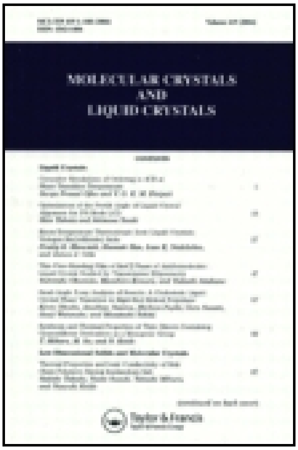

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Daniel Budaszewski [a], Rafal Cieslak [a] & Andrzej W. Domanski [a]

[a] Faculty of Physics, Warsaw University of Technology, Warsaw, Poland

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Birefringence Measurements of Photonic Liquid Crystal Fibre by Use of the Depolarization Method

Daniel Budaszewski, Rafal Cieslak, and Andrzej W. Domanski
Faculty of Physics, Warsaw University of Technology, Warsaw, Poland

In the paper we present the results of investigating the effective birefringence of prototype photonic crystal fibre, partially infiltrated with "1550" liquid crystal mixture. We use the modified Mueller matrix method with an additional depolarization matrix to calculate degree of polarization changes of the light propagating in the liquid-crystal infiltrated microstructured optical fibres.

We conducted the research for red and infrared semiconductor laser diodes. The research may lead to construction of temperature controlled depolarizer.

Keywords: birefringence; depolarisation; liquid crystals; photonic crystal fibres

1. INTRODUCTION

Recently, there has been a great interest in photonic crystal fibres, and particularly in yet more advanced microstructures known as photonic liquid crystal fibres (PLCFs) [1–4]. The PLCFs consisting of a photonic crystal fibre (PCF) infiltrated with a liquid crystal (LC) benefit from a combination of a 'passive' PCF host structure and an 'active' LC guest material and are responsible for a diversity of new and uncommon properties including also particular polarization properties of light passing through such structure [5]. State and degree of the light polarization depend on birefringence of medium. The PCLFs may be

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Address correspondence to Daniel Budaszewski, Faculty of Physics, Warsaw University of Technology, Koszykowa 75, Warsaw 00-662, Poland. E-mail: danielb@if.pw.edu.pl

highly birefringent and may change their parameters dependent on external parameters such as temperature, electric and optical fields [5].

There are several methods of the optical fibre birefringence measurements, like wavelength scanning [6], or interferometric methods [7–8]. In the paper we present a method based on application depolarization measurements of light passing through the fibre.

2. DEPOLARIZATION OF PARTIALLY COHERENT LIGHT IN BIREFRINGENT MEDIA

In general, partially temporal coherent light may be depolarized in birefringent medium, including low-birefringent and high-birefringent optical fibres [9,10], as well as liquid crystals [11]. The depolarization phenomenon depends on length of coherence (ΔL), length of the medium l, birefringence defined as $\Delta n = |n_{fast} - n_{slow}|$, as well as the azimuth between light beam polarization plane and birefringence axes of the medium [12]. Both components of wave package may have different phase and group velocities, which may result in changes of the state and degree of polarization (SOP and DOP). For the totally coherent light, its state of polarization (SOP) is being modified during propagation but its degree of polarization (DOP) is equal to 1 even for long path lengths of light in the crystal. For the partially coherent light sources characterized by a coherence length, light outgoing from the birefringent medium may be almost totally unpolarized due to the fact that both electric field components of the light propagating with different velocities are shifted into different wave packages (Fig. 1).

Hence the DOP measurements allow finding effective birefringence of the PLCFs. Theoretical basis for calculations of the PLCF birefringence utilizes modified Mueller matrix formalism extended by depolarization matrix [12]:

$$[\mathrm{S_{out}}] = [\mathrm{D}][\mathrm{M}_l][\mathrm{S_{in}}], \tag{1}$$

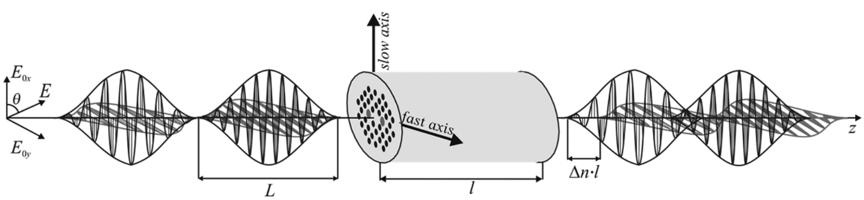

FIGURE 1 Depolarization effect in photonic crystal fibre.

where:

$[S_{in}]$, $[S_{out}]$ are the Stokes vectors of the input and output light beams ($[S] = [S_0, S_1, S_2, S_3]$),

$[M_l]$ is the Mueller matrix of the fibre:

$$[M_l] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\left(\frac{2\pi \cdot l \cdot \Delta n_{eff}}{\lambda}\right) & \sin\left(\frac{2\pi \cdot l \cdot \Delta n_{eff}}{\lambda}\right) \\ 0 & 0 & -\sin\left(\frac{2\pi \cdot l \cdot \Delta n_{eff}}{\lambda}\right) & \cos\left(\frac{2\pi \cdot l \cdot \Delta n_{eff}}{\lambda}\right) \end{bmatrix}, \quad (2)$$

and [D] is the depolarization matrix expressed as [12]:

$$[D] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & P_C & 0 & 0 \\ 0 & 0 & P_C & 0 \\ 0 & 0 & 0 & P_C \end{bmatrix}, \quad (3)$$

in which P_C is given by the following formula:

$$P_C = \sqrt{1 - 2[1 - \exp(-2\eta_S)] \sin^2 2\theta} \quad (4)$$

where:

$\eta_S = \frac{\Delta n_{eff} \cdot l}{\Delta L_L}$ – for Lorentzian light sources,

$\eta_S = \left(\frac{\Delta n_{eff} \cdot l}{\Delta L_G}\right)^2$ – for Gaussian light sources,

$\theta = \tan^{-1}\left(\frac{E_{0y}}{E_{0x}}\right)$ – azimuth between polarization plane and birefringence axes (Fig. 1).

DOP may be directly calculated from the parameters of the Stokes vector:

$$\mathrm{DOP} = \frac{I_{polarized}}{I_{total}} = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0} \quad (5)$$

The Stokes parameters can be calculated by four light measurements with different configurations of quarter-wave plate and an analyzer, according to the formula 6:

$$[S^{out}] = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} \langle E_x E_x \rangle + \langle E_y E_y \rangle \\ \langle E_x E_x \rangle - \langle E_y E_y \rangle \\ \langle E_x E_y \rangle + \langle E_y E_x \rangle \\ i\left(\langle E_y E_x \rangle - \langle E_x E_y \rangle\right) \end{bmatrix} = \begin{bmatrix} I_{-,0^0} + I_{-,90^0} \\ I_{-,0^0} - I_{-,90^0} \\ 2I_{-,45^0} - I_{-,0^0} - I_{-,90^0} \\ 2I_{\lambda/4,45^0} - I_{-,0^0} - I_{-,90^0} \end{bmatrix} \quad (6)$$

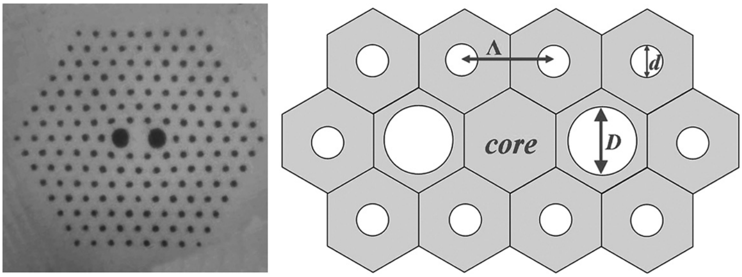

FIGURE 2 070119P2 Photonic Crystal Fibre structure (D = 3.6 μm; Λ = 3.6 μm; d = 1.35 μm).

where: ⟨⟩ stands for temporal mean value, * means the complex conjugate value,—means lack of quarter-wave plate in front of analyzer and second subscript means azimuth of analyzer.

In the experiment we used PCF (fibre type 070119P2) manufactured by the University of Mary Curie Sklodowska in Lublin, Poland. The fibre has a silica glass core and the light is index-guided. The fibre structure is shown in Figure 2.

Liquid crystals are found to be a birefringent media, due to their anisotropic nature, hence they are considered as a suitable material for depolarization effect studies. The birefringence of LC defined as

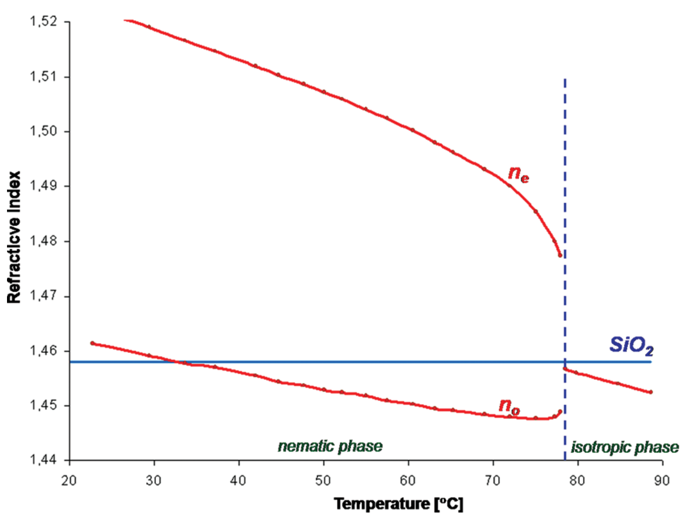

FIGURE 3 Thermal characteristics of relative indices for “1550” LC mixture.

difference between refractive indices may range between 0.05 and 0.5 and strongly depends on temperature. The research on depolarization in LC under external conditions was described previously [11].

Figure 3 presents ordinary and extraordinary refractive indices in function of temperature for "1550" mixture used in the experiment.

For temperatures lower than 30°C, ordinary refractive index is higher than refractive index of silica glass; hence light inside PLCF filled with "1550" mixture is guided by photonic bandgap mechanism (PBG). The PBG mechanism occurs when core refractive index is lower than cladding refractive index. In such case, only some of the wavelengths are transmitted and rest is being scattered. For temperatures higher than 30°C light is guided by modified total internal reflection mechanism (mTIR).

By the thermal control it is possible to change birefringence of the PLCF structure.

3. EXPERIMENTAL SETUP

The main aim of the research was to obtain a value of the studied fibre effective birefringence responsible for light depolarization, and to compare it with the results for empty PCF. The PLCF structure was obtained by immersing a PCF in the LC. The holes were infiltrated with LC material, due to capillary forces. The procedure mainly depends on viscosity of the LC and its phase [4]. In the investigated PCF all holes were partially filled with 1550 LC mixture on the distance $l_{PLCF} = 20\,\text{mm}$, as shown in Figure 4.

We used red and infrared laser diodes in the experiment to obtain the character of effective birefringence wavelength dependence. In the experimental setup we divided laser beam by a light-splitting prism into two orthogonal paths (Fig. 5). The coherence length of laser beam necessary for birefringence calculations was measured in one path by depolarization of light in anisotropic solid crystal with well

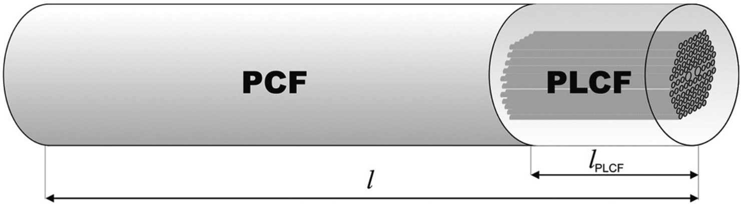

FIGURE 4 Photonic crystal fibre (PCF) partially filled with liquid crystal (PLCF).

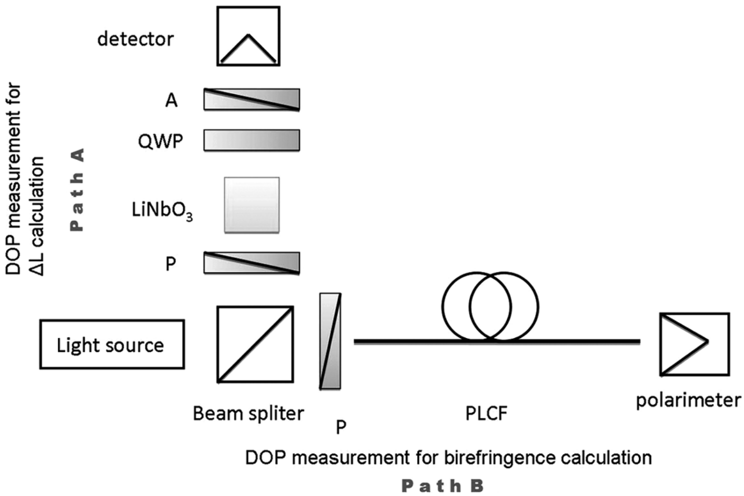

FIGURE 5 Experimental setup; P-polarizer, QWP-quarter-wave plate, A-analyzer.

known birefringence ($LiNbO_3$). In the second path we measured light depolarization in PLCF, and thus we calculated the effective birefringence of the fibre based on found length of coherence.

To provide high sensitivity detection, laser beam was modulated and the detectors placed at the end of each path were connected to a selective nanovoltometers.

After splitting a laser beam into optical path A, a Glann-Thomson polarizer was used to introduce the linearly polarized light into $LiNbO_3$ ($\Delta n = 0.086$) anisotropic solid crystal at an azimuth of 45° to its birefringence axes. A quarter-wave plate and analyzer were used to estimate elements of Stokes vector, and hence to calculate degree of polarization of outgoing light beam according to the Eqs. (5) and (6). Thus the length of coherence of the light beam could be estimated.

In the path B we placed investigated PLCF and coupled linearly polarized light under 45° to the fibre birefringence axes. The output of the PLCF was placed on Peltiere device and heated up to 48°C to obtain mTIR propagation mechanism. The signal was measured in the same way as in path A, and DOP has been obtained.

4. RESULTS AND ANALYSIS

Lengths of coherence of quasi-monochromatic waves were obtained for both laser sources used in the experiment. As all of the sources were

TABLE 1 Experimental Results

Wavelength λ [nm]	Length of coherence ΔL [mm]	Fibre length L [m]	DOP at fibre output	Effective fibre birefringence Δn [$\times 10^{-5}$]
675.3 ± 0.3	1.08 ± 0.05	0.86 ± 0.01 (PCF)	0.94 ± 0.1	9.1 ± 3.5
		$0.84 + 0.02$ (PLCF)	0.25 ± 0.1	173.6 ± 31.9
784.6 ± 0.3	0.71 ± 0.15	1.05 ± 0.01 (PCF)	0.75 ± 0.1	19.6 ± 4.1
		$1.03 + 0.02$ (PLCF)	0.2 ± 0.1	109.5 ± 21.8

the semiconductor laser diodes, theoretical Lorentzian spectra were calculated for these values.

Table 1 presents results obtained in the experiment. The coherence length of the light source measured in the path A was necessary to calculate DOP at fibre output in the path B, and next to calculate effective birefringence of the PLCF structure. It should be pointed out, that in this method we do not distinguish a sign of group and phase birefringence.

The values of calculated effective birefringence for PCF and PLCF are compared in Figure 6 for both wavelengths used in the experiment.

The birefringence of PLCF structure is higher than for empty PCF. We have noticed a decreasing tendency of the absolute value of effective birefringence in the PLCF with increasing of wavelength, which was also observed by research group applying other method of birefringence research [4].

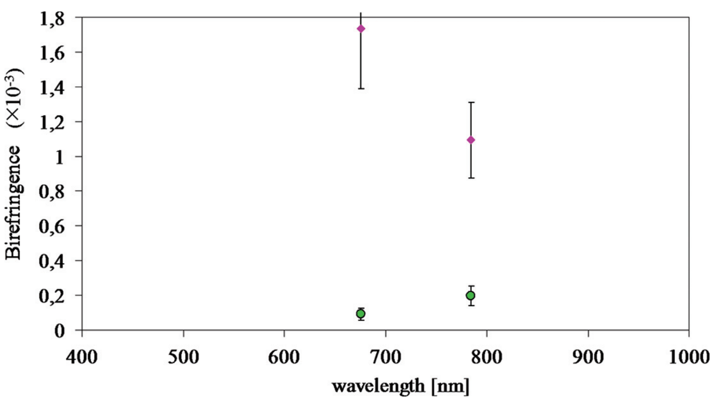

FIGURE 6 Experimental results for birefringence measurements for PCF (green dots) and PLCF (red rhombuses) in function of wavelength.

5. CONCLUSIONS

Experimentally observed depolarization of light in microstuctured optical fibres infiltrated with liquid crystals is much higher than DOP changes in PCFs and HB fibres. Depolarization of light in PLCFs is also very sensitive to the external electric field. It means that PLCF may be used as an electric field sensor and also as a compensator element of the polarization mode dispersion effect that significantly decreases bit rate in telecommunication fibres. Since the effect is caused by random birefringence of the fibre and also depends on temporary coherence of the incoming light it may be effectively controlled and potentially compensated by a short section of the PLCF introduced into the telecommunication lines as it has been recently outlined [4,5].

REFERENCES

[1] Sun, J., Chan, C. C., & Ni, N. (2007). Analysis of Photonic crystal fibres infiltrated with nematic liquid crystal. *Optics Communications*, *278*, 66–70.

[2] Zografopoulos, D. C., Kriezis, E. E., & Tsiboukis, T. D. (2006). Photonic crystal-liquid crystal fibres for single-polarization or high-birefringence guidance. *Optics Express*, *14*(2), 914–925.

[3] Domański, A. W., Budaszewski, D., Ertman, S., Lesiak, P., Nowecka, K., & Wolinski, T. R. (2007). Propagation of partially coherent light in liquid crystal fibres. *SPIE*, 6608, 660807-1-660807-6.

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

[5] Alkeskjold, T. T., Scolari, L., Noofdegraaf, D., Laegsgaard, J., Weirich, J., Wei, L., Tartarini, G., Bassi, P., Gauza, S., Wu, S.-T., & Bjarklev, A. (2007). Integrating liquid crystal based devices in photonic crystal fibres. *Opt. Quant. Electron*, 11082-007-9139-8.

[6] Hlubina, P., Ciprian, D., & Knyblová, L. (2006). Interference of white light in tandem configuration of birefringent crystal and sensing birefringent fibre. *Optics Communications*, *260*, 535–541.

[7] Shibata, N., Nakazono, A., & Inoue, Y. (2005). Interference between two orthogonally polarized modes traversing a highly birefringent air-silica microstructure fibre. *Journal of Lightwave Technology*, *23*(3), 1244–1252.

[8] Tang, F., Wang, X., Zhang, Y., & Jing, W. (2007). Characterization of birefringence dispersion in polarization-maintaining fibres by use of white-light interferometry. *Appl. Opt.*, *46*(19), 4073–4080.

[9] Sakai, J. I., Machida, S., & Kimura, T. (1982). Degree of polarization in anisotropic single-mode optical fibres. *IEEE J. Quantum Electron*, *OE-18*, 488–495.

[10] Domanski, A. W., Karpierz, M. A., Kujawski, A., & Woliński, T. R. (1996). Polarimetric fibre sensors for partially polarized laser source. Laser in Research and Engineering, Proceedings of the 12th International Congress Laser 95, Springer Verlag: Berlin, 684–687.

[11] Domański, A. W., Budaszewski, D., Marek Sierakowski, & Woliński, T. R. (2006). Depolarization of partially coherent light in liquid crystals. *Opto-electr. Rev.*, *14*(4), 305–310.
[12] Domański, A. W. (2005). Polarization fading of partially coherent light in birefringent media. *Opto-electr. Rev.*, *13*(2), 171–176.