OPTO-ELECTRONICS REVIEW **14**(4), 329–334

DOI: 10.2478/s11772-006-0045-6

Photonic liquid crystal fibers – a new challenge for fiber optics and liquid crystals photonics

T.R. WOLIŃSKI*[1], S. ERTMAN[1], P. LESIAK[1], A.W. DOMAŃSKI[1], A. CZAPLA[1], R. DĄBROWSKI[2], E. NOWINOWSKI-KRUSZELNICKI[2], and J. WÓJCIK[3]

[1]Faculty of Physics, Warsaw University of Technology, 75 Koszykowa Str., 00-662, Warsaw, Poland
[2]Military University of Technology, 2 Kaliskiego Str., 00-908 Warsaw, Poland
[3]Maria Curie Skłodowska University, 5 Curie Skłodowskiej Sq., 20-031 Lublin, Poland

The paper reviews and discusses the latest developments in the field of the photonic liquid crystal fibers that have occurred for the last three years in view of new challenges for both fiber optics and liquid crystal photonics. In particular, we present the latest experimental results on electrically induced birefringence in photonic liquid crystal fibers and discuss possibilities and directions of future developments.

Keywords: liquid crystals, photonic crystal fibers, induced birefringence.

1. Introduction

In the last few years, there was a great interest in photonic crystal fibers (PCFs) which properties could be relatively easily changed after infiltrating with liquid crystals. Such a combination creates a new class of microstructured fibers – photonic liquid crystal fibers (PLCFs) in which thermal and electrical tuning possibilities along with their unique spectral and polarization properties have been recently demonstrated. These microstructured PLCFs benefit from a merge of passive PCF host structures with "active" LC guest materials and could be responsible for diversity of new and uncommon propagation and polarization properties.

Highly birefringent (HB) optical fibers and their polarization properties have been extensively investigated for over the last two decades [1,2]. Single polarization propagation effects have been observed also in fibers with elliptical cores filled with liquid crystals (LCs) [3–5].

First evidence of the band-gap tuning, occurring with a PCF filled with high index oil, was demonstrated in 2002 by Bise *et al.* [6]. However, in the field of liquid crystals infiltration, first experimental demonstration of the performance of LC photonic band gap fibers was reported by Larsen *et al.* in 2003 [7]. Electrical tuning in hollow-core PLCF was demonstrated in 2004 [8] and in 2005, all-optical modulation in dye doped PLCF [9] was reported. Simultaneously, there has been interest both (theory and experiment) in possibility of birefringence tuning in different types of microstructured fibers (MOFs) [10] and also to manipulate light in MOFs by microfluid motion [11]. HB tunable photonic band-gap fibers were numerically analyzed in Ref. 12 and similarly PLCFs for single-polarization or high-birefringence guidance were theoretically modelled in Ref. 13.

We have very recently experimentally demonstrated numerous propagation and polarization properties of the solid-core PLCFs, mostly under the influence of temperature and electrical field in both, visible and infrared wavelength regions [14–19].

This paper presents our latest experimental results on electrically induced birefringence in PLCFs. As a host material, we used a prototype isotropic PCF, manufactured at Maria Curie Skłodowska University in Lublin, that was infiltrated in the length of few millimetres with different nematic liquid crystals (both pure compounds and mixtures) of low (~0.05), medium (~0.15), and relatively high (~0.3) material birefringence synthesized at Military University of Technology in Warsaw. Without the influence of the external electric field, fiber birefringence is equal to zero due to the fact that liquid crystal molecules tend to orient parallel to the optical fiber axis (flow orientation). By applying an external electrical field, perpendicular to the fiber long axis, we observed a threshold molecular reorientation effect. The reorientation effect introduced changes in the effective refractive index of the holes infiltrated with LCs and induced birefringence in the PLCF cross section. As a result, a change in transmission spectra as a result of electrically-induced birefringence could be observed. It appeared that a modal birefringence of the PLCF depended on both amplitude of electric field and material birefringence of the LC used to infiltrate the PCF.

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*e-mail: wolinski@if.pw.edu.pl

2. Photonic liquid crystal fibers: materials and experimental methods

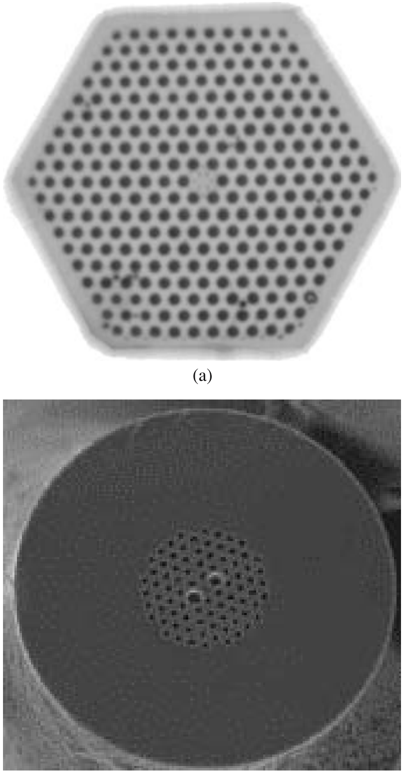
As host materials for fabrication of the PLCFs presented in this report we used two different PCFs structures. The first one was a prototype and isotropic PCF manufactured at Maria Curie Skłodowska University (MCSU), Lublin (Poland). Cross section of this fiber shortly named as MCSU-1023 is shown in Fig. 1(a). This PCF structure contains a solid core surrounded with nine rings of air holes characterized by diameters and holes spacing of 4.8 µm and 6.5 µm, respectively. The second host PCF was an anisotropic highly-birefringent fiber commercially available and known as Blazephotonics PM-1550-01 [Fig. 1(b)]. In this fiber, solid core is surrounded with two big holes of the diameter 4.5 µm along with a set of smaller holes of the diameters 2.2 µm. The PLCF, based on the PM-1550-01 fiber, had only two big holes infiltrated with the guest LC, contrary to the MCSU-1023 in which all the holes have been infiltrated with LCs.

As an "active" element of the PLCFs we used two different LC materials, either with very low or with medium material birefringence. Low-birefringence nematic LC prototype mixtures abbreviated as 1110 and 1550 were composed of alkyl 4-trans-(4-trans-alkylcyclohexyl) cyclohexylcarbonates. They were synthesized according to the route presented in details elsewhere [19] and their optical properties were described in Ref. 20. The main difference between both, 1110 and 1550 mixtures was their clearing temperature, which was 40.6°C and 78°C, respectively.

Temperature dependences of refractive indices for both LCs with very low birefringence (1110 and 1550) are shown in Fig. 2. Those LC mixtures are especially interesting for infiltrating silica glass fibers, since their ordinary refractive indices in specific temperature ranges are lower than the refractive index of the silica glass.

As LCs with medium birefringence, we used commonly-known nematics: PCB 4'-pentyl-4-cyanobiphenyl [21] and 6CHBT 4-(trans-4-hexyl-cyclohexyl)-isothiocyanatobenzene [22]. Thermal characteristics of the refractive indices for these LCs are shown in Fig. 3. There have also initial attempts to use a higher birefringence nematic LC mixture cat. number 1702 (Δn ~0.3). Each of the LC mixtures used in the experiments has been synthesized at the Military University of Technology in Warsaw.

The simplest infiltration method to obtain a PLCF consists in immersing the "host" PCF into a container with the "guest" liquid crystal. Due to the capillary forces, LC molecules are "sucked' into the holes and their penetration speed depends generally on LC viscosity, temperature and phase, but can be significantly increased by using high-pressure air pumped into the hermetically sealed LC container. In our investigations, we usually filled a small section (typically 10–30 mm long) of the PCF (~50 cm long). Then, we placed the PLCF into the thermo-electric module allowing for temperature changes in the 10–120°C range


(a)

(a)

Fig. 1. Photonic crystal fibers used as PLCF host matrix, (a) MCSU 1023 PCF and (b) Blazephotonics PM-1550-01.

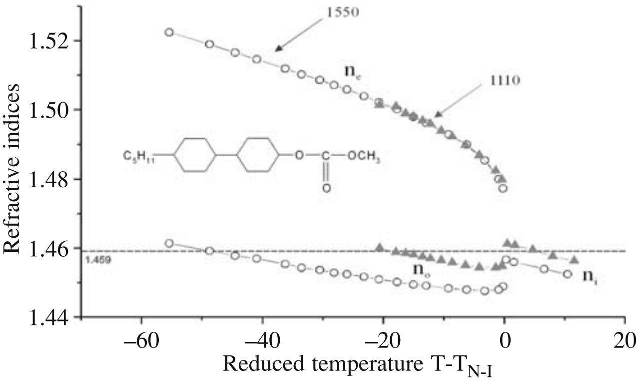


Fig. 2. Refractive indices as a function of temperature for low-birefringence LC mixtures, 1110 and 1550.

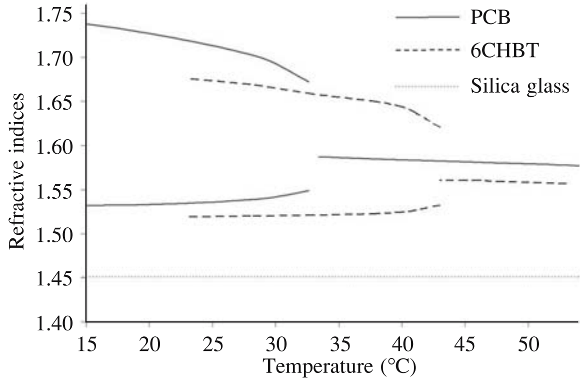


Fig. 3. Refractive indices as a function of temperature for PCB and 6CHBT nematic LCs.

with 0.1°C long-term stability and also under the influence of an external electric field (controlled by voltage changes in the 0–1000 V range with the frequency from 50 Hz to 2 kHz). As a light source, we used a high-power halogen lamp, and the output signal was analyzed by the HR4000 fiber optics spectrometer (Ocean Optics). To investigate PLCFs polarization properties in the infrared range, we used a tunable laser source (Tunics Plus CL, spectral range 1500–1640 nm) and a modular system for polarization analysis PAT 9000B polarimeter (Tektronix).

3. Band-gap propagation tuning

Generally, liquid crystals are characterized by refractive indices higher than the refractive index of the silica glass used for PCF fabrication. As a result, in PLCFs, effective index of cladding is usually higher than refractive index of the fiber core, so only photonic band-gap propagation is possible. It means that propagation in the fiber core is possible only for the wavelengths that correspond to the photonic band gaps formed in cladding. Since LCs optical properties can be relatively easy modified with external thermal, magnetic or electric fields, PBGs tuning in PLCFs is possible.

Results of thermal PBGs tuning in the MCSU-1023 photonic crystals fiber filled with the 1702 LC mixture are shown in Fig. 4. Thermal dependences of both refractive indices for this mixture have not been measured yet, however, by analyzing thermal performance of this PLCF we can qualitatively describe thermal dependence of the ordinary refractive index n_o. Since the LC molecules within the PLCF are predominantly oriented along the fiber axis, the PBGs positions are determined by the value of n_o, and hence if n_o decreases with temperature, the blue shift of the PBGs is observed, Fig. 4(a). Similarly, a thermal increase in the value of n_o leads to the red shift of the PBGs, Fig. 4(b).

Interesting effects were observed in the PLCF filled with the LCs characterized by extremely low birefringence. In this case, the LC ordinary refractive index for certain region of temperature was below the refractive index of the silica glass (Fig. 2). In this situation, the refractive index of the PLCF core is higher than the effective index of the PLCF cladding, and the whole wavelength spectrum propagates within the PLCF by the modified total internal refraction (mTIR) mechanism [19]. Figure 5 shows a thermally-controlled change of the guiding mechanism observed for the MCSU-1023 fiber infiltrated with the low-birefringence 1550 LC mixture. Initially, a blue shift was observed

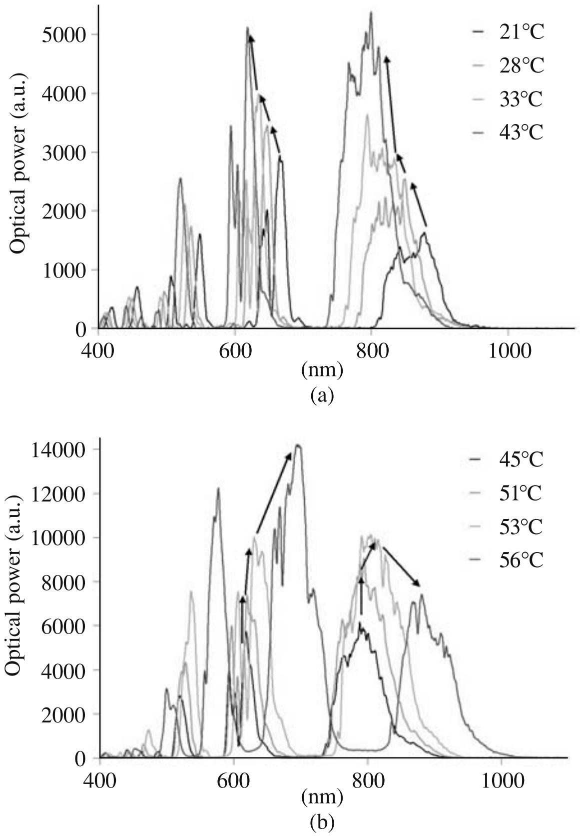


Fig. 4. Thermal tuning in the 1023 PCF filled with the 1702 LC mixture, (a) red shift is observed if ordinary refractive index decreases with temperature and (b) blue shift could be observed if ordinary refractive index increases with temperature.

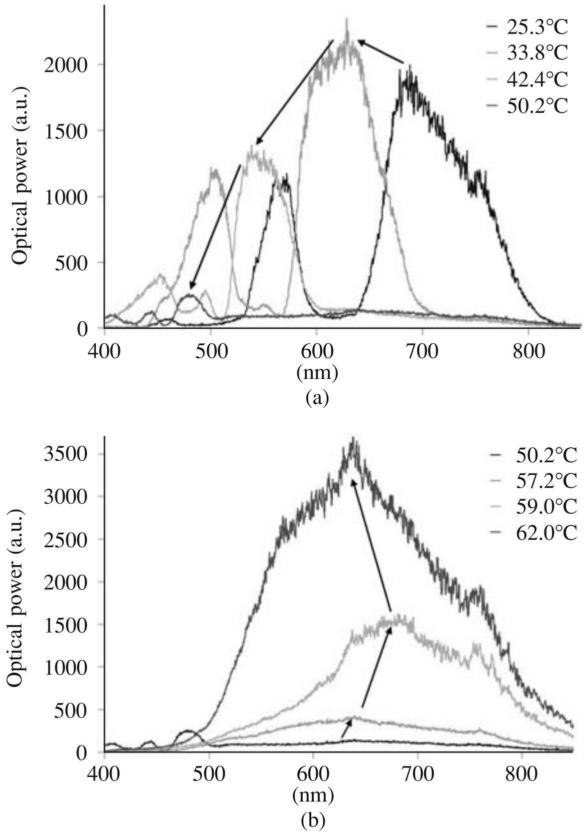
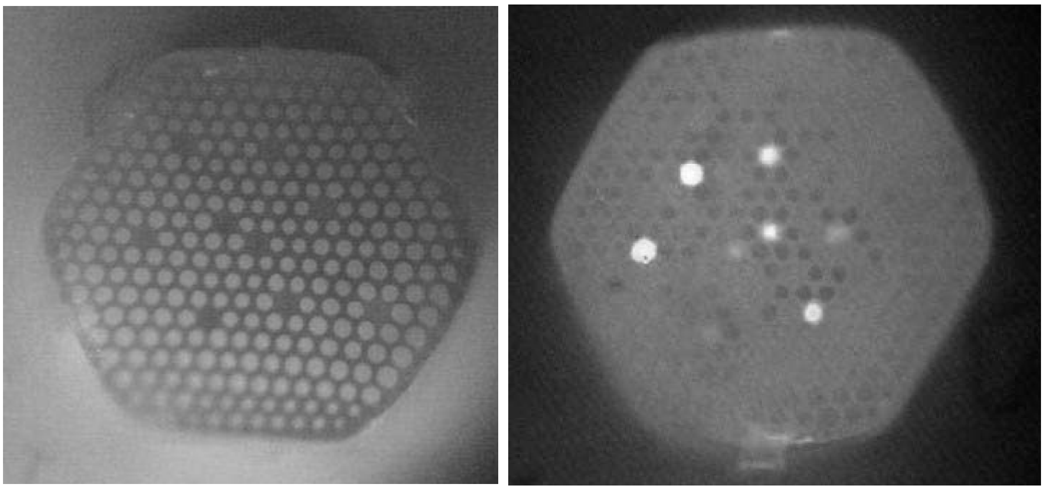


Fig. 5. Change of guiding mechanism in the PLCF filled with the 1550 LC mixture, (a) PBG propagation and band-gap tuning if the LC ordinary refractive index (nLCo) is higher then the refractive index of silica glass ($nSiO_2$) and (b) TIR guiding if $nLCo < nSiO_2$.



(a) (b)

Fig. 6. End-face of a multi-core photonic crystal fiber, (a) empty structure and (b) fiber filled with 6CBHT, different propagation spectra observed in each core as a result of hole diameter fluctuations.

[Fig. 5(a)] as the ordinary index n_o was decreasing with temperature. No propagation is observed if n_0 is equal to the refractive index of the fiber core, but further temperature increase leads to propagation by the modified TIR mechanism [Fig. 5(b)].

It is quite obvious, that to achieve a quality band gap in the PLCF cladding, drawing process of the host PCF should be well controlled to ensure that diameters of every hole will be the same. Even small fluctuations in the holes size have very destructive impact on PBG propagation. To show how these fluctuations affect photonic bandgaps, we used a multicore PCF, this cross section is shown in Fig. 6(a). After infilling this fiber with 6CHBT, we observed band-gap propagation in every core, however, in every core different spectra were guided, Fig. 6(b). This clearly demonstrates importance of the appropriate PCF structures to achieve repeatable PLCFs with low attenuation.

4. Birefringence: inducing and tuning

PBGs positions in the PLCF strongly depend on the effective refractive index of the micro holes infiltrated with LCs. Birefringence of LCs can be adjusted not only by temperature changes but also by molecules orientation modification. The simplest way to obtain dynamical LC reorientation is to apply an external electric field. Transmission spectra of the MSCU-1023 fiber with PCB for three different values of electric field applied perpendicularly to the PLCF axis is shown in Fig. 7. Below a threshold voltage (~41 V), propagation is governed by the ordinary refractive index within the LC micro capillaries. However, above the threshold value, the reorientation effect occurs and the PBGs positions depend on the LC extraordinary refractive index.

Electrically-induced molecular tilt introduces not only changes in the effective refractive index of the holes infiltrated with LCs, but also creates anisotropy in the PLCF cross section. In the off-voltage state, fiber birefringence is equal to zero due to the fact that liquid crystal molecules tend to orient parallel to the fiber axis. By changing the azimuth of linearly polarized light launched into the PLCF we introduce only a small modulation of the optical power transmitted trough the fiber (this modulation results probably from the spectrometer grating polarization response).

By switching the electrical field (on-voltage state) we observed a threshold molecular reorientation effect. As a result, a change in transmission spectra and also an electrically-induced birefringence can be observed. In this case, changing the azimuth of linear polarization coupled into the PLCF leads to the ~98% power modulation (Fig. 8).

The use of a highly-birefringent PCF as a host for the PLCF fabrication opens a new possibility for more advanced birefringence tuning. As an example, the results of thermal birefringence tuning in the PM-1550-01 HB fiber with two big holes filled with the 1110 LC are presented.

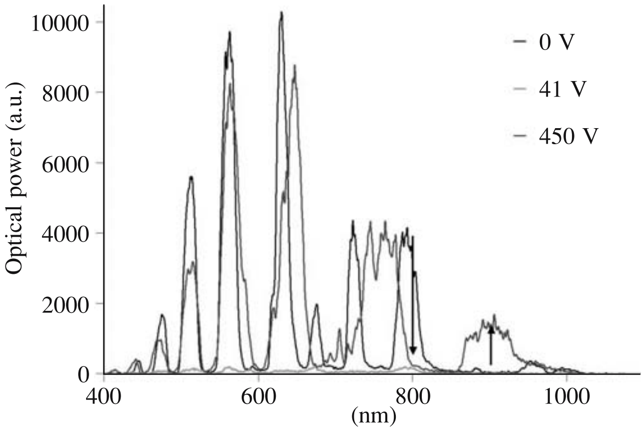


Fig. 7. Electrical band-gap tuning in the PLCF (1023 filled with PCB). After increasing voltage up to 41 V, propagation in PLCF disappears but further voltage increase induces propagation in new photonic band gaps.

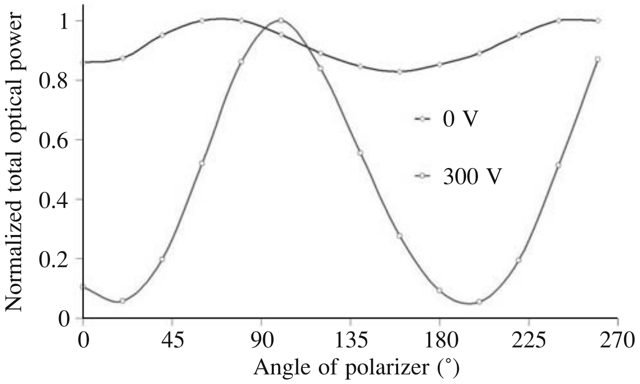


Fig. 8. Modulation of the optical power transmitted in the PLCF through rotating the input polarization azimuth. At the off-voltage state, only small changes of the power are observed. At the higher voltages, the PLCF becomes highly sensitive to polarization (at 580 nm, similar effect was observed for different wavelengths).

The ordinary refractive index of the 1110 mixture is below the value of the core index, so the whole spectrum is guided by the mTIR mechanism, however, significant power modulation is observed, Fig. 9(a). This effect occurs since the spectrometer grating efficiency is different for both polarizations and eventually the grating acts as a "partial analyzer". Therefore transmission maxima and minima can be observed, and the distance between maxima depends on the value of PLCF birefringence. Transmission spectra for different temperatures are shown in Fig. 9(b). The characteristics have been limited to the 725–875 nm spectral range in order to visualize a change in maxima positions. Since density of the maxima increases with temperature, hence birefringence of PLCF is also growing.

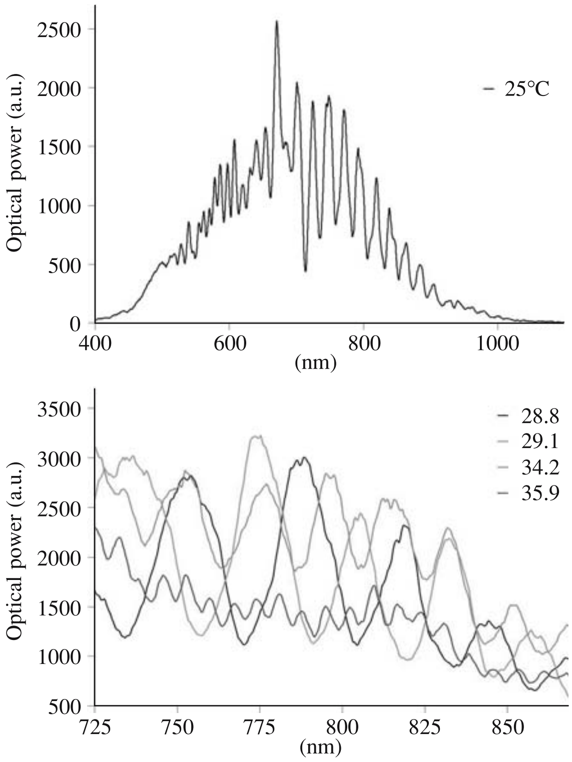


Fig. 9. Thermal birefringence tuning in the PLCF (PM-1550-01 filled with 1110), (a) transmission spectra at 25°C – whole spectrum guided by the TIR mechanism, the distance between maxima depends on PLCF birefringence and (b) transmission in the 725–870 nm range at different temperatures, maxima density and PLCF birefringence increase with temperature.

5. Conclusions

Photonic liquid crystal fibers benefiting from a merge of passive photonic crystal fibers host structures with "active" liquid crystal guest materials create a new challenge for both, fiber optics and liquid crystal photonics. They introduce new levels of tunability to photonic crystal fibers – the "hot topic" of modern fiber photonics and boost performance of these fibers due to diversity of new and uncommon propagation and polarization properties.

In particular, we have demonstrated our latest results on electrically induced birefringence in PLCFs and for the first time possibility of multi-core PLCFs. It appeared that modal birefringence of the PLCF depends on both amplitude of electric field and material birefringence of the LC used to infiltrate the PCF. These phenomena open up possibilities of new applications both for optical signal processing and multi-parameter fiber-optic sensing.

In context of potential mass production for commercial purposes, some technology of LC molecules orientation control should be developed. It is especially important to reduce the PLCFs losses and should guarantee repeatable results. Recently, in our laboratory we have worked on PLCFs with thin photopolymer film, in which photoinduced molecular alignment is possible. Detailed results of these experiments will be reported soon.

Acknowledgements

The work was supported by the Polish Ministry of Science and Education under grant 3T10C 016 28.

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