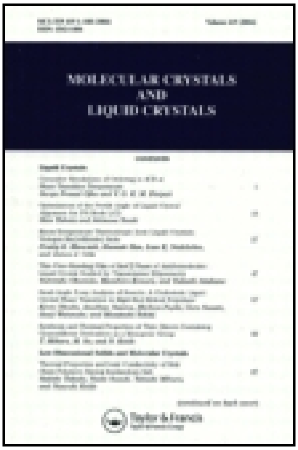

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Polarization Properties of Liquid Crystal-Core Optical Fiber Waveguides

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Polarization effects in liquid crystal-core optical fiber waveguides have been investigated based on extremely low-birefringence liquid crystal mixture acting as an optical fiber core characterized by an index ellipsoid. In certain conditions the liquid crystal elliptical-core fiber acts as a single-polarization fiber in which only one polarization mode is guided. The paper presents first experimental results of the liquid crystal fiber in the polarimetric configuration subjected to the influence of hydrostatic pressure and electric field.

Keywords: liquid crystal-core fiber waveguides; polarization

INTRODUCTION

Liquid crystal-core fiber (LCF) optic waveguides are of interest to modern optoelectronic systems, since they hold great potential for in-line modulation of intensity, phase or polarization properties of the guided light due to the presence of a liquid crystal core [1-3]. Moreover, the predominant feature of liquid crystals is that they are extremely sensitive to external fields and perturbations and consequently, in the past years much research effort has been devoted to exploring combined use of optical fibers and liquid crystals, especially for sensing applications [4-6]. In studies of waveguide structures, liquid crystals were used both as cladding [2] and also as the fiber core [1].

The paper presents analysis of polarization properties of the lowest-order modes in an elliptical liquid crystal-core cylindrical waveguide composed of an extremely low-birefringence liquid crystal acting as the fiber core. After a short theoretical approach results of the experimental studies of polarization properties of the light propagating in the liquid crystal-core fibers influenced by external perturbation effects are also presented.

POLARIZATION OF LIGHT IN OPTICAL FIBERS

Optical fibers exhibit particular polarization properties [7]. *Contrary to* ordinary plane waves in bulk media which amplitudes are constant in the wave plane guided electromagnetic fields in optical fiber waveguides are called inhomogenous plane waves since their amplitudes are not stable any more within the plane wave and the fields are characterized, in most cases, by non-transverse components.

In the description of polarization phenomena an optical fiber is generally treated as an optical waveguide in which light can be guided in the form of waveguide modes. This approach identifies basic polarization eigenmodes of a fiber and relates them to the polarization state of the guided light. A significant simplification in the description of waveguide modes is based on the fact that most fibers use core materials which the refractive index (n_{co}) is only very slightly higher than that of the surrounding cladding (n_{cl}), *i.e.*

$$n_{co} - n_{cl} << 1 \tag{1}$$

This assumption leads to the so-called "weakly-guiding approximation" in which instead of six-component field only four field components need to be considered. For a weakly-guiding fiber ($n_{co} \approx n_{cl}$), there are approximate mode solutions defined as linearly polarized LP_{lp} modes of different azimuthal (l) and radial (p) mode numbers and in the lower-order LP modes, the combination modes have the electric field configuration resembling a linearly polarized pattern. In order to excite stable LP modes in a LCF (1) should be fulfilled for at least the ordinary refractive index of the LC core medium (n_o).

LIGHT PROPAGATION IN ELLIPTICAL-CORE LCF

The liquid crystalline-core optical fiber acts as an optically anisotropic medium characterized by an index ellipsoid and can serve as a fiber with a controlled birefringence. However, the fiber birefringence is equal to zero when the liquid crystal molecules are parallel to the fiber axis, and also this is the typical structure of liquid crystal inside the hollow-core fiber. In elliptical-core fibers the birefringence has always non-zero value due to the non-symmetrical geometry of the core.

In theory, one should starts with the Maxwell equations and the Frank free energy density [5,6], that assumes that the orientation order of molecules is constant without changing the environmental parameters. Then the characteristic equations for the following modes: TE_{01}, TM_{01} and HE_{11} are derived. These formulas are called as Hondros - Debay equations and thanks to them the propagation constant β for each of the modes can be found.

As it has been previously demonstrated TE and TM modes exhibit different behavior [5]. TE_{01} mode is a guided mode and its propagation constant has zero imaginary component so the loss coefficient disappears. On the contrary, TM modes are leaky modes, so their propagation constants consist of both imaginary and real part.

An idea of investigation of the induced birefringence in the LC fiber leads to the fibers with elliptical liquid crystal core. First rough analysis of the birefringence has been performed utilizing the following expression form [6]:

$$B = \Delta^2 F(e,V), \tag{2}$$

where:

$\Delta = (n_1 - n_2)/n_1$; $e = \sqrt{1 - \left(\frac{a_x}{a_y}\right)^2}$ (ellipticity); a_x, a_y : ellipse semi-axes; $V_i = a_i k_0 n_1 \sqrt{2\Delta n}$, (normalized frequency) $i = x, y$; $k_0 = \frac{2\pi}{\lambda}$ and function F is a function of ellipticity and normalized frequencies [6].

The more accurate theoretical analysis can be done using the method proposed in [7]. Starting from the vector wave equation:

$$\nabla_t^2 \bar{E}_t + \left(n^2 k^2 - \beta^2\right)\bar{E}_t = -\nabla_t \left[\bar{E}_t \cdot \frac{1}{n^2} \nabla_t \left(n^2\right)\right] \tag{3}$$

where $\overline{E}_t$ is the transverse electric field; $\nabla_t = \frac{\partial}{\partial x}\hat{e}_x + \frac{\partial}{\partial y}\hat{e}_y$, $n = n(x,y)$ and $\Delta \ll 1$ (weakly guiding approximation), we arrive at scalar wave

of the LCF under the polarizing microscope between the crossed polarizers indicating homogenous orientation of the molecules perpendicular to the fiber axis (z).

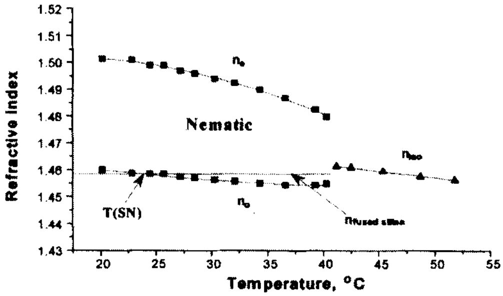
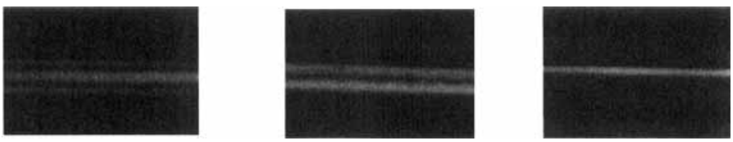


FIGURE 1 Temperature dependence of refractive indices (at $\lambda = 589$ nm) of the 3-component low–birefringence LC mixture described in Tab. I;T(SN)=24.7^{0}C is the S_B-N transition temperature.



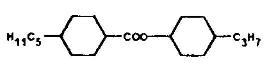
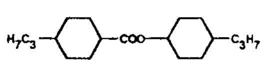
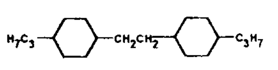
a) b) c)

FIGURE 2 The LCF under the polarizing microscope between the crossed polarizers: a) 45^0 and b) 90^0 (0^0) to the fiber axis; picture c) confirms the uniformity of the molecular orientation within the fiber See Color Plate X at the back of this issue.

The experimental set-up for measuring polarization effects in the LCF into account the anisotropy of liquid crystal. Changes in output polarization are described in terms of polarization-mode coupling due to birefringence changes acting as perturbations along the fiber.

LOW-BIREFRINGENCE LIQUID CRYSTAL

TABLE I Composition of the low-birefringence LC mixture

Structure of the components	wt. %
	44.06
	48.26
	7.68

To investigate polarization phenomena in liquid crystalline-core optical fiber waveguides an extremely low-birefringence LC material is required. Taking into account value of the refractive index n = 1.4580 (λ = 600 nm) of the fused silica it is evident that at least one of the LC refractive indices should be close to this value.

To fulfill this requirement a new class of LC mixtures has been prepared. The investigated mixture was composed of three components (see Tab. I) containing compounds with a saturated cyclohexane ring. The low-birefringence LC mixture exhibits the following phase transition: S_B24.7N40.6I. The temperature dependence of its refractive indices is presented in Fig. 1.

EXPERIMENTAL

The polarization-based effects have been investigated in elliptical-core (4x18 μm) liquid crystal fibers. Specially drawn hollow-core fibers were initially treated by a polyimide solution (PI TH-20) then heated and cured, and finally were filled by a long-term capillary action with a low-birefringence liquid crystal mixture. The whole fill-up process was controlled under the polarizing microscope. Fig. 2 presents photographs of the LCF under the polarizing microscope between the crossed polarizers indicating homogenous orientation of the molecules perpendicular to the fiber axis (z).

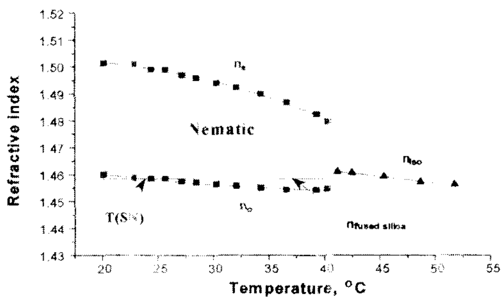


FIGURE 1 Temperature dependence of refractive indices (at $\lambda = 589$ nm) of the 3-component low–birefringence LC mixture described in Tab. I; T(SN)=24.7^{0}C is the S_B-N transition temperature.

a) b) c)

FIGURE 2 The LCF under the polarizing microscope between the crossed polarizers: a) 45^0 and b) 90^0 (0^0) to the fiber axis; picture c) confirms the uniformity of the molecular orientation within the fiber See Color Plate X at the back of this issue.

The experimental set-up for measuring polarization effects in the LCF and the influence of external parameters is pictured in Fig. 3 and schematically presented in Fig. 4.

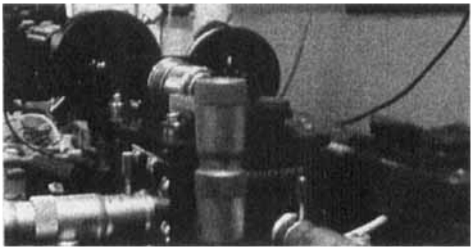


FIGURE 3 Experimental setup to investigate polarization effects in the liquid crystal-core fiber. See Color Plate XI at the back of this issue.

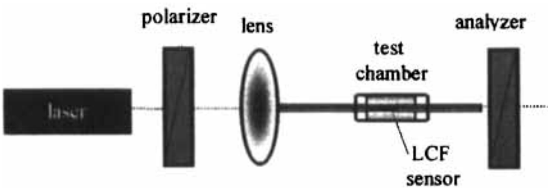


FIGURE 4 The liquid crystal-core fiber waveguide in the polarimetric configuration.

Polarization properties of the LCF are presented in Fig. 5 and 6. Even without any input polarizer we have obtained linearly polarized light at the output what is clearly pictured in Fig. 6. The effect enhances with temperature (Fig. 7)

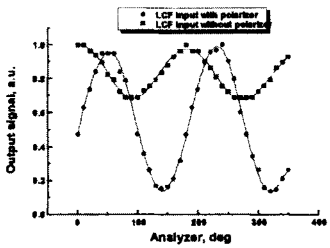


FIGURE 5 Single polarization properties of the LCF fiber. The non-zero polarization modulation has been achieved without any input polarization.

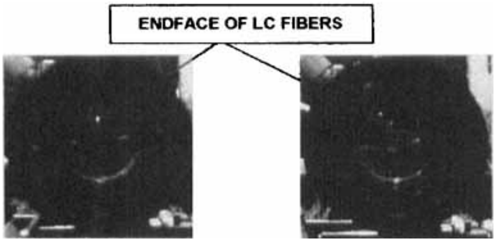


FIGURE 6 Single polarization performance of the LCF fiber. The light injected into the LCF is unpolarized.
See Color Plate XII at the back of this issue.

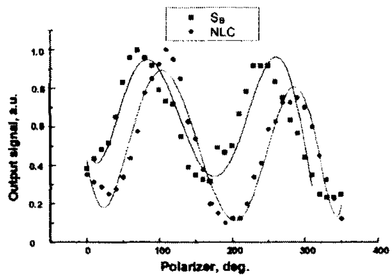
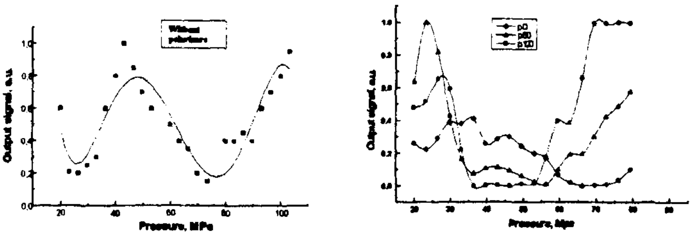


FIGURE 7 Output signal *vs* input polarization direction without any analyzer at the output. Both input/output SM fibers were connected to the LC fiber operating at smectic (B) and nematic temperature ranges.

Then the LCF placed between crossed polarizers has been subjected to selected perturbations such as those induced by hydrostatic pressure and external electric field whereas its polarization characteristics were investigated. The light source was a modulated He-Ne laser at 632.8 nm wavelength. As the input/output fibers we used single mode fibers which can preserve linear polarization for short distances. The length of the liquid crystal fibers was 15 mm. Lead-in and lead-out fibers with sensing part were glued together in the capillary to avoid direct splicing of the liquid crystal waveguide that exhibits high thermal sensitivity [4].

To show the potential for pressure sensing we inserted our sample of the liquid crystal fiber into the pressure chamber. Both intensity (Fig. 8a) and polarimetric (for different input polarizations angles – see Fig. 8b) configurations have been applied indicating large dynamics of the output signal along with the reasonable good repeatability of the pressure measurements. This is very important from the potential applications of LC-core fibers in pressure measurement. The LC-core fiber was also subjected to influence of the external electric field (Fig. 9). The experiment was performed in the polarimetric configuration confirming both: transverse orientation of LC molecules and field-induced reorientation, which can be used in sensing applications.



a) b)

FIGURE 8 Pressure characteristics of the single-polarization LCF: a) intensity modulation, b) polarimetric configuration for 3 different input polarizations

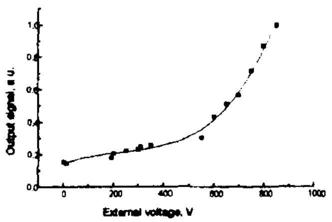


FIGURE 9 Polarimetric LCF influenced by external electric field (distance between electrodes is 130 μm)

CONCLUSIONS

We have studied the polarization properties of lowest-order LP modes in an elliptical-core cylindrical waveguide filled-in with low-birefringence liquid crystal. We also presented initial experimental polarization characteristics of the liquid crystal fiber subjected to the influence of external electric field and hydrostatic pressure. The results obtained indicate a possibility of single-polarization propagation within the liquid crystal fiber also suggesting its great potential for multi-parameter sensing.

ACKNOWLEDGMENTS

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