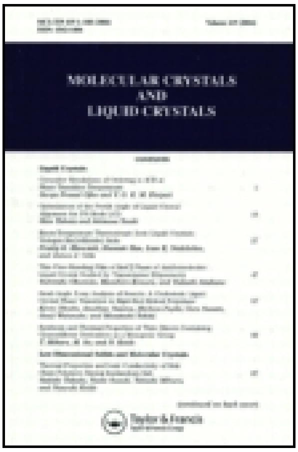

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

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Version of record first published: 18 Oct 2010

Mol. Cryst. Liq. Cryst., Vol. 375, pp. 723-733

1058-725X/02 $12.00 + .00

Polarization Properties of Birefringent Systems with Liquid Crystal-core Optical Fibers

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Polarization phenomena in birefringence optical fiber systems comprising highly birefringent (HB) polarization-maintaining fibers and elliptical-core liquid crystal-core fibers (LCFs) have been investigated. Elliptical cores of the LCFs are composed of nematic mixtures characterized by extremely low values of refractive indices.

Keywords liquid crystal-core waveguides; optical polarization; HB fibers

INTRODUCTION

The polarization properties of solid-core optical fibers have been extensively investigated for over the last two decades [1] and significant progress in optical fiber technologies from the use of intensity (amplitude) modulation to the modulation of the optical polarization of the electromagnetic wave propagating along a fiber has been achieved.

In the description of polarization properties in optical fibers there are generally two approaches. The first one treats an optical fiber as an optical waveguide in which light being a kind of electromagnetic wave of optical frequencies 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. Changes in output polarization are described in terms of polarization-mode coupling due to birefringence changes acting as perturbations along the fiber. Another approach treats an optical fiber like any other optical device, which transmits light and the fiber, can be divided into separated sections behaving like polarization state shifters. Here, polarization evolution in a fiber can be described by one of the three general formalisms: by the Jones formalism, by the Stokes-Mueller formalism, or by the Poincaré's sphere representation.

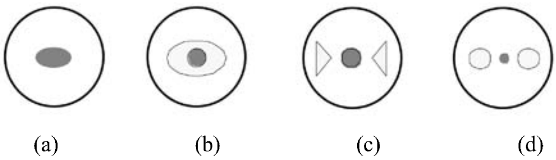

FIGURE 1. Various types of HB polarization-maintaining fibers: a - elliptical core, b - elliptical internal cladding, c - bow-tie, d - PANDA.

In HB polarization-maintaining fibers, the difference between the phase velocities for the two orthogonally polarized modes is high enough to avoid coupling between these two modes. Fibers of this class have a built-in well-defined, high internal birefringence obtained by designing core and/or cladding with noncircular geometry, or by using stress applying parts built into the cross-section of the fiber as presented in Figure 1. These include elliptical-core (a), stress-induced elliptical internal cladding (b), bow-tie (c) or PANDA (d) fibers. The magnitude of the internal birefringence characterized by the beat length parameter:

$$L_B = 2\pi/|\beta_y - \beta_x| \qquad (1)$$

is responsible for phase difference changes along the longitudinal axis z of the HB fiber. The spatial period of these changes reflects the changes in the polarization states along the fiber (Figure 2).

Since linearly birefringent optical fibers have a pair of preferred orthogonal axes, two orthogonal quasilinear polarized field components HE_{11}^x and HE_{11}^y of the fundamental mode HE_{11} have electric fields that are polarized along one of these two birefringence axes. Hence, light polarized in a plane parallel to either axis will propagate separately without any change in its polarization but with different velocities. However, injection of any other input polarization excites both orthogonal mode components characterized by different propagation constants β_x and β_y. Hence they run into and out of phase at a rate determined by the birefringence of the HB fiber producing at the same time a periodic variation in the transmitted polarization state from linear through elliptic to circular and back again (Figure 2).

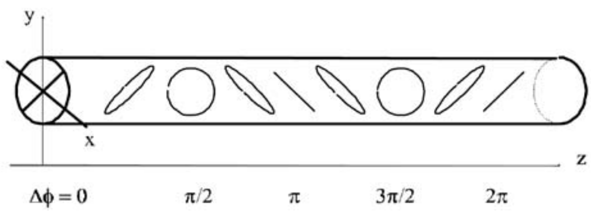

FIGURE. 2. The definition of the beat length of the fundamental mode HE_{11} in a single-mode HB polarization-maintaining fiber.

ELLIPTICAL-CORE LIQUID CRYSTAL FIBERS

Highly birefringence fibers and LCFs exhibit particular polarization properties. Liquid crystals possess high optical anisotropy and their macroscopic optical properties (including polarization) can be easily altered by any external factors.

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

The present analysis concerns systems consisted of elliptical-core LCFs [2,3] and HB fibers. The LCFs were composed of extremely low-birefringence LC mixtures (described elsewhere [2]) introduced into a hollow elliptical-core fibers (capillaries). One of the low-birefringence LC compositions (cat. no. 1335-1) was characterized by ordinary $n_o = 1.464$ and extraordinary $n_e = 1.488$ refractive indices at 20°C with phase transition order: K13.5S$_A$19N25I. In certain region of nematic phase (above 22°C), its ordinary refractive index (n_o = 1.456) is below the refractive index of the fused silica n_{cl} = 1.458 (λ = 600 nm) while their extraordinary index was still a little bit higher (n_e=1,480). Consequently, only one polarization can be guided within the fiber. The ellipse axes of the LCF have the following dimensions: $a_X = 9*10^{-6}$ [m], $a_Y = 2*10^{-6}$ [m], what is schematically shown in Figure 3.

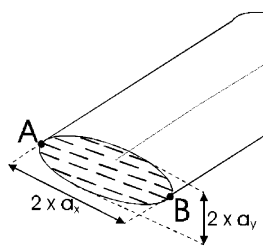

FIGURE 3 Elliptical-core liquid crystal fiber with the homogeneous transverse orientation of the LC molecules.

If a nematic LC is surrounded by a capillary of elliptical cross section, its molecular orientation strongly depends on capillary dimensions, boundary conditions, and on physical fields influencing the LC medium. Any external factor acting on the nematic LC changes their refractive indices. The extraordinary index of refraction n_e depends on α, the angle between direction of propagation and the optical axis and is described by:

$$n_e(\alpha) = \frac{n_o n_e}{\sqrt{n_o^2 \cos^2\alpha + n_e^2 \sin^2\alpha}} \tag{2}$$

where: n_o, n_e are ordinary and extraordinary refractive indices, respectively.

In order to analyze polarization evolution and properties of the elliptical liquid crystal-core fiber the Mueller-Stokes formalism and the Poincare sphere representation can be applied. In the Mueller-Stokes formalism, the Stokes parameters have a simple physical interpretation and are related to intensity measurements. It is thus useful to gather these parameters in a four-component array, the Stokes vector (S):

$$S = \begin{bmatrix} I \\ M \\ C \\ S \end{bmatrix} = \begin{bmatrix} I_{xx} + I_{yy} \\ I_{xx} - I_{yy} \\ I_{xy} + I_{yx} \\ i(I_{yx} - I_{xy}) \end{bmatrix} \qquad (3)$$

where I, M, C, S are the Stokes vector parameters, $I = I_s + I_n$ (I_s signifies polarized, and I_n unpolarized light, respectively) is the total light intensity, $I_{xx}=<E_xE_x^*>$, $I_{xy}=<E_xE_y^*>$, $I_{yy}=<E_yE_y^*>$, $I_{yx}=<E_yE_x^*>$, and E is the electric field vector.

TOMOGRAPHIC INTRFEROMETRIC METHOD

To investigate the internal structure of the elliptical-core LCF the tomographic interferometry technique has been applied.

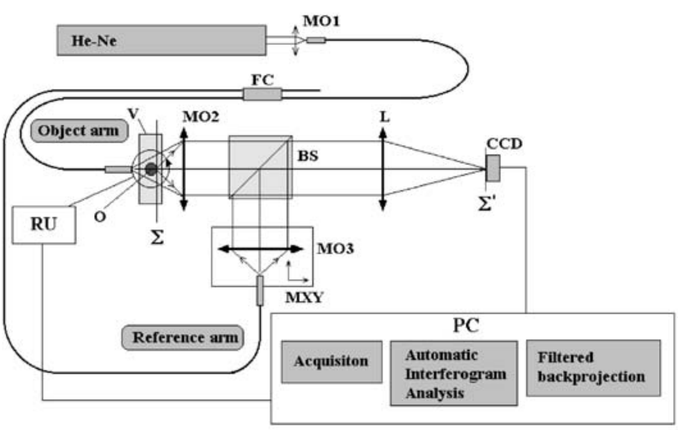

FIGURE 4 Automatic tomographic microinterferometer (He-Ne - helium-neon laser; MO1, MO2, MO3 – microscopic objectives, FC – fiber coupler, O – liquid crystal fiber, V – immersion vessel, RU – rotary unit, BS – beamsplitter cube, L – lens, CCD - camera, MXY – manipulator, PC – computer.

Methodology of reconstruction of the 3-dimensions refractive index distribution in optical phase microelements has been created and verified by the experiment [4]. The automated tomographic microinterferometer has been developed on the basis of the classical Mach-Zehnder interferometer. Figure 4 shows the experimental set-up for refractive index distribution measurements of elliptical-core LCFs.

The laser beam is introduced through a microscopic objective into the single mode optical fiber. A fiber coupler divides the light into object and reference beams while both the coupler and the fiber preserve linear polarization of light. The LCF is immersed in the vessel. Immersion liquid used in the experiment was characterized by the refractive index n_d=1,474 and dn/dT=0. The whole imaging system consists of a microscopic objective, a beam-splitter cube and a lens. Wavefront Σ is imaged on a CCD array by the microscopic objective with magnification 40*x*. A *MXY* manipulator in the reference beam is used to adjust the whole set-up and to introduce spatial carrier frequency into the fringe pattern. A PC controls the whole measurement process including rotation of the LCF, interferogram acquistion and analysis, as well as tomographic reconstruction. Details about this method are presented elsewhere [4]. A typical interferogram of the elliptical-core LCF is shown in Figure 5.

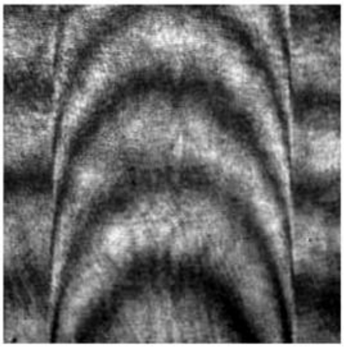

FIGURE 5 Interferogram of the ECLCF.

With the use of the setup described above a three-dimensional refractive index map of the fiber has been created. The LCF was rotated within the range of 180 degrees with a step equal to one degree. Hence, 180 interferograms have been recorded and processed with the resolution

512x512. The results obtained allow determining orientation of LC molecules within the core region of the fiber. When the LCF was placed with its major elliptical axis in the plane of Figure 5 we could observe slight perturbations of the interferogram within the core region due to the fact that extraordinary refractive index of the LC core is higher than that of silica cladding. When we rotate the LC fiber by 90 degrees the core perturbation practically disappears. This confirms the predominant orientation of LC molecules along the major elliptical axis.

Figure 6a presents cross-sectional distribution of the refractive index $n(x,y,z_{120})$ within the elliptical-core LCF while Figure 6b and Figure 6c show horizontal and vertical profiles, respectively.

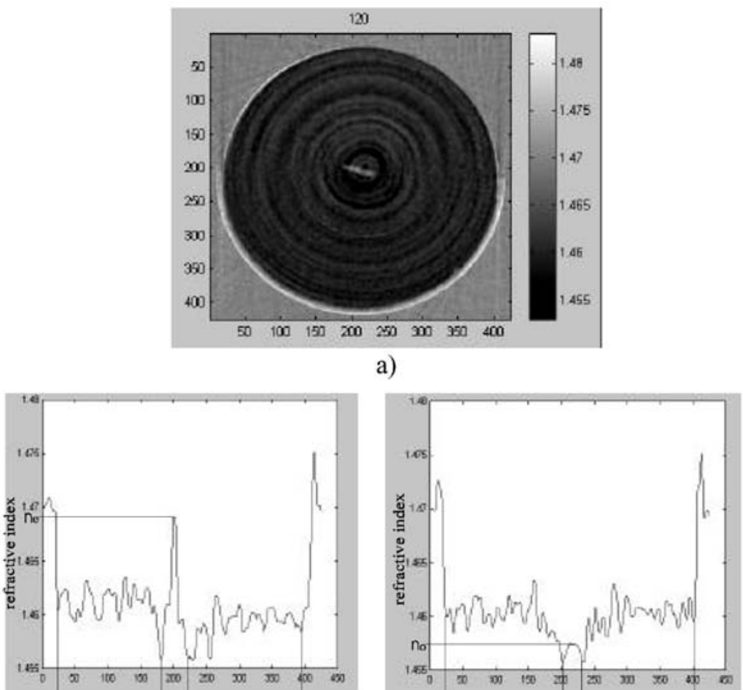

FIGURE 6 Results of refractive index measurement within the ECLCF a) cross-section refractive index distribution $n(x,y,z_{120})$; b) horizontal profile from cross section $n(x,y,z_{120})$; c) vertical profile from cross section $n(x,y,z_{120})$.

These observations confirm homogeneous orientation of LC molecules within the core with their long axes parallel to the major axis of the ellipse. The extraordinary refractive index is higher than ordinary refractive index.

EXPERIMENTAL AND RESULTS

In the experimental, the elliptical-core (4*x*18μm) LCF with the homogeneous transverse orientation of the LC molecules have been manufactured (Figure 3). The whole fill-up process was described elsewhere [3].

Figure 7 shows the experimental set-up for polarimetric measurements of the birefringence optical fibers. An elliptical-core LCF of the length c.a. 5 cm, (LC mixture no. 1335-1) was connected to the HB *bow-tie* fiber (c.a 50 cm long). The fibers were placed between crossed polarizers whereas their polarization characteristics were investigated.

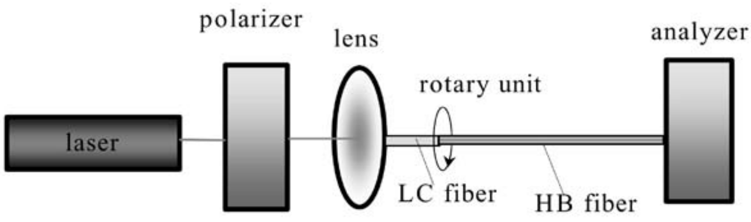

FIGURE 7 Experimental setup to investigate polarization effects in the birefringent system composed of LC and HB fibers.

The linearly polarized light at an angle θ (θ = 0°, 45°, and 90°) with respect to the major axis of the ellipse was injected to the elliptical-core LCF, see Figure 8.

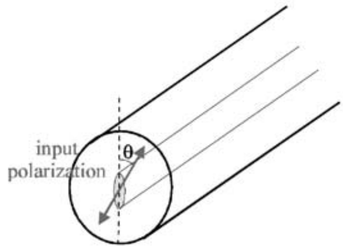

FIGURE 8 Input polarization direction injected into the elliptical-core LCF (θ = 0°, 45°, 90°).

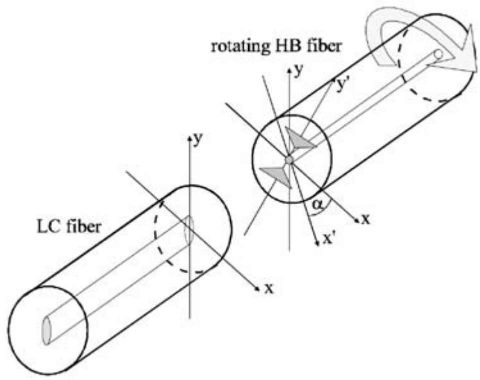

FIGURE 9 Configuration of the birefringent systems with LC and HB fibers to study polarization phenomena.

There was a possibility to rotate the HB fiber along its long *z* axis as it is schematically presented in Figure 9.

Preliminary results of the polarization measurements of the birefringent system composed of the LC and HB fibers are presented in Figures 10 and 11. The results confirm single-polarization properties of the LCF (Figure 10: when θ = 90° and α = 0°) as well as polarization maintaining possibilities of the system (when θ = 0° and α = 0°).

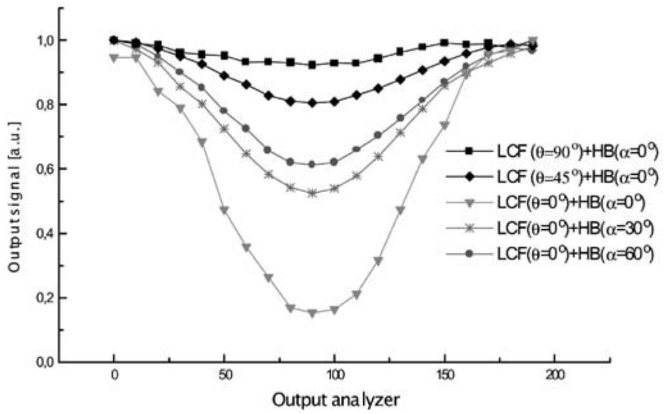

FIGURE 10 Output signal as a function of the output polarization for different configurations of the LCF (1335-1; 5 cm long) and the rotated HB fiber (50 cm long), and for different directions of the input polarization.

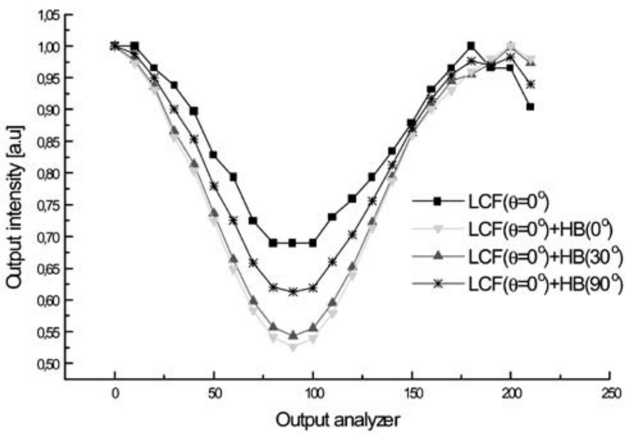

FIGURE 11 Output signal as a function of the output polarization for different configurations of the LCF (1335-1; 5 cm long) and the rotated HB fiber (50 cm long).

CONCLUSIONS

To conclude, we have studied the polarization properties of birefringence optical fibers. The elliptical-core LCFs connected with solid-core HB PM fibers exhibit good polarization properties. Apart from sensing applications we envisage the use of birefringent systems with LCFs in optical communication to compensate polarization-mode dispersion in optical telecommunication systems.

ACKNOWLEDGMENTS

The work was supported by the Polish State Committee for Scientific Research (KBN) under grants nos. 8T11D027019 and 7T11B08021.

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