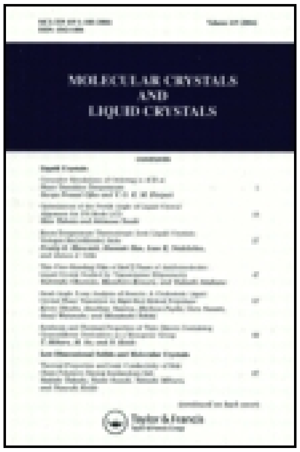

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In-Line Fiber Polarization Selector and Intensity Modulator

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IN-LINE FIBER POLARIZATION SELECTOR AND INTENSITY MODULATOR

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Abstract Liquid-crystal-based fiber components that exploit the high birefringence and electrooptic effect of liquid crystals, are versatile. A single-mode fiber enclosed with planar-aligned liquid crystals is reported on in this paper. The fiber was etched nearly to its core. The output light was exercised through the evanescent field coupling between the fiber and surrounding liquid crystals. To achieve an effective access to the evanescent field, the etch depth was studied first. When the fiber was etched to 10-μm diameter, obvious light leakage occurred. Once the electric field was switched on, the polarization selection and intensity modulation were examined. A theoretical description of the optical characteristics were also given.

INTRODUCTION

In-line fiber components are attractive owing to their mechanical stability, low insertion loss, and miniature size. Such fiber components realized by combining optical fibers and liquid crystals have the great advantage of easy handling because of the fluid properties of liquid crystals. Moreover, the large electrooptic effect and high birefringence of liquid crystals can be exploited to modulate the optical intensity or select polarization states by applying external electric fields.

Liquid-crystal-based fiber components are fabricated in a variety of ways. The most often used being the evanescent-field technique, which is based on the interaction between a guided-mode evanescent field and liquid crystals. Access to the guided-mode evanescent field can be achieved by either polishing or etching the cladding and then overlaying liquid crystals. Most in-line components made this way use side-treated fibers. They can function as polarizers or modulators.[1-4]

In this report, a single-mode fiber was symmetrically etched to very nearly the surface of the core and enclosed with planar-aligned liquid crystals. The wave propagation behavior in this device configuration depends on the etch depth of the fiber and refractive indices of the liquid crystals. An appropriate etch depth was chosen to effectively approach the evanescent field. When an electric field was applied to the liquid crystals, the response of the lightwave propagation to liquid crystals' refractive indices was altered. Thereby optical polarization and intensity were exercised.

LIQUID-CRYSTAL-CLAD FIBER

A schematic view of the liquid-crystal-clad fiber is shown in Figure 1(a)(b). A strand of 633-nm single-mode fiber, with a core diameter (2a) of 3.8 μm and a cladding diameter of 125 μm, was stripped from its jacket and immersed in hydrofluoric acid (48% HF) to remove the cladding. One 3-cm-long section of the cladding was etched off to leave its diameter (2b) in the range of 6-12 μm and was sandwiched between two ITO-coated glass

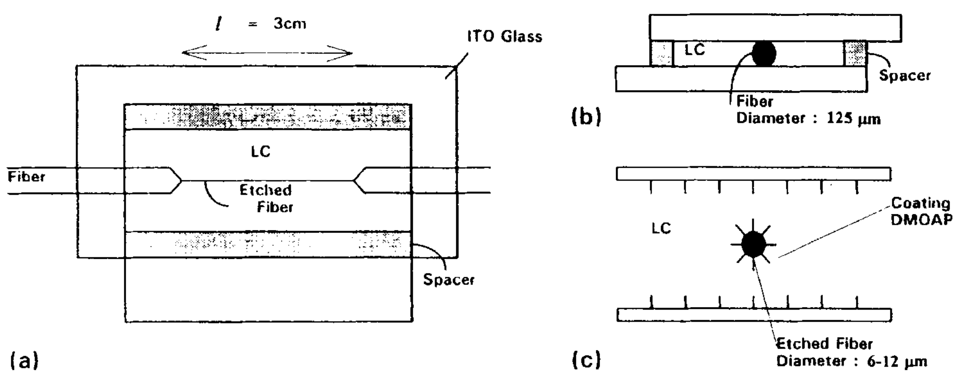

FIGURE 1 The geometry of a liquid-crystal-clad fiber: (a) top view (b) side cross-sectional view (c) perpendicular-aligned liquid crystals.

slides with a spacing of 125 μm. The liquid crystal was then inserted by capillary action. The liquid crystal used was nematic mixture 14616 obtained from Merck. The NLC used exhibited a nematic phase between 10 and 50°C over which the ordinary refractive index always remained lower than that of fused silica. The extraordinary index (n_e) and ordinary index (n_o) are given as 1.498 and 1.452, respectively, operating at a wavelength of 633 nm and a temperature of 25°C. Whereas the fiber had a core index (n_{co}) of 1.462 and a cladding index (n_{cl}) of 1.458.

In order to effectively approach the evanescent field, we conducted qualitative study of the effect of residual cladding thickness on lightwave propagation. The liquid crystal was perpendicularly aligned in the sample, as shown in Figure 1(c), where the glass slide and etched section were coated with DMOAP (N, N-dimethyl-N-octadecyl-3-

aminopropyltrimethoxysilyl chloride). The evanescent field in the LC, which "sees" the LC's extraordinary index n_e, greater than the core index n_o, leaked out. This allowed us to observe the effect of cladding thickness on access to the evanescent field. For b= 6 μm, the light leakage during propagation through the etched section of the fiber sample was not clear, while for b= 5 μm, the light obviously leaked out in the etched section, but output at the fiber end continued. For b= 3 μm, the light propagation decayed dramatically and disappeared completely from the output end. The observed results are shown in Figure 2. The radiation formed a conic fan with an angle of about 24 degrees obeying Snell's law.

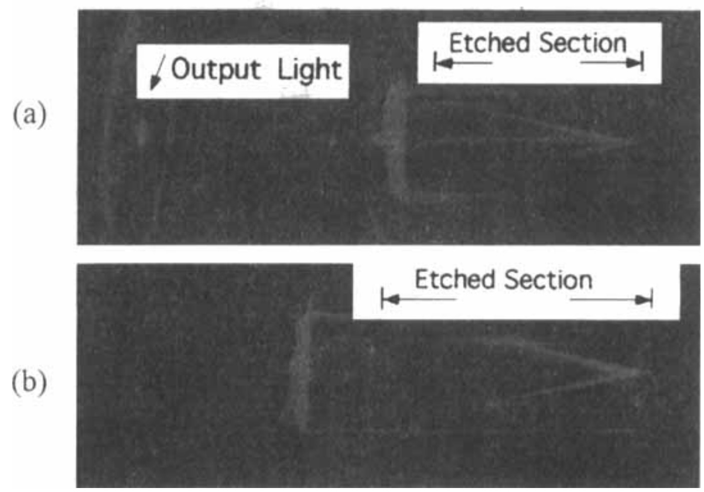

FIGURE 2 The effect of residual cladding thickness on lightwave propagation. (a) For b= 5 μm, the light leaked out in propagating through the etched section of the fiber, but output from the fiber end continued. (b) For b= 3 μm, the light decayed dramatically and disappeared completely from the output. (See Color Plate XVIII).

EXPERIMENTAL SETUP

The geometry in Figure 3(a) was used to investigate the electrooptic properties of liquid-crystal-clad fiber. In order to study the electrooptic effect of the fiber sample, the liquid crystal molecules were planar-aligned in the axial direction. This was achieved by coating PVA on the ITO-coated glass slides and rubbing their surfaces in the axial direction, as shown in Figure 3(b). The fiber had an etched section with 10-μm diameter of residual cladding. An ac electric field of 110 volt at 60 Hz was applied to the sample. A polarized He-Ne laser beam with a wavelength of 633 nm was passed through the halfwave plate to

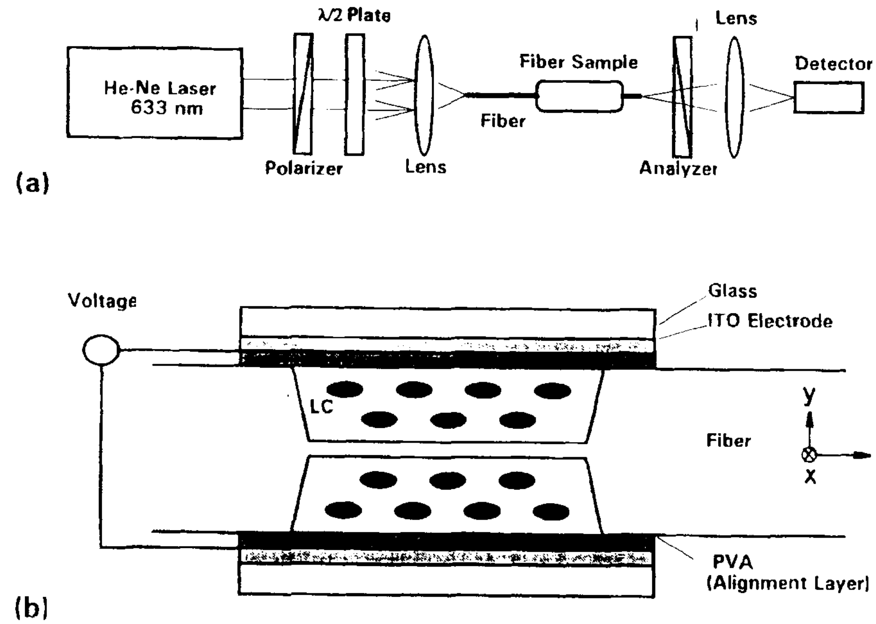

FIGURE 3 Schematic drawing of (a) experimental setup and (b) the planar-aligned liquid-crystal-clad fiber sample: side view.

vary the input light polarization and then focused into the fiber by a 20x microscopic objective; input power was 5 mW. The output light was examined using an analyzer and measured with a photodiode.

POLARIZATION SELECTION AND INTENSITY MODULATION

Theoretical Description

Figure 4 shows the liquid crystal molecules' orientations when the electric field was switched off and on, and the corresponding refractive index profiles. A theoretical consideration of optical characteristics used the calculation for W-type fibers. For x-polarized light, there is a guided solution, denoted as HE_x mode. Its propagation constant satisfies the following equation:[5]

$$\left[\frac{uJ_1(ua)}{J_0(ua)}+\frac{wI_1(wa)}{I_0(wa)}\right]\left[\frac{wK_1(wb)}{K_0(wa)}\frac{K_0(vb)}{J_0(ua)}-\frac{K_0(wb)}{K_0(wa)}\frac{vK_1(vb)}{J_0(ua)}\right] + \left[\frac{uJ_1(ua)}{J_0(ua)}-\frac{wK_1(wa)}{K_0(wa)}\right]\left[\frac{wI_1(wb)}{I_0(wa)}\frac{K_0(vb)}{J_0(ua)}+\frac{I_0(wb)}{I_0(wa)}\frac{vK_1(vb)}{J_0(ua)}\right]=0\,, \quad (1)$$

where $u=\left(n_{co}{}^2k^2-\beta^2\right)^{1/2}$, $w=\left(\beta^2-n_{cl}{}^2k^2\right)^{1/2}$, and $v=\left(\beta^2-n_o{}^2k^2\right)^{1/2}$; J_m, I_m, K_m are the Bessel and modified Bessel functions of the mth order. The k is the free-space propagation constant and β is the propagation constant in the fiber. As for the y-polarized light, there is a leaky solution when the voltage is switched on. The solution is denoted as HE_y mode and has the following characteristic equation:

$$\left[\frac{uJ_1(ua)}{J_0(ua)}+\frac{wI_1(wa)}{I_0(wa)}\right]\left[\frac{wK_1(wb)}{K_0(wa)}\frac{H_0^{(2)}(v'b)}{J_0(ua)}-\frac{K_0(wb)}{K_0(wa)}\frac{v'H_1^{(2)}(v'b)}{J_0(ua)}\right]$$
$$+\left[\frac{uJ_1(ua)}{J_0(ua)}-\frac{wK_1(wa)}{K_0(wa)}\right]\left[\frac{wI_1(wb)}{I_0(wa)}\frac{H_0^{(2)}(v'b)}{J_0(ua)}+\frac{I_0(wb)}{I_0(wa)}\frac{v'H_1^{(2)}(v'b)}{J_0(ua)}\right]=0, \qquad (2)$$

where $v'=(n_e{}^2k^2-\beta^2)^{1/2}$; $H_m^{(2)}$ is the mth-order Hankel function of the second kind.

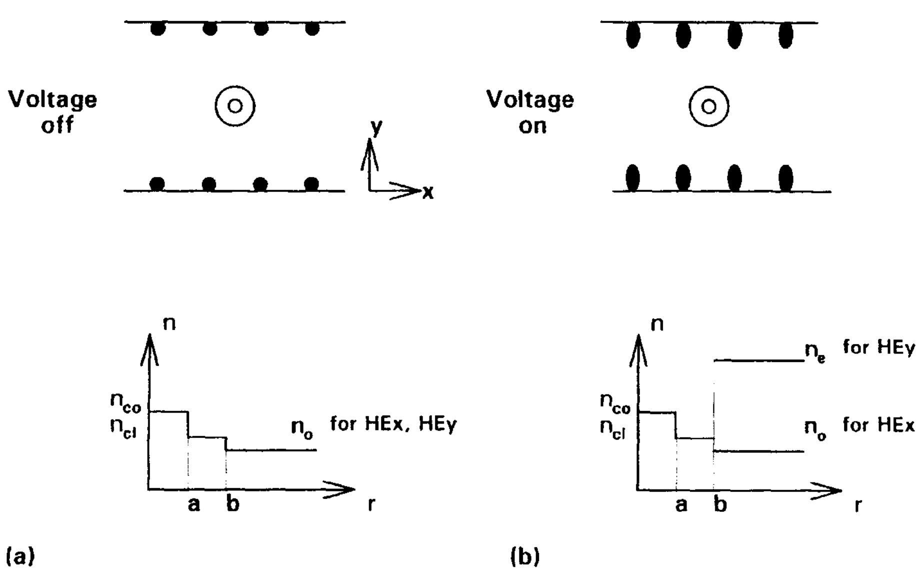

FIGURE 4 The orientations of liquid crystal molecules and the corresponding refractive index profiles without (a) and with (b) an applied voltage.

We used the following parameters to calculate Equations (1)(2): $n_{co}=1.462$, $n_{cl}=1.458$, $n_e=1.498$, $n_o=1.452$, $a=1.9\ \mu m$, and $\lambda=633$ nm. A decay constant is defined as $\alpha=-2\beta_i$, where β_i is the imaginary part of β. The decay constant versus residual cladding radius b is shown in Figure 5. Without an electric voltage, both HE_x and HE_y modes are guided. When the voltage is switched on, the HE_x mode is guided with zero decay constant, while the HE_y mode becomes leaky. The cladding thickness plays an important role because α for the HE_y mode increases dramatically as the cladding radius b is reduced. For b= 5 μm, α = 1.902 cm^{-1} and the output attenuation are proportional to $e^{-\alpha l} \sim 10^{-3}$, where l= 3 cm.

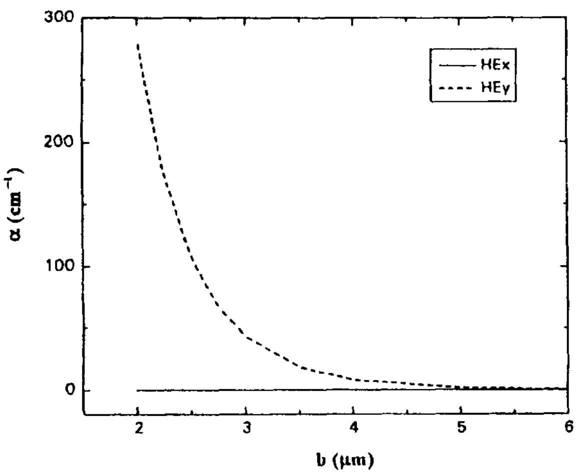

FIGURE 5 The calculated results of the decay constant α vs. residual cladding radius b.

Experimental Results

The experimental output variations in x-polarized and y-polarized lights with an electric field applied are shown in Figure 6(a). When the voltage was switched on, the x-polarized light continued propagating, but the y-polarized light was attenuated. As the applied voltage was raised, the attenuation became more severe. This demonstrates the electrically-controlled polarization selectivity of the fiber sample.

Figure 6(b) shows the modulation of output light and its y-polarized component when an ac voltage of 110 volts was switched on and off manually over a time duration of 2 sec. for each state. The optical output was out of phase with the electric input. The optical rise time is not dependent on voltage but is relative to the liquid crystal molecular relaxation response, which is determined by the elastic constants, viscosity coefficient of the liquid crystal and sample thickness. Whereas the optical decay time decreases with voltage increases and thinner samples produce faster decays. In the case of an applied voltage of 110 volt and a sample thickness of 125 μm, the decay time constant is of the order 100 msec, while the rise time is about 15 sec. Moreover, the described modulation is obviously polarization-dependent. This can be used to polarize light instantaneously along

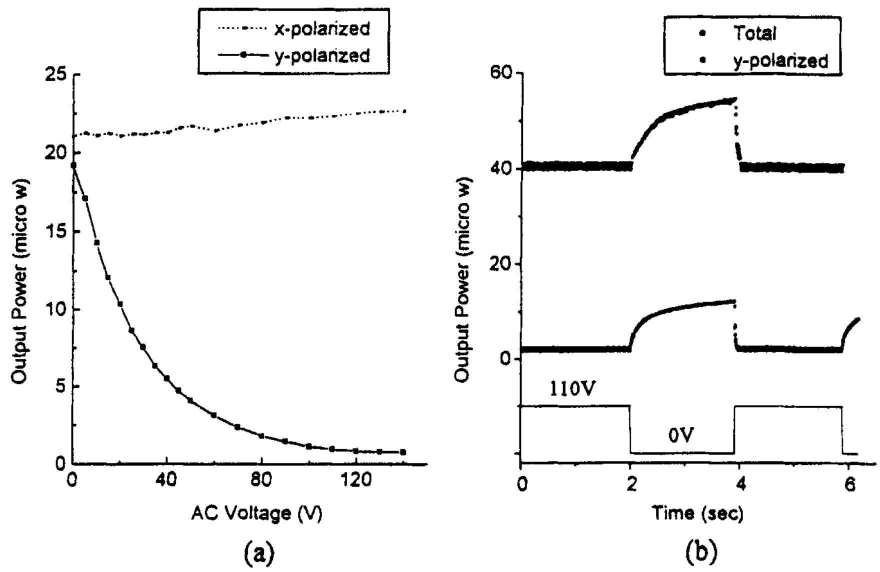

FIGURE 6 (a) Optical polarization selection with an applied electric field and (b) modulation of output light and its y-polarized component.

the direction for which modulation occurs. This may be important in polarization-preserved fiber systems.

DISCUSSIONS AND CONCLUSIONS

We have reported a new type of fiber-optic polarizer made of liquid-crystal-clad single-mode fiber. The key feature is the symmetrically etched fiber and planar-aligned nematic liquid crystal. The evanescent field was effectively approached with a proper cladding thickness, which can be determined by observing when light leakage occurs. Basically, the optical polarization selection and intensity modulation are based on the birefringence of liquid crystal. Therefore, the modulation is polarization-dependent. Moreover, the modulation frequency is limited by the relaxation time constant of the liquid crystal.

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