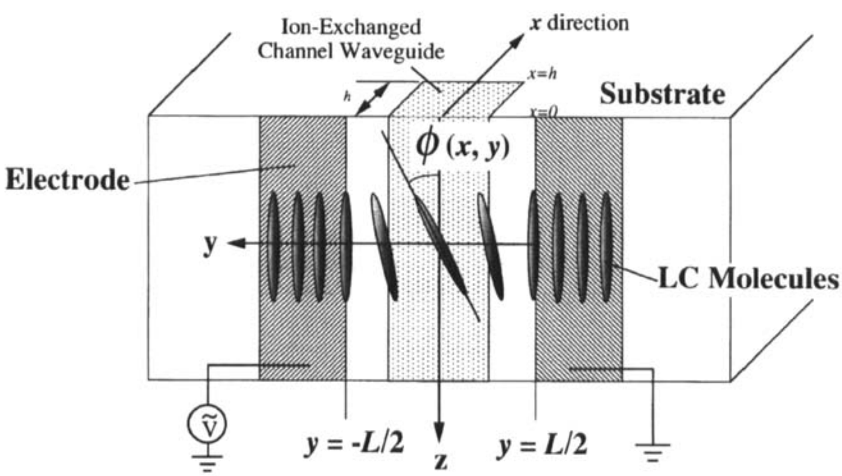

FIGURE 2 An analysis model of the device. Liquid crystals are deformed under the lateral electric field.

encoded TE mode propagates along the z direction. In scalar case, the electromagnetic field distribution for TE modes in LC cladding, waveguide and glass substrate can be written as

$$E_{Y,m}(x) = \begin{cases} E_m \exp(\gamma_{LC} x) & -\infty < x \leq 0 \\ E_{Y,m}(0)\left[\cos(\gamma_W x) + \left(\frac{\gamma_{LC}}{\gamma_W}\right)\sin(\gamma_W x)\right] & 0 \leq x \leq h, \\ E_{Y,m}(h)\exp[-\gamma_S(x-h)] & h \leq x < +\infty \end{cases} \tag{6a}$$

with the propagation constants of

$$\begin{aligned} \gamma_{LC}^2 &= \beta^2(N_m^2 - n_{LC}^2), \\ \gamma_w^2 &= \beta^2(n_w^2 - N_m^2), \\ \gamma_s^2 &= \beta^2(N_m^2 - n_s^2), \end{aligned} \tag{6b}$$

respectively, h is the thickness of the ion-exchanged channel waveguide, N_m is the effective index of an mth-order mode, $\beta=\omega/c$ is the propagation constant in the vaccum, $E_{Y,m}(x)$ is a normalization field of the mth-order mode, n_{LC}, n_W and n_S are the refractive indices of the LC cladding, waveguide and glass substrate, respectively, E_m is a constant of the mth-order guided mode. By normalizing the output power of the guided modes with the input light power, a power transfer ratio can be obtained as

$$T = \frac{P_{out}}{P_{in}} = \sum_m \left(\frac{\beta N_m}{2\mu\omega}\int_0^\infty E_{Y,m}^2(x)dx\right), \tag{7}$$

where $P_{out} = P_S + P_w$ and P_S and P_w are the power transmitted ratio in the glass substrate and the waveguide, respectively. Therefore, the power transfer ratio T depending on the refractive index n_{LC} of the LC cladding can be modulated by the electrically controllable orientation of the LC medium.

3. EXPERIMENTAL

A channel waveguide in a BK7 glass substrate (n_s = 1.515 at 633 nm) was fabricated by an Ag^+ ion-exchange process at 300°C for an hour in $AgNO_3$ solution. The numbers of guided modes supported by the waveguide can be controlled by the ion-exchange time. In our experiment, a waveguide supporting two guided modes was fabricated. The effective refractive indices of the two guide modes were measured by using a prism-coupling method. They were 1.5750 and 1.5396 at 633 nm for TE_0 and TE_1 modes, respectively. A pair of lateral electrodes separated by 30 μm-gap was formed by vacuum evaporation of aluminum and a subsequent photolithographic lift-off process. The liquid crystal alignment film was used a photo-dimerization material, the poly (vinyl cinnamate) (PVCi). That was spin-coated on the electrodes patterned glass substrate and then backed at 100°C for 30 min. The thickness of the result film was measured to be 20 nm. Then the PVCi film was exposed to a linearly-polarized UV light from the substrate normal direction. The UV light source was a high-pressure mercury lamp with a total output power of 0.8 kW. A linearly-polarized UV light was obtained by a multi-coated dielectric polarizer, and the intensity was 5 mW/cm^2 at 313 nm. The upper substrate was spin coated with a rubbed polyimide film (JSR). The liquid crystal layer thickness was 4.0 μm, and the LC material (ZLI-2293, $n_{\parallel}$ = 1.630, $n_{\perp}$ = 1.498 at 633 nm, Merck) was filled into the cell via a capillary action. The surface anchoring energy of LC molecules on the PVCi surface was measured by using a Neel wall technique [8]. For comparison, we also fabricated a waveguide sample with strong surface anchoring, in which both the electrodes patterned substrate and the opposite one were coated the rubbed PI film. So that, for observing details of the switching performance of the PLC modulators, three different orientation treatment samples have been fabricated. They are, the one side rubbing (treatment 1), the UV exposure (treatment 2) and the PI rubbing (treatment 3) samples, listed in Table I.

4. RESULTS AND DISCUSSION

As shown in Figure 3, the cut-off voltage in the LC-covered waveguide shows quite different while the boundary coupling was varied From the result of Neel wall width measurement [8], the azimuthal anchoring energies in the UV-exposed samples of 2 sec and 10 sec (treatment 2) were measured

TABLE I Experimental sample preparation

	Upper substrate	*Lower substrate (electrodes side)*
Treatment 1	PI buffing	non-treated PVCi
Treatment 2	PI buffing	UV-exposed PVCi*
Treatment 3	PI buffing	PI buffing

*The light source is a linearly polarized UV light (5 mW/cm^2).

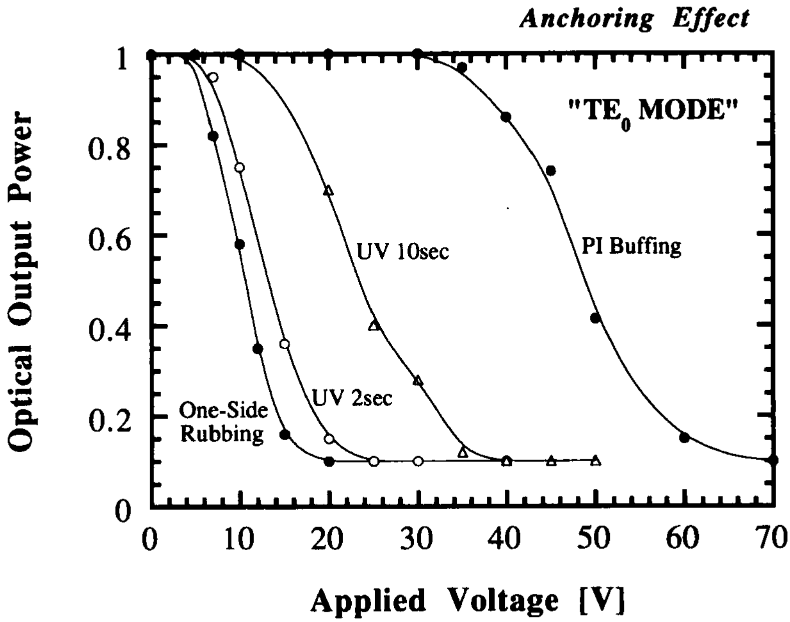

FIGURE 3 The cut-off voltage in the liquid crystal covered waveguide was increased while the anchoring energy was increased. The one side rubbing (treatment 1), the UV exposure (treatment 2) and the PI rubbing (treatment 3).

to be the order of 10^{-7} and $10^{-6}\,J/m^2$, respectively. That of rubbed PI film (treatment 3) was measured to be $10^{-4}\,J/m^2$. The non-treated PVCi film (treatment 1) cannot be measured.

The LC surface alignments are generally considered to be affected by various interactions, such as the surface microgroove effect, the anisotropic van der Waals force, the steric effects and other physical-chemical interactions. In treatment 1, there are no surface microgrooves and optical anisotropy generated in the PVCi films. The only considerable interface interaction is the memory effect of the liquid crystal molecules adsorbed on the surface of the alignment films [8–10]. In treatment 2, the anchoring energies are varied from 10^{-7} to $10^{-6}\,J/m^2$ by controlling the optical anisotropy of the PVCi film through the linearly polarized UV exposure dosage. In treatment 3, the anchoring energy of polyimide buffing alignment is strong enough to be $10^{-4}\,J/m^2$, owing to the large optical and/or geometrical anisotropy on the polymer surface by the buffing process. With applying by a lateral electric field, weak surface LC anchoring leads to large deformation of the surface LC molecules, even at low electric voltage. The rigid molecules align on the polymer film surface, do not deviate from their initial direction in this electric bias range, because of the strong surface anchoring interactions such as treatment 3, however. So that the cut-off voltage becomes higher in the sample with the stronger surface anchoring energy. It is notable that the optical anisotropy in LCs is so large that even a few angle deflections can lead to a rather significant average refractive index change in the LC cladding layer.

The electro-optical performance of a low power driving waveguide modulator was measured as shown in Figure 4. By controlling the surface anchoring energy to be $10^{-7}\,J/m^2$ using the photo-alignment method, the cut-off voltages are 12 V and 20 V for TE_1 and TE_0 mode, respectively. This cut-off voltage is much lower than that for the PI buffing sample.

5. CONCLUSION

Liquid crystal claddings aligned on a channel waveguide with different boundary couplings were electrically switched. By varying LC surface alignment treatments such as one-side rubbing, photo-alignment and

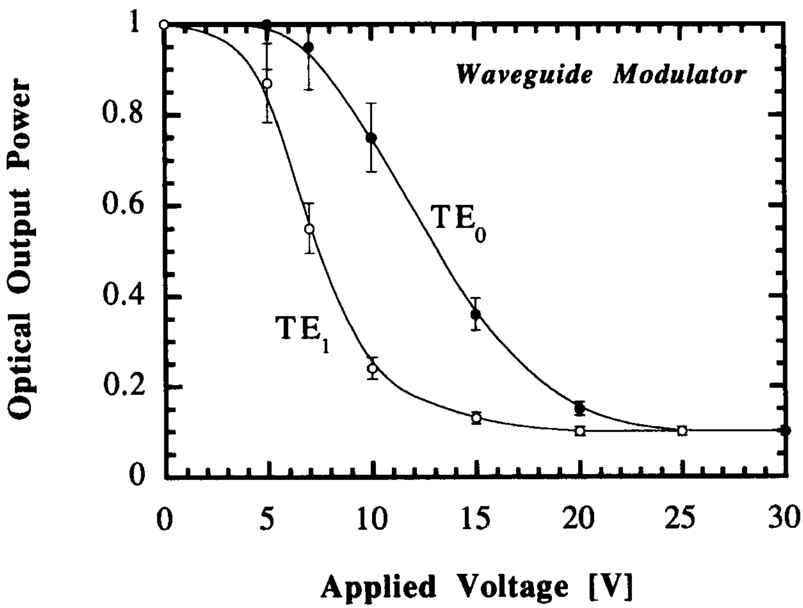

FIGURE 4 The electro-optical performance of a low power operating waveguide modulator was measured. By controlling the surface anchoring energy to be $10^{-7}\,J/m^2$ using the photo-alignment technique, the cut-off voltages are lowered to be 12 V and 20 V for TE_1 and TE_0 respectively.

polyimide buffing treatment, LC-covered optical waveguide modulators were fabricated. The output power of the LC-cladded optical waveguide modulator was measured as a function of the surface azimuthal anchoring energy. A comparison of electro-optical characteristics for the sample with different boundary couplings was carried out. Consequently, we found that the cut-off voltage of guided modes decreased with decreasing the surface anchoring energy of LCs, and the modulators with LC cladding fabricated by photo-alignment and one-side rubbing show rather lower driving voltage than the polyimide buffing one. The experimental results reported in this paper may also provide useful information for the investigation of the lateral electric field LCD that shows extremely wide view angle owing to the significant effect of the surface anchoring energy on the electro-optical performance.

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