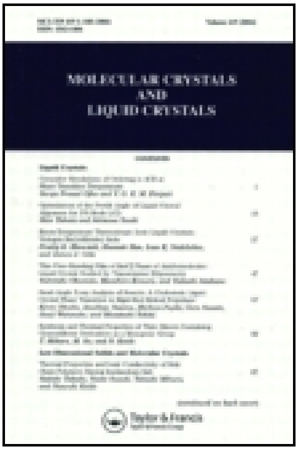

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Tomasz R. Woliński [a], Agnieszka Szymańska [a], Tomasz Nasiłowski [a], Mirosław A. Karpierz [a], Adam Kujawski [a] & Roman Dabrowski [b]

[a] Institute of Physics, Warsaw University of Technology, Koszykowa 75, 00-662, Warszawa, Poland

[b] Military University of Technology, Warszawa, Poland

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Propagation Effects in Liquid Crystal-Core Optical Fiber Waveguides

TOMASZ R. WOLIŃSKI[a], AGNIESZKA SZYMAŃSKA[a], TOMASZ NASIŁOWSKI[a], MIROSŁAW A. KARPIERZ[a], ADAM KUJAWSKI[a], and ROMAN DĄBROWSKI[b]
[a]Institute of Physics, Warsaw University of Technology, Koszykowa 75, 00-662 Warszawa, Poland; [b]Military University of Technology, Warszawa, Poland

Propagation effects in liquid crystal-core optical fiber waveguides have been investigated. In theory, propagation properties of the TE_{01} and TM_{01} modes in the waveguide composed of a low-birefringence nematic liquid crystal acting as an optical-fiber core have been analyzed. For smaller diameters of the liquid crystal-core, the TE_{01} mode is guided and TM_{01} is the leaky mode, but for larger diameters differences between both modes decrease. The paper presents initial experimental transmission characteristics of the liquid crystal fiber subjected to the influence of selected external perturbations. The experimental results have been compared with the theory in view of some typical optical fiber parameters suggesting a great potential of the liquid crystal-core fibers for environmental sensing.

Keywords: nematic liquid crystals; optical fibers

INTRODUCTION

Waveguided optoelectronics offers a lot of interesting solutions, but the necessity of leaving the fiber by the optical signal in the extrinsic sensors and afterwards its electronic modulation often introduces important limits for designing and systems solutions. Hence, in fiber optics technology there is a general tendency to replace optical bulk elements by equivalent all-fiber realizations. The advantage of fiber-optic liquid-crystal devices is the fact, that optical signal can be held all the time inside the optical system and the modulation of intensity, phase or polarization is done by the presence of liquid crystal. In addition, the predominant feature of liquid crystals is that they are extremely sensitive to any external fields and perturbations. 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[3-4]. In the most studies of waveguide structures, liquid crystals were used both as cladding[2] and also as the fiber core[1].

The paper presents analysis of propagation effects of the lowest-order modes in an radially anisotropic cylindrical waveguide with the liquid crystal core. The waveguide is composed of a low-birefringence nematic liquid crystal acting as an optical-fiber core characterized by an index ellipsoid. Starting from Maxwell's equations selected configurations of the nematic liquid crystal confined in the optical fiber core - creating a liquid crystal fiber (LCF) - and their influence on the modal structure of the radially anisotropic cylindrical waveguide have been analyzed. Depending on the studied geometries different propagation conditions for the lowest-order TE_{01} and TM_{01} modes have been obtained. The theoretical analysis was accompanied by initial results of experimental studies of light propagation by optical fibers with liquid crystalline cores influenced by selected external perturbation effects such as external electric field and hydrostatic pressure. Specially drawn hollow-core optical fibers with typical core diameters of 3 to 30 μm were filled with low-birefringence nematic liquid crystals. The liquid crystalline-core fiber waveguide acts as an optically anisotropic medium characterized by an index ellipsoid resulting in a new class of fiber-optic sensors.

THEORETICAL ANALYSIS OF LIGHT PROPAGATION IN LCF

It is considered a nematic liquid crystal confined in a cylinder with radius a (see Fig. 1). Consequently, the cylindrical coordinates system will be used. The director field configurations in the cylinder are determined by elastic torque and surface interactions. Basically, there are three types of alignment of the LC director inside the fiber: radial (homeotropic), the planar and a combination of two previous structures, so-called the escaped radial or axial geometry.

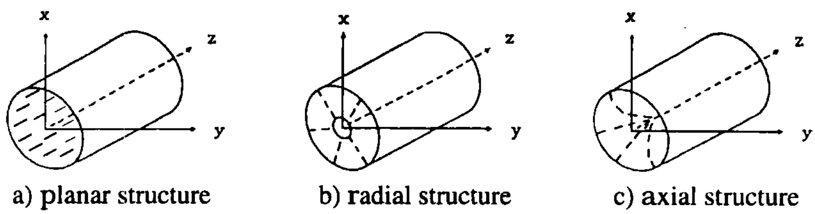

FIGURE 1 Types of alignment of the LC director inside the fiber.

In our analysis we are concentrated on investigation of the lowest-order TE_{01} mode for planar configuration and TM_{01} mode for both planar and radial configurations.

TE Modes

For the TE modes the vectors of electric and magnetic field have nonvanishing components:

$$\boldsymbol{E} = \left[0, E_\varphi, 0\right]\exp(i\omega t - i\beta z), \ \boldsymbol{H} = \left[H_r, 0, H_z\right]\exp(i\omega t - i\beta z)$$

and the Maxwell's equations have the form:

$$\begin{cases} H_r = -\dfrac{\beta}{\mu_0\omega} E_\varphi \\ H_z = \dfrac{i}{\mu_0\omega}\left(\dfrac{E_\varphi}{r} + \dfrac{\partial E_\varphi}{\partial r}\right) \\ \dfrac{\partial^2 E_\varphi}{\partial r^2} + \dfrac{1}{r}\dfrac{\partial E_\varphi}{\partial r} + \left(\varepsilon_0\mu_0\varepsilon\omega^2 - \dfrac{1}{r^2} - \beta^2\right)\cdot E_\varphi = 0 \end{cases}, \quad (1)$$

where ε is a dielectric constant. For $r \le a$ (a is radius of LC core) $\varepsilon = \varepsilon_\perp$ and for $r > a$ $\varepsilon = \varepsilon_c$, where ε_c is dielectric constant of fiber optic silica cladding.

Both tangential and longitudinal components of electric and magnetic fields have to be continuos at the core-cladding border. Then the solution of eq. (1) has the form:

$$E_\varphi(r) = \begin{cases} A_\varphi J_1(ur) & \text{for } r \le a \\ B_\varphi K_1^{(1)}(vr) & \text{for } r \ge a \end{cases},$$

where J_1 - first order Bessel function, K_1 - modified first order Hankel function, $u = (\omega^2\mu\varepsilon_\perp - \beta^2)^{0.5}$, $w = (\beta^2 - \omega^2\mu\varepsilon_c)^{0.5}$ and it should be fulfilled the Hondros - Debye characteristic equation:

$$uX + wY = 0, \quad (2)$$

where $$X = \frac{J_0(ua)}{J_1(ua)}, \quad Y = \frac{K_0^{(1)}(wa)}{K_1^{(1)}(wa)}. \quad (3)$$

TM Modes

In this case the vectors of electric and magnetic field are:

$$\boldsymbol{E} = [E_r, 0, E_z]\exp(i\omega t - i\beta z), \quad \boldsymbol{H} = [0, H_\varphi, 0]\exp(i\omega t - i\beta z),$$

and then the Maxwell's equations have the form:

$$\begin{cases} E_r = \dfrac{1}{i\omega\varepsilon_0\varepsilon_{//}\varepsilon_\perp}\left[i\beta\varepsilon_{zz}H_\varphi - \varepsilon_{rz}\left(\dfrac{\partial H_\varphi}{\partial r}+\dfrac{H_\varphi}{r}\right)\right] \\ E_z = \dfrac{i}{\omega\varepsilon_0\varepsilon_{//}\varepsilon_\perp}\left[i\beta\varepsilon_{rz}H_\varphi - \varepsilon_{rr}\left(\dfrac{\partial H_\varphi}{\partial r}+\dfrac{H_\varphi}{r}\right)\right] \\ \dfrac{\partial^2 H_\varphi}{\partial r^2}+\left(\dfrac{1}{r}+\dfrac{1}{\varepsilon_{rr}}\dfrac{\partial\varepsilon_{rr}}{\partial r}-2i\beta\dfrac{\varepsilon_{rz}}{\varepsilon_{rr}}\right)\dfrac{\partial H_\varphi}{\partial r}+\left[\dfrac{\mu_0\varepsilon_0\varepsilon_{//}\varepsilon_\perp\omega^2}{\varepsilon_{rr}}-\beta^2\dfrac{\varepsilon_{zz}}{\varepsilon_{rr}}-\right. \\ \left. -\dfrac{1}{r^2}-\dfrac{i\beta}{\varepsilon_{rr}}\left(\dfrac{\partial\varepsilon_{rz}}{\partial r}+\dfrac{\varepsilon_{rz}}{r}\right)+\dfrac{1}{r\varepsilon_{rr}}\dfrac{\partial\varepsilon_{rr}}{\partial r}\right]H_\varphi = 0 \end{cases} \tag{4}$$

where for r ≥ a the components of a dielectric permitivity tensor are equal to $\varepsilon_{zz} = \varepsilon_{rr} = \varepsilon_{\parallel} = \varepsilon_\perp = \varepsilon_c$ and $\varepsilon_{rz} = 0$. In the core we analyze two configurations: planar structure and radial structure.

<u>1. Planar structure:</u>

$$\varepsilon_{rr} = \varepsilon_\perp$$
$$\varepsilon_{rz} = 0$$
$$\varepsilon_{zz} = \varepsilon_{\parallel}$$

<u>2. Radial structure:</u>

$$\varepsilon_{rr} = \varepsilon_{\parallel}$$
$$\varepsilon_{rz} = 0$$
$$\varepsilon_{zz} = \varepsilon_\perp$$

The solution has the form

$$H_\varphi(r) = \begin{cases} A_r \cdot r \cdot J_1(ur) & \text{for } r \le a \\ B_r K_1^{(1)}(wr) & \text{for } r \ge a \end{cases}$$

and the Hondros - Debye characteristic equation for TM_{01} mode for two mentioned above cases are:

1. Planar structure

$$\varepsilon_{//} rwY + \varepsilon_\perp (ruX + 1) = 0 \tag{5}$$

2. Radial structure

$$\varepsilon_\perp rwY + \varepsilon_{//}(ruX + 1) = 0, \tag{6}$$

where *X* and *Y* were defined in eq. (3).

Due to these formulas, called as Hondros - Debye equations (2), (5), and (6), the propagation constant β for each of the modes can be found. In our case, we consider both: leaky modes represented by imaginary part β_i, which describes losses of the energy, and guided modes represented by real part β_r, which is inversely proportional to the phase velocity. Hence general formula describing the complex propagation constant is as follows: $\beta = \beta_r + i\beta_i$. Then the effective refractive index n_{eff} and loss coefficient α, which depend on components of the propagation constant can be defined:

$$n_{eff} = \frac{\beta_r}{k} \qquad \text{and} \qquad \alpha = -2\beta_i. \tag{7}$$

Fig. 2 presents effective refractive indices for the lowest-order TE_{01}, TM_{01} modes of LC-core optical fiber waveguide calculated from the characteristics equations, while Fig. 3 presents loss coefficients for the same modes. In calculations we used low-birefringence nematic liquid crystal characterized by refractive indices: $n_e = 1.5600$, $n_o = 1.4862$ and refractive index of silica cladding $n_{cl} = 1.4585$. The same LC material was used in experimental part of the work.

As it can be seen from the Fig. 2 and Fig. 3 TE and TM modes behave in different way. TE_{01} mode is a guided mode and its propagation constant has zero imaginary component so the loss coefficient disappears. In the contrary, TM_{01} modes are leaky modes, so their propagation constants consist of both imaginary and real part. Moreover, the real part becomes higher for bigger core radius. Generally, the value of the effective index for TE_{01} mode is much smaller then this for TM_{01} mode, but the difference disappears with the increasing radius. This phenomenon is very interesting for application of LC fibers in environmental sensing.

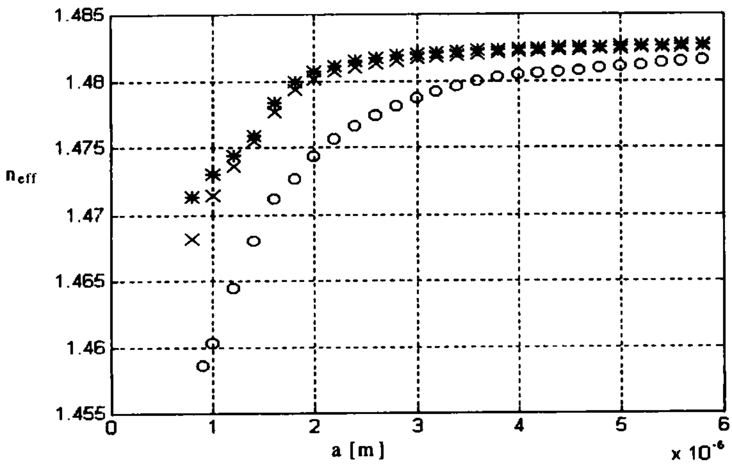

FIGURE 2 Effective refractive index *vs.* core radius; where *o* stands for TE_{01}, * for TM_{01} and planar structure, *x* for TM_{01} and radial structure.

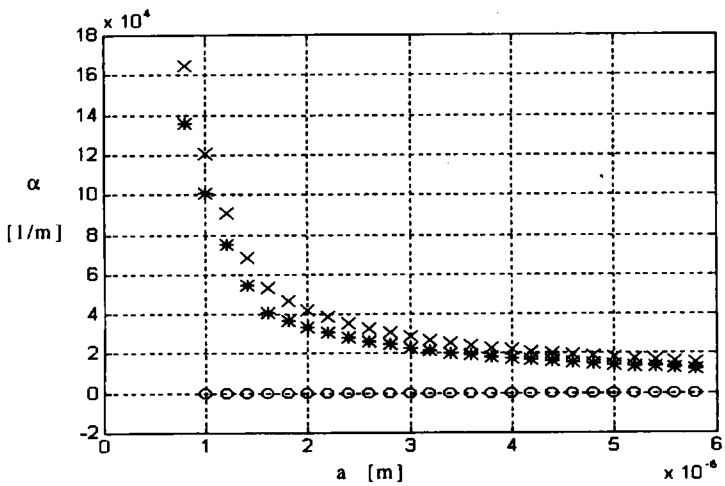

FIGURE 3 Loss coefficient *vs.* core radius; where *o* stands for TE_{01}, * for TM_{01} and planar structure, *x* for TM_{01} and radial structure.

However, it is possible to compute numerically propagation constant, but it is difficult to measure it experimentally and hence we cannot compare the theory with the experiment. That is why we define the numerical aperture NA which defines the divergence angle 2θ of the light outgoing from the fiber: $NA = \sin\theta$. This can be calculated from theory (Tab. I):

$$NA^{th} = \frac{\sqrt{k^2 - \beta^2}}{k_0} = \sqrt{n_{LC}^2 - n_{eff}^2} \quad (8)$$

and it can be compared with the data obtained from measurements: (Tab. II):

$$NA^{ex} = \frac{L}{\sqrt{d^2 + L^2}}, \quad (9)$$

where k - wave vector inside fiber, k_0 - wave vector outside fiber (in vacuum), d - distance from fiber to the light spot and L - radius of the light spot in distance d.

Experimental

The experimental set-up for measuring propagation effects in the liquid crystal-core fiber (numerical aperture, NA) and its behavior influences of external electric field is shown in Fig. 4.

The light source was a He-Ne laser at 632,8 nm wavelength modulated using a standard technique. A liquid crystalline material was placed inside the hollow core fibers with a different internal diameters: 3-4 μm, 5 μm, 7-8 μm, 10 μm, 15 μm and 30 μm.

It needs to be emphasized that the special method of coupling lead-in and lead-out fibers with the sensing waveguide filled up with liquid crystal was proposed. Such a configuration was proposed to avoid direct splicing of the liquid crystal waveguide that exhibits high thermal sensitivity[4]. As the input fibers the single mode fibers were used. 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 which is also presented in Fig. 4.

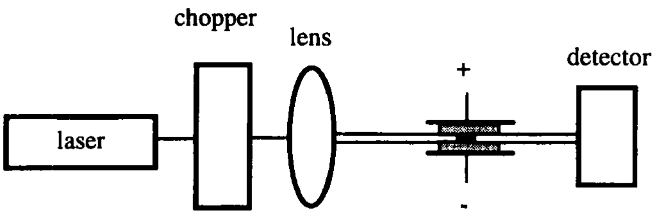

FIGURE 4 The experimental set-up for investigating the liquid crystal fiber under influence of external electric field

Based on the data presented in Tab. I and Tab. II we can easily conclude that the investigated liquid crystal-core optical fiber waveguide has mostly planar structure, what is evident from a direct comparison of the numerical apertures calculated theoretically and measured in the experiment, see (8),(9).

To check the possibilities of electrooptical modulation, we launched the laser light into liquid crystal fiber and perturbed it with an AC electric field. We can see a significant difference in the transmission of light with applied voltage and without it in the Fig. 5.

TABLE I Theoretical values of numerical apertures (NA^{th}) for two LC-core optical fibers (r=3μm and r=5μm) with two orientations

	radius of LC core	Type of nematic liquid crystals		
		1110	*1115*	*1140*
Planar Orientation	r=3μm	0.066	0.122	0.112
	r=5μm	0.057	0.077	0.09
Radial Orientation	r=3μm	0.358	0.499	0.464
	r=5μm	0.356	0.49	0.459

TABLE II Experimental values of numerical apertures (NA^{cx}) for different LC-core optical fiber

	Type of nematic liquid crystals		
radius of LC core [μm]	*1110* $n_e = 1.5017$, $n_o = 1.4600$	*1115* $n_e = 1.5600$, $n_o = 1.4862$	*1140* $n_e = 1.5528$, $n_o = 1.4862$
3	0.045±0.01	0.075±0.01	0.1±0.01
5	0.04±0.01	0.065±0.01	0.06±0.01
7	0.04±0.01	0.07±0.01	0.08±0.01
10	0.075±0.01	0.085±0.01	0.075±0.01
15	0.08±0.01	0.08±0.01	0.075±0.01
30	0.1±0.01	0.1±0.01	0.085±0.01

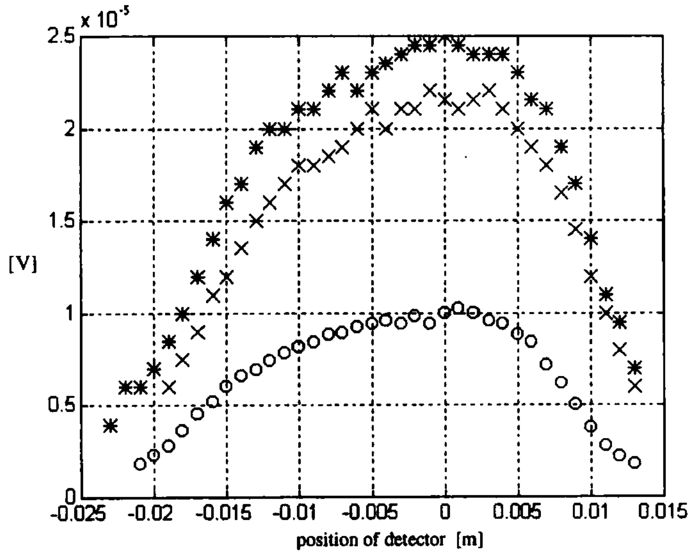

FIGURE 5 Intensity of light vs. detector position: without electric field (o); with electric field 1V/μm and frequencies 26 Hz (*) or 42 Hz (x).

It is evident that external electric field change the orientation of the molecules and in such a way change the transmission coefficient. Data presented in Fig. 5 was performed for E = 1V/μm and two frequencies: 26 Hz and 42 Hz.

To show the potential for pressure sensing we inserted our sample of the liquid crystal fiber into the pressure chamber and large dynamics of the output signal along with the reasonable good repeatability of the pressure measurements has been obtained[6]. This is very important from the point of view of potential applications of LC-core fibers in pressure measurement.

CONCLUSION

We have studied the propagation properties of the TE_{01} and TM_{01} modes in a hollow core cylindrical waveguide filled-in with liquid crystal for different diameter of the core. For such a waveguide structure and for smaller diameters the TE_{01} is the guided mode and TM_{01} is the leaky mode, but for bigger diameters differences between these modes decrease. We also presented initial experimental transmission characteristics of the liquid crystal fiber subjected to the influence of external electric field and hydrostatic pressure. It appeared that numerical aperture of a LCF can be directly connected with the type of director orientation inside the liquid crystal core. The results obtained suggest a great potential of liquid crystal-core fibers for environmental sensing.

Acknowledgements

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