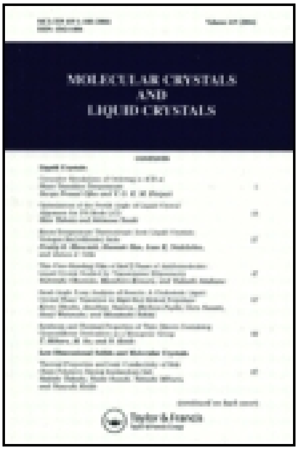

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Polarizing and Depolarizing Optical Effects in Photonic Liquid Crystal Fibers

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Polarizing and Depolarizing Optical Effects in Photonic Liquid Crystal Fibers

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The paper describes polarization phenomena occurring in photonic crystal fibers infiltrated with liquid crystals and presents latest experimental results of the influence of temperature, external electric field and hydrostatic pressure on their polarization properties. Also depolarization effects in photonic liquid crystal fiber induced by an external electric field are brought forward.

Keywords: depolarization; liquid crystals; photonic crystal fibers; polarization

INTRODUCTION

In the last few years there has been observed an enormous development of research activities in the field of photonic crystal fibers (PCFs) in which guiding of the optical waves is governed by one of two principal mechanisms responsible for light trapping within the fiber core. The first one is a simple propagation effect based on the modified total internal reflection (mTIR) phenomenon, which is well known and similar to wave guiding within a conventional fiber. The other, known as the photonic band gap (PBG) effect [1], occurs when the refractive index of the fiber core is lower than averaged effective refractive index

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in the cladding region. In this case the guiding mechanism relies on the coherent backscattering of light into the core. The PBG effect is usually observed in hollow-core photonic crystal fibers, whereas solid-core photonic crystal fibers can guide light by the mTIR phenomenon.

Photonic liquid crystal fibers (PLCFs) i.e. photonic crystal fibers in which air holes are infiltrated with liquid crystals can guide the light by both mechanisms [2–4]. It has been recently demonstrated [5] that light propagation in a PLCF exposed to external influences of temperature, electrical field and hydrostatic pressure can lead to interesting changes in its polarization properties. This paper presents our recent experimental results on polarizing and depolarizing effects observed in PLCFs.

POLARIZATION AND DEPOLARIZATION PHENOMENA IN OPTICAL FIBERS

Polarization is one of fundamental properties of electromagnetic waves describing spatial direction of the transverse electric field. A general polarization state of the monochromatic plane wave in a homogenous medium is the state of elliptical polarization and in a geometrical description of polarization the polarization ellipse describes state of polarization (SOP) of the totally polarized light [6]. Due to the vectorial nature of SOP the Jones matrix formalism can be used to describe optical polarization and any SOP can be expressed by a two-line column vector, called the Jones vector:

$$[E(z_0)] = \begin{bmatrix} E_{0x}\exp(i\delta_x) \\ E_{0y}\exp(i\delta_y) \end{bmatrix} \tag{1}$$

where E_{0x}, E_{0y} are components and δ_x, δ_y are initial phases of the wave electric field vector **E**.

The Jones vectors method enables to determine the output SOP of the totally polarized light after passing through many elements of an optical system but also to trace SOP in any point of the light beam track. Polarization properties of an optical element may be described adequately in the monochromatic case by a 2×2 unitary complex matrix known as the Jones matrix J – and the resulting output field can be described by the following matrix equation:

$$[E(z_2)] = [J][E(z_1)] \tag{2}$$

A strictly monochromatic light wave is completely polarized. This is not the case if the spectral width of the light source is limited or if a monochromatic wave passes through depolarizing media that introduce random shifts between two orthogonal base states. In such situations as a result we obtain partially polarized light. For partially polarized light, the Stokes vector describes both: SOP as well as degree of the polarization (DOP) and is defined as follows:

$$[S] = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} J_{xx} + J_{yy} \\ J_{xx} - J_{yy} \\ J_{xy} + J_{yx} \\ i(J_{yx} - J_{xy}) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 0 & -i & i & 0 \end{bmatrix} \cdot \begin{bmatrix} J_{xx} \\ J_{xy} \\ J_{yx} \\ J_{yy} \end{bmatrix} \tag{3}$$

where S_0, S_1, S_2, S_3 are the Stokes vector parameters and J_{xx}, J_{yy}, J_{xy}, J_{yx} are elements of the coherence matrix.

Polarization evolution of both: totally and partially polarized light occurring in different birefringent media can be represented by the Poincaré sphere.

To characterize highly birefringent fibers we have to refer to polarization mode dispersion (PMD) and modal birefringence $\Delta\beta$. PMD is expressed in terms of differential group delay (DGD) over the length of the fiber (ps/km) [2,7], while DGD, defined by time delay between orthogonal polarization modes and usually expressed in ps:

$$PMD = \frac{DGD}{L} = \frac{d(\Delta\beta)}{d\omega} = \frac{1}{c}\left(\Delta n_{eff} + \omega \frac{d\Delta n_{eff}}{d\omega}\right) \tag{4}$$

Modal birefringence in a single-mode HB fiber can be expressed in terms of propagation constants difference between both orthogonally-polarized modes.

$$B_m = \frac{|\beta_x - \beta_y|}{k} = |n_x - n_y| \tag{5}$$

The beat length [8,9] is the length of the optical fiber section over which the input SOP is reconstructed (Fig. 1).

$$L_B = \frac{2\pi}{|\beta_x - \beta_y|} = \frac{\lambda}{B_m} \tag{6}$$

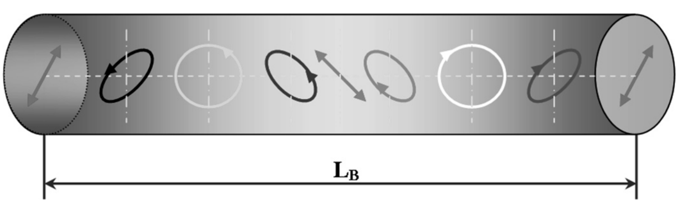


FIGURE 1 The beat length.

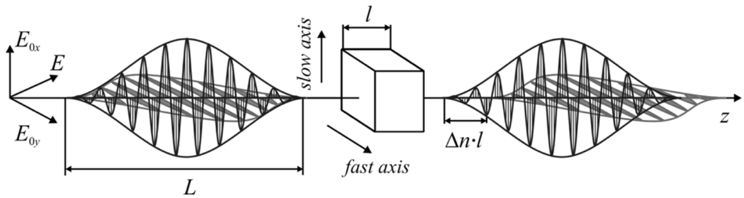


FIGURE 2 Propagation of wave-packet along a birefringent crystal and a phase shift which causes changes in SOP and DOP.

Partially temporal coherent light propagating in a birefringent crystal or in an optical fiber becomes depolarized (Fig. 2), so its DOP decreases. The depolarization effect depends on coherence of the light $\Delta L(\Delta\lambda)$, birefringence of the medium $\Delta n_{eff} = n_{fast} - n_{slow}$ and the azimuth θ between a plane of linear polarization and the birefringence axis [10]. The effect of depolarization in optical fibers (induced by PMD) is responsible for lengthening of light pulses what significantly decreases transmitting information (bit rate).

For the same value of the input beam DOP we can obtain different degrees of polarization of the transmitted light depending on temporary coherency of the light source used which significantly reduces the maximum transmittable information rate.

$$DOP_{in} = \frac{\sqrt{S_1^{in^2} + S_2^{in^2} + S_3^{in^2}}}{S_0^{in}} > DOP_{out} = \frac{\sqrt{S_1^{out^2} + S_2^{out^2} + S_3^{out^2}}}{S_0^{out}} \quad (7)$$

To describe the phenomenon of depolarization we used the Mueller-Stokes matrix formalism modified by a depolarization matrix D_p:

$$\left[S^{out}\right] = [D_P][M]\left[S^{in}\right] \quad (8)$$

where:

$$\left[S^{out}\right] = \begin{bmatrix} S_0^{out} \\ S_1^{out} \\ S_2^{out} \\ S_3^{out} \end{bmatrix} \left[S^{in}\right] = \begin{bmatrix} S_0^{in} \\ S_1^{in} \\ S_2^{in} \\ S_3^{in} \end{bmatrix} \quad (9)$$

are the Stokes vectors of outgoing and incoming light beams, respectively and

$$[D_P] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & P_c & 0 & 0 \\ 0 & 0 & P_c & 0 \\ 0 & 0 & 0 & P_c \end{bmatrix} \quad (10)$$

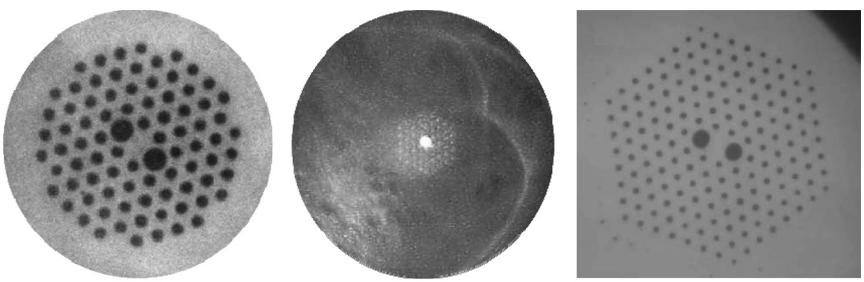
is the depolarization matrix in which P_c characterizes light sources: either the Lorentzian spectrum (laser diodes LDs) or the Gaussian spectrum (gas laser, light emitting diodes LED and superluminescent diodes SLDs), and finally

$$[M] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\left(\frac{2\pi\Delta nl}{\lambda}\right) & \sin\left(\frac{2\pi\Delta nl}{\lambda}\right) \\ 0 & 0 & -\sin\left(\frac{2\pi\Delta nl}{\lambda}\right) & \cos\left(\frac{2\pi\Delta nl}{\lambda}\right) \end{bmatrix} \tag{11}$$

is the Mueller matrix of birefringent medium.

MATERIALS AND EXPERIMENTAL SETUP

In our experiment we used two commercially available highly birefringent PCFs. One of them – HB PM-1550-01 produced by *Blazephotonics* (Fig. 3a) is characterized by two big holes which surround solid core of the fiber. Diameter of the large hole is 4.5 μm and whereas the small hole diameter is 2.2 μm. In contrast, a non-circular core combined with a large air-glass refractive index difference creates a strong form birefringence. This fiber was used to investigate temperature and electric field influence. The second one, LMA-PM-5 produced by *Crystal Fibre* (Fig. 3b) is characterized by stress elements in its cross section and a solid core (diameter 4.9 μm). This fiber was used to investigate influence of hydrostatic pressure. The third fiber used in our experiments was a PCF cat. number 070119P2 produced by *UMCS Lublin* (Fig. 3c). It is characterized by two large holes which have 3.5 μm diameters and the solid core size is 1.35 μm. This fiber was used to investigate depolarization effect in photonic liquid crystal fiber.



(a) (b) (c)

FIGURE 3 Cross sections of the investigated host HB PCF, (a) PM-1550-07 *Blazephotonics* fiber, (b) LMA-PM-5 *Crystal Fibre* fiber, and (c) HB PCF 070119P2 (*UMCS Lublin*).

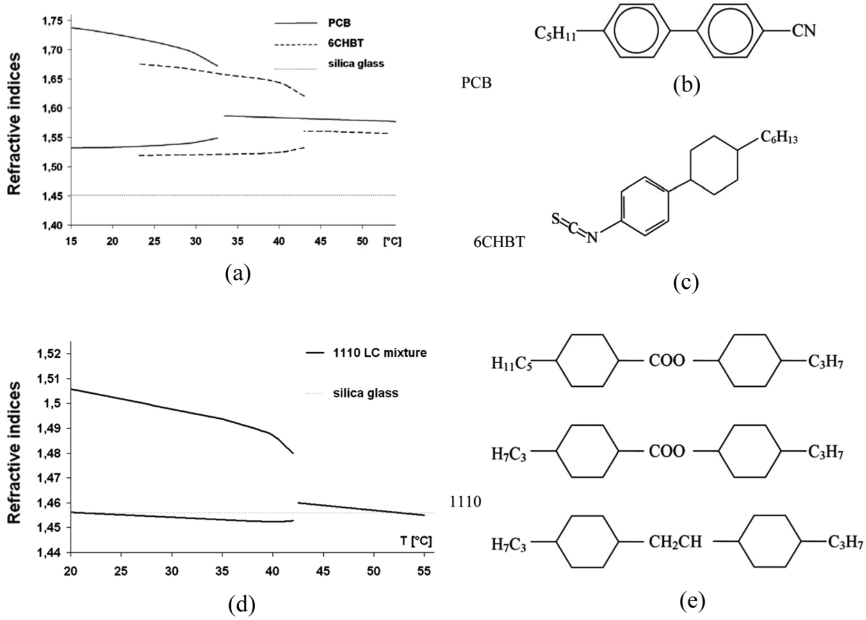


FIGURE 4 Refractive indices as a function of temperature for nematic LCs: with medium birefringence PCB, 6CHBT (a) with low birefringence 1110 (d) along with their structural formula: PCB, 6CHBT (b, c) and for 1110 (e).

All of these fibers were infiltrated with liquid crystals. PM-1550-01 was filled with PCB (4′-n-pentyl-4-cyanobiphenyl) (Fig. 4b) with birefringence ~0.17 at 23°C. The next one LC was 6CHBT [4-(trans-4-hexylcyclohexyl)isothiocyanatobenzene] (Fig. 4c) with birefringence 0.16 at 23°C. Thermal characteristic of refractive indices for PCB and 6CHBT are shown in Figure 4a. The 1110 nematic LC mixture (Fig. 4e) composed of alkyl 4-trans-alkylcyclohexyl 4-trans-alylcyclohexanecarboxyte is characterized by extremely low birefringence ~0.04 at 23°C. Thermal characteristics of both refractive indices of the 1110 nematic mixture are shown in Figure 4d (only two big holes of the PM-1550-01 fiber have been LC infiltrated). The nematic LCs used for PCF infiltration were synthesized at the Military University of Technology, Warsaw, Poland.

The experimental setup for investigation of polarization and propagation properties of the PLCFs under the influence of temperature and external electric field is shown in Figure 5. This setup consists of a light source (halogen lamp or a tunable laser). The input light is coupled into a PCF (host) that is connected with a PLCF located in a

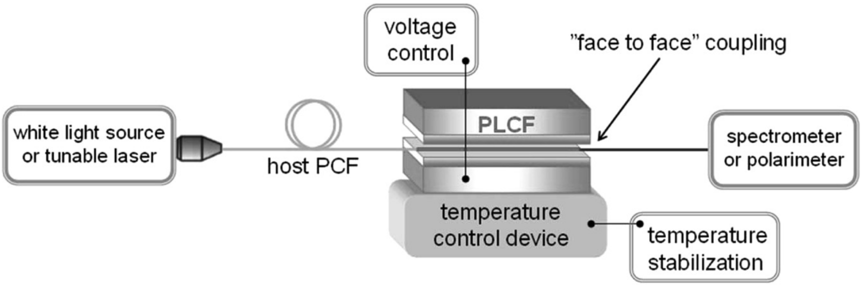


FIGURE 5 Experimental setup for investigation of propagation and polarization properties of the HB PLCF under the influence of temperature and external electric field.

thermo-electric control device (with regulation in the 10°C–120°C range with ~0.1°C resolution or regulation for electrical field in the 0–1000 V range with frequency from 50 Hz to 2 kHz) through to the Ocean Optics HR4000 spectrometer or PAT9000B polarimeter (*Tektronix*) to analyze spectral and polarization properties of light. The Ocean Optics HR4000 is characterized by the spectral range 195 nm–1120 nm whereas a tunable laser (*Tunics Plus*) operates in the spectral range: 1500 nm–1640 nm.

Another experimental setup presented in Figure 6 was used to investigate an influence of hydrostatic pressure on PLCFs. This setup consists of white-light source (halogen lamp) and the HR4000 spectrometer to analyze the light coming out of the HB PLCF. An initial section of ~20 mm of the 35 cm-long PCF was filled with a LC and then the LC was moved to the middle part of the PCF by using the pressurized air. The PLCF was next introduced into a high – pressure chamber through a specially designed leadthrough system. Then the PLCF sample was connected to the white – light source and to the spectrometer by using capillary connections and single – mode (SM) leading fibers. Finally, hydrostatic pressure (from the range 20 to

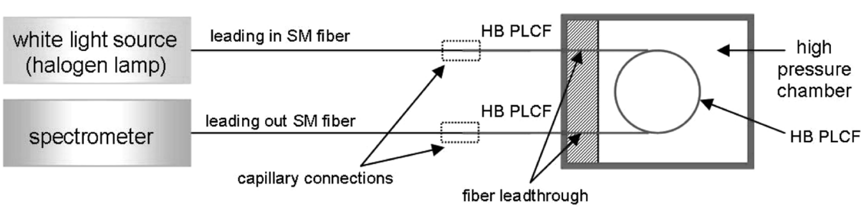


FIGURE 6 Experimental setup to investigate propagation and polarization properties of the HB PLCF under influence of high hydrostatic pressure.

70 MPa) was applied to the chamber, modified and controlled with a dead – weight piston manometer.

TEMPERATURE, ELECTRICAL FIELD AND HYDROSTATIC PRESSURE EFFECTS

Temperature

We observed temperature-induced changes in SOP of the light coming out of the photonic liquid crystal fibers. Consequently this property may be used to propose advanced optical fiber sensors. In this experiment we used the empty PM-1550-01 HB PCF whereas the light source was a high-power halogen lamp.

Temperature control and stabilization was in the range from 10°C to 120°C. Any temperature-induced change in the value of refractive index of LC introduced changes in its polarization properties.

As we can see in Figure 7 the group birefringence of the Blaze photonics PM-1550-01 HB photonic crystal fiber – measured by the wavelength scanning method [2]:

$$B_g = \frac{\bar{\lambda}^2}{\Delta\lambda L} \qquad (12)$$

where $\Delta\lambda$ is the wavelength spacing between neighboring peaks (maxima), and L is a fiber length and $\bar{\lambda}$ is the center wavelength between two peaks – increased with the operating wavelength. According to the formula (12) we measured the group birefringence of the empty PM-1550-01 fiber by measuring its output spectra when it was placed between crossed polarizers. Then the PCF was selective infiltrated (only to bigger holes) with 1110 LC mixture and we measured birefringence of the resulting PCLF for three different temperatures (Fig. 8).

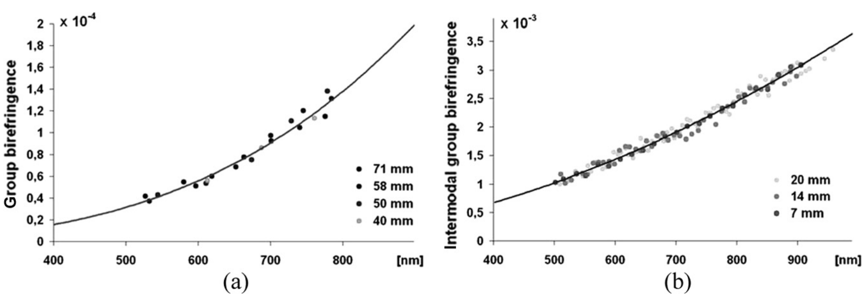


FIGURE 7 Modal (a) and intermodal (b) group birefringence dispersion of the empty Blazephotonics PM-1550-01 HB photonic crystal fiber.

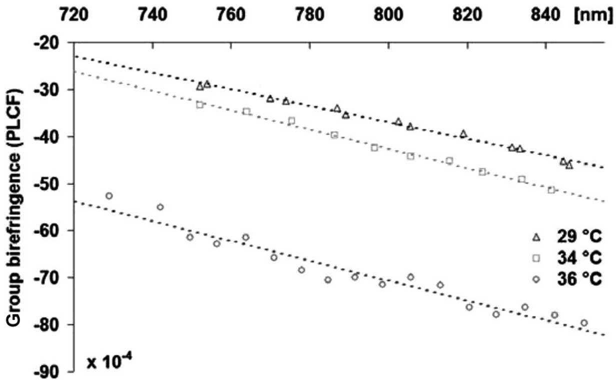


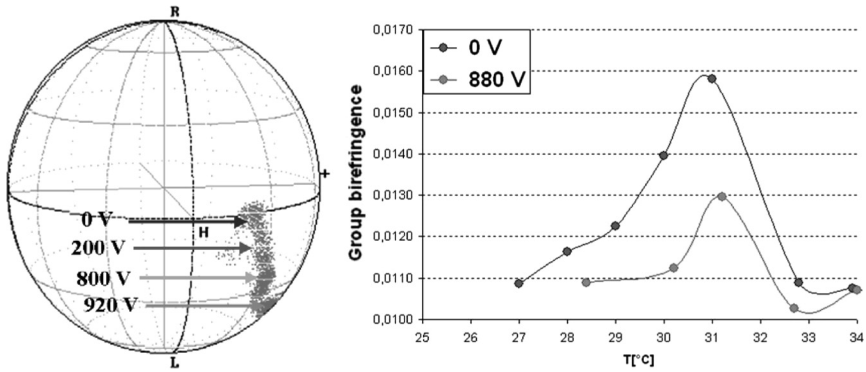
FIGURE 8 Group birefringence of the PLCF (PM-1550-01 PCF filled with the 1110 LC mixture.

The group birefringence of the PLCF is temperature dependent so the group birefringence is about 20–30 times higher (Fig. 8) than the empty PCF group birefringence (Fig. 7a). In connection with this slow and fast birefringence axes in the PLCF and in the empty PCF are reversed.

Electric Field

It is evident that an external electric field can reorient LC molecules infiltrating the photonic crystal fiber. In this experiment we used the HB PM-1550-01 Blazephotonics photonic crystal fiber infiltrated with PCB nematic LC. Only two big holes were filled with the LC. To achieve selective infiltration we used a conventional fusion splicer to collapse smaller holes in the PCF cladding (the bigger holes still remained open). The nematic liquid crystal was pushed into the micro holes of the photonic crystal fiber by the capillary effect. Then finally it was cut off collapsed region of PCF. The total length of the PCF was 27.6 cm whereas the guest liquid (PCB) infiltrated only the 1.7 cm long section of the PCF. To investigate polarization properties under the influence of the external electrical field we used a tunable laser *Tunics PLUS* operating at the range of 1500–1600 nm. The polarimeter PAT9000B with POL 9320FIR module served as an analyzer.

Initially (without field) the LC molecules tend to reorient themselves parallel to the fiber axis (so-called “orientation by flow”) and propagation is governed by the ordinary refractive index of the LC. The electrical field was controlled by voltage from 0 to 1000 V, within



(a) (b)

FIGURE 9 Changes in the polarization state visualized on the Poincaré sphere (a) and thermal dependence of the group birefringence without and with external electric field (b) PLCF based on PCB.

the 50 Hz–2 kHz frequency range. Since PCB is characterized by positive dielectric anisotropy therefore under the influence of the electric field above the Frederiks threshold, the LC molecules will reorient perpendicularly to the fiber axis.

We can see (Fig. 9a) that under varying voltages we observed changes in the light polarization visualized on the Poincaré sphere (voltages up to 920 V). This effect indicates that the electric field can tune polarization properties of the HB PLCF. Moreover, the results obtained suggest that the phase birefringence is being changed under influence of the external electric field.

Figure 9b presents results of the group birefringence changes observed under simultaneous action of thermal and electric fields in the PCB-based PLCF. Birefringence increases with temperature in the nematic phase due to enhancement of molecular disorder. However application of external electric field introduces better ordering of LC molecules and hence diminishes the group birefringence.

Hydrostatic Pressure

In the next step we infiltrated with the 6CHBT nematic liquid crystal a 2 cm section of the 35 cm long LMA-PM-5 photonic crystal fiber and the fiber was introduced into a high pressure chamber. In the PCF filled with 6CHBT selected wavelengths can be guided by the Photonic Band Gap mechanism since both refractive indices of 6CHBT are higher than the refractive index of the silica glass used for PCF fabrication, so

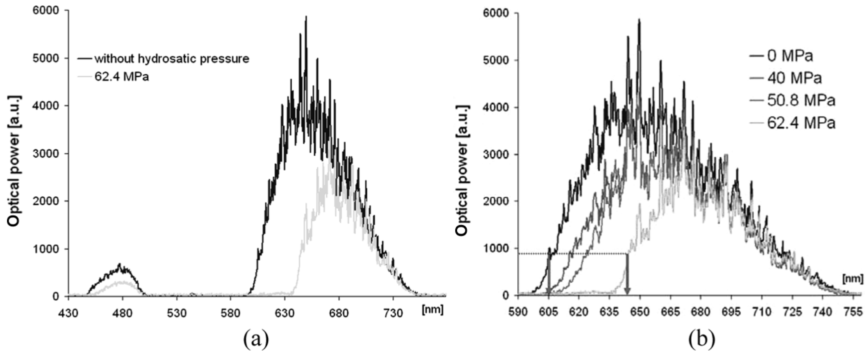


FIGURE 10 Transmission spectra for LMA-PM-5 PCF infiltrated with 6CHBT LC under influence of hydrostatic pressure.

the effective index of the cladding is higher than the refractive index of the fiber core. The PBG effect is observed in the range 450 to 490 nm and also 600 to 750 nm. It appeared that hydrostatic pressure caused a red shift of the photonic band gap (towards longer wavelengths) as it is demonstrated in Figure 10 along with a narrowing effect of the order of 40 nm. This opens up possibilities of prospective constructions of the PLCF-based hydrostatic pressure sensors (Fig. 11a).

The Poincaré sphere (Fig. 11b) presents state of polarization evolution for selected values of hydrostatic pressure applied to the photonic liquid crystal fiber. Hydrostatic pressure can tune polarization properties of the HB PLCF due to modification of its phase birefringence.

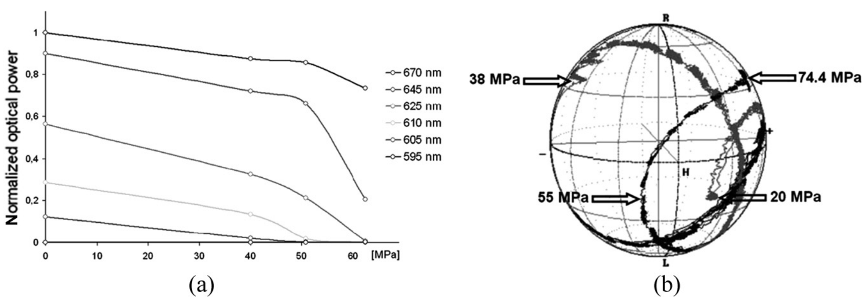


FIGURE 11 (a) Normalized optical power for selected wavelengths in function of hydrostatic pressure for LMA-PM-5 PCF with the nematic 6CHBT. (b) Change of polarization state in LMA-PM-5 PCF with 6CHBT LC under hydrostatic pressure – visualization of the Poincaré sphere.

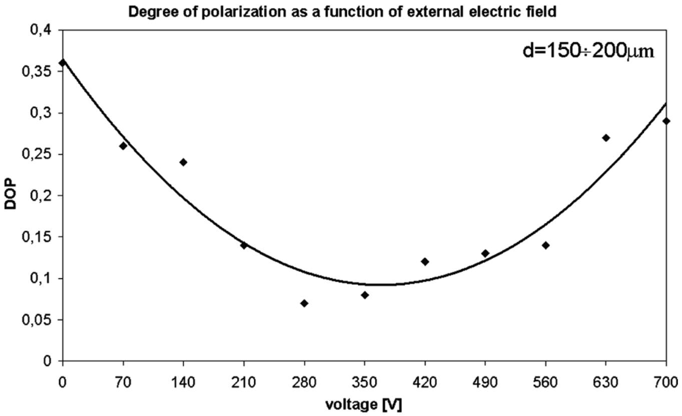


FIGURE 12 Minimal DOP as function of external electric field for PCF (600 mm) filled with 5CB (5 mm) (d- distance between electrodes).

Hydrostatic pressure sensitivity of the phase birefringence can be calculated as follows:

$$K = \frac{2\pi}{T_p L} \cong 0.18 \left[\frac{rad}{m \cdot MPa} \right] \tag{13}$$

DEPOLARIZATION EFFECT

To investigate depolarization effects in PLCFs we infiltrated a 600 mm long PCF either with 5CB or 6CHBT only at the 5 mm distance and then output spectra of the transmitted light have been measured. A single mode laser diode operating at $\lambda = 674$ nm with spectral width $\Delta\lambda = 0.058$ nm was used as a light source. The results of minimal

TABLE 1 Comparison of DOP in Different Birefringent Fibers

$\Delta\lambda$	Medium		Length	Azimuth	DOP
0.058 nm	PCF		600 mm	0°	0.94
				45°	0.95
	PLCF	5CB	595 + 5 mm	0°	0.93
				45°	0.30
		6CHBT	594 + 6 mm	0°	0.96
				45°	0.20
	Classical HB fiber		1000 mm	0°	0.99
				45°	0.94

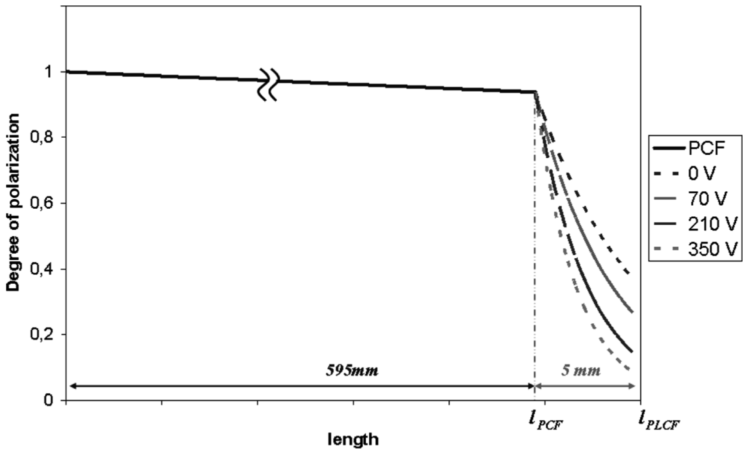


FIGURE 13 DOP changes of the laser diode light in PCF and PLCF for different values of the external electric field (distance between electrodes was 150–200 μm).

DOP ($\theta = 45^{\circ}$) in different types of birefringent fibers are presented in Table 1.

An external electric field introduces reorientation of the LC molecules infiltrating the PCF and this effect modifies the minimal value of DOP (Fig. 12, 13).

DOP (as it results from Table 1) achieves for HB (bow-tie) and photonic crystal fibers its highest value (close to 0.95). However, in the photonic liquid crystal fiber (filled with PCB) a significant decrease of the degree of polarization (to the value ~ 0.30) was observed.

CONCLUSIONS

In this work we have presented polarization effects in photonic liquid crystal fibers (photonic crystal fibers infiltrated with liquid crystals) induced by external electric field, temperature and/or hydrostatic pressure and also we discussed their depolarization properties. Temperature was found to strongly influence birefringence of the PLCF through thermal dependence of the refractive index of the LC-infiltrated cladding holes. The resulting tunable birefringence influences polarization properties (SOP and DOP) of the light propagating within the PLCF. Consequently, this property may be used to propose fiber-optic sensors of a new generation and devices for in-line polarization mode dispersion compensation.

REFERENCES

[1] Knight, J. C. (2003). Photonic crystal fibres. *Nature*, *424*, 847–851.

[2] Wolinski, T. R., Lesiak, P., Domański, A. W., Ertman, S., Szaniawska, K., Dabrowski, R., Nowinowski-Kruszelnicki, E., & Wojcik, J. (2006). Polarization optics of microstructured liquid crystal fibers. *Mol. Cryst. Liq. Cryst.*, *454*, 333/[735]–350/[752].

[3] Wolinski, T. R., Szymanska, A., Nasilowski, T., Nowinowski-Kruszelnicki, E., & Dabrowski, R. (2000). Polarization properties of liquid crystal-core optical fiber waveguides. *Mol. Cryst. Liq. Cryst.*, 352, 361–70.

[4] Alkeskjold, T. T., Scolari, L., Noordegraaf, D., Lægsgaard, J., Weirich, J., Wei, L., Tartarini, G., Bassi, P., Gauza, S., Wu, S. T., & Bjarklev, A. Integrating liquid crystal based optical devices in photonic crystal fibers. *Opt. Quant. Electron.*, 10.1007/s11082-007-9139-8 (in press).

[5] Woliński, T. R. (2000). Polarimetric optical fibers and sensors. In: *Progress in Optics*, Wolf, E. (Ed.), Elsevier Science B. V.: North-Holland, XL, 1–75.

[6] Woliński, T. R. (2003). Polarization phenomena in optical systems. In: *Encyclopedia of Optical Engineering*, Diggers, R. (Ed.), M. Dekker: New York, 2150–2175.

[7] Wolinski, T. R., Ertman, S., Czapla, A., Lesiak, P., Nowecka, K., Domanski, A. W., Nowinowski-Kruszelnicki, E., Dabrowski, R., & Wojcik, J. (2007). Polarization effects in photonic liquid crystal fibers. *Meas. Sci. Technol.*, *18*, 3061–3069.

[8] Bock, W. J., Domanski, A. W., & Wolinski, T. R. (1990). Influence of high hydrostatic pressure on beat length in highly birefringent optical fibers. *Appl. Opt.*, *29*, 3484–3488.

[9] Xin Chen, Ming-Jun Li, Venkataraman, N., Gallagher, M. T., Wood, W. A., Crowley, A. M., Carberry, J. P., Zenteno, L. A., & Koch, K. W. (2004). Highly birefringent hollow-core photonic bandgap fiber. *Opt. Express*, 12, 3888–3893.

[10] Domański, A. W., Budaszewski, D., Sierakowski, M., & Woliński, T. R. (2006). Depolarization of partially coherent light in liquid crystals. *Optoelectronics Review*, *14*(4), 305–310.