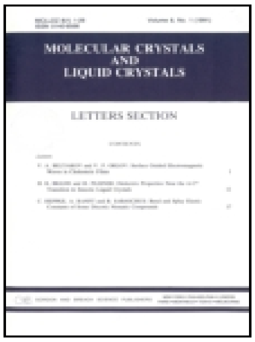

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Tunable Optofluidic Polymer Photonic Liquid Crystal Fibers

TOMASZ R. WOLIŃSKI,[1] AGATA SIARKOWSKA,[1,*] KATARZYNA RUTKOWSKA,[1] MIŁOSZ CHYCHŁOWSKI,[1] KAMIL ORZECHOWSKI,[1] DANIEL BUDASZEWSKI,[1] SŁAWOMIR ERTMAN,[1] MAREK SIERAKOWSKI,[1] PAWEŁ MERGO,[2] AND ROMAN DĄBROWSKI[3]

[1]Warsaw University of Technology, Warszawa, Poland
[2]Maria Curie-Skłodowska University, Lublin, Poland
[3]Warsaw Military University of Technology, Warszawa, Poland

New trends are presented in optofluidics based on microstructured photonic crystal fibers filled with liquid crystals. It significantly enhanced optical properties of the fibers and introduced new levels of tunability to photonic crystal fibers. The paper discusses basic research directions in fiber-based optofluidics and, in particular, in polycarbonate-based photonic liquid crystal fibers. Experimental and theoretical results are presented on polymer crystal fibers filled with nematic liquid crystal with two different types of dielectric anisotropies.

Keywords polycarbonate polymer photonic crystal fiber

1. Introduction

Optofluidics as a combination of photonics and microfluidics offers a variety of novel photonic and sensing devices gaining their unique capabilities from the specific integration of optical and fluidic technologies. Until recently optical systems have been mostly made with solid materials such as polymers or glasses. However, they have many limitations related to their physical state. Free from these limitations are fluids, where the interaction between them and light can be used in many ways. An example of such unique abilities is the possibility to change the optical properties of optofluidic devices simply by replacing one fluid with another [1-2]. The replacement of traditional non-ordered liquids with highly anisotropic liquid crystals (LCs) that are extremely sensitive to external filed enhances the optofluidic toolbox and can lead to a new generation of highly tunable and cost-effective sensing elements and subsystems [3].

Photonic crystal fibers (PCFs) and especially micro-holes that construct them can provide a perfect host medium for the fluid phase. Optical wave guiding in a PCF can be controlled by one of two mechanisms responsible for light trapping within the fiber core:

*Address correspondence to Agata Siarkowska, Warsaw University of Technology, Warszawa, Poland. E-mail: siarkowska@if.pw.edu.pl

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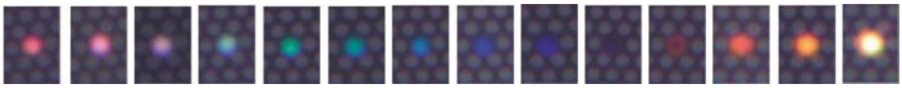

Figure 1. Temperature-induced reversible mTIR/PBG propagation mechanisms switching in an optofluidic PLCF (a silica-glass PCF infiltrated with a low-birefringence 1550 LC mixture [3]).

modified Total Internal Reflection (mTIR) that resembles a classical propagation effect and the Photonic Band Gap (PBG) effect occurring when the refractive index of the cladding region is higher than the refractive index of the core (Fig. 1). Infiltrating the PCF air-holes with LCs enhances the optical properties of the fiber, creating a new photonic structure known as a photonic liquid crystal fiber (PLCF) [4-5].

Recently, polymers have been used to produce fibers leading to creating polymer optical fibers (POFs). POFs are usually made of materials such as: polymethyl methacrylate (PMMA), polycarbonate (PC) as well as polystyrene (PS). In contrast to silica-glass optical fibers, POFs have a very large diameter, where the core size can be almost 96% of the cross section. Such large cores allow easy alignment as well as connecting to other fibers. The next step in polymer fiber development was creating microstructured polymer optical fibers (mPOFs) [6-8]. Unlike the traditional POFs, mPOFs form patterns of microscopic air channels that go along the full length of the fiber and, as a result, the guiding mechanism in mPOFs is similar to the one that can be observed in photonic crystal fibers.

The paper presents recent experimental results of light guiding inside mPOFs made of PC with the use of different light sources, as well as light input methods. Also the initial results are presented of infiltrating mPOFs with nematic liquid crystals characterized by either negative or positive dielectric anisotropies.

2. Materials

The first ever mPOF was made of PMMA by Eijkelenborg in 2001 [9]. Polymers used to produce optical fibers are commonly called optical polymers. They are mostly chosen for their high impact resistance and ability to integrate mechanical and optical features [10-11].

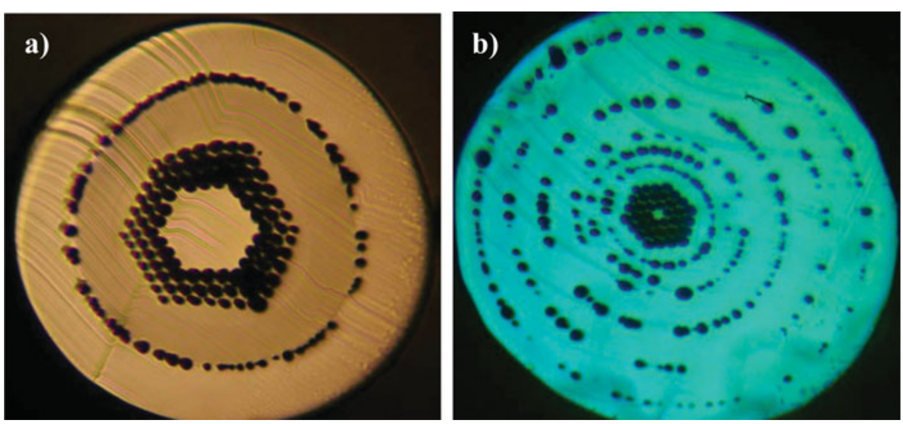

Figure 2. Microstructured polymer optical fiber a) with a large core diameter (PC-1); b) with a small core diameter (PC-2).

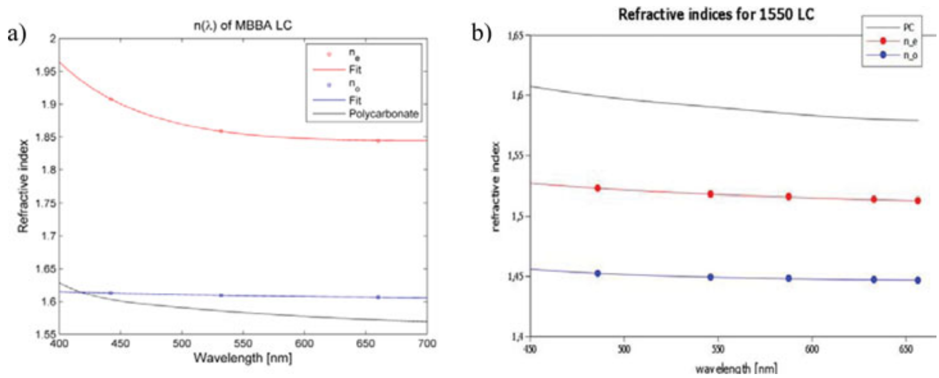

Figure 3. Experimental data of dispersion curves for MBBA (a) and 1550 LC mixture (b) in comparison to the refractive index of PC (data from Ref.[10]). In MBBA, monochromatic linear dichroism at $\lambda = 405$nm was observed. (only a light beam for an ordinary index was observed while there was no light beam for an extraordinary index, even after changing the state of polarization of an input light beam).

In this paper two microstructured polymer optical fibers made out of PC, fabricated by Maria Curie Skłodowska University (UMCS, Lublin, Poland) were investigated. The material properties of PC are similar to those of PMMA. However, polycarbonate is more stable in higher temperature ranges up to 155°C, stronger, and can undergo plastic deformations without breaking. The refractive index of PC is 1.5849 at 588 nm and its light transmittance reaches 87% (for a thickness of 3mm) for a visible range [12-13].

The first of the used mPOFs (called PC-1) has a large core and its lattice constant is equal to 7.2 μm, assuring good core-guiding propagation (Fig. 2a). The outer- and core-diameters of fibers are equal to 224 μm and 40 μm, respectively. Another mPOF (called PC-2) is characterized by the outer- and core-diameters equal to 301 μm and 9 μm, respectively, and its 8-μm lattice constant. The PC-2 fiber was manufactured by putting

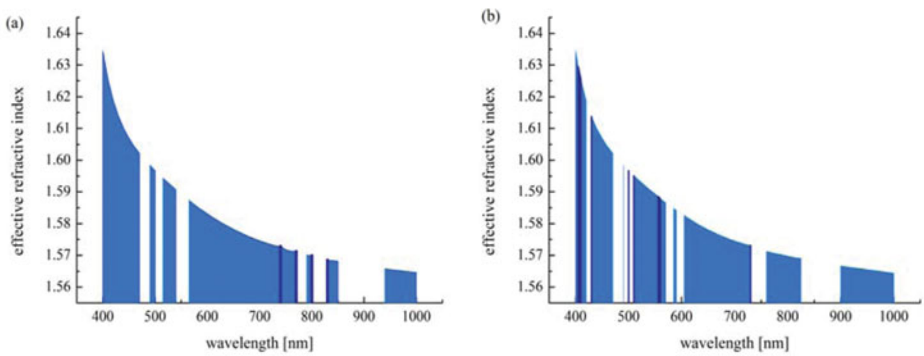

Figure 4. Effective refractive index of the fundamental core-mode in PC-2 mPOF infiltrated with MBBA NLC for planar (a) and random (b) orientation of NLC molecules inside air-channels. The white stripes corresponds to the wavelengths for which no core-modes are present, while the dark-blue ones show the wavelengths for which fundamental modes exceed the core region (e.g. when light is guided in the air-channels infiltrated with NLC).

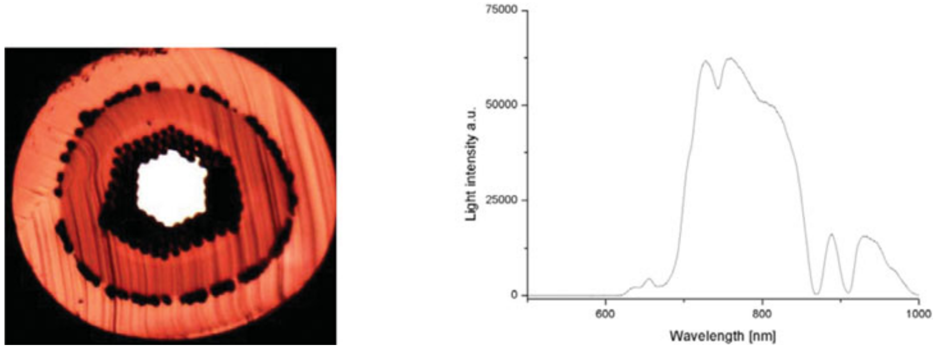

Figure 5. Propagation (left) and spectrum (right) of the empty PC-1 mPOF, with a halogen lamp as light source.

one capillary into another, resulting in multiple bubbles at the cross section of the fiber, which can be seen in Fig. 2b.

In this work two types of nematic LCs were used: with negative (MBBA) and positive (1550) dielectric anisotropies, which were synthesized at the Military University of Technology (Warsaw, Poland). Both extraordinary and ordinary refractive indices of MBBA (4-methoxybenzylidene-4'- butylaniline) are higher than the refractive index of PC [14] as shown in Fig. 3a. An example of the LC material with positive dielectric anisotropy is a low-birefringence nematic 1550 LC mixture composed of alkyl 4-trans-(4-trans-alkylcyclohexyl) cyclohexyl-carbonates. Its dispersion curve is shown in Fig. 3b, in comparison to the PC refractive index. Additionally, in the experiment two commonly known LCs: 6CHBT and 5CB, were used (data from Ref.[15]).

3. Theoretical Predictions

In order to check how the light guidance in a core of PC-2 mPOF depends on the molecular orientation of LC inside its air-channels, numerical simulations based on the finite elements method have been performed (with use of the COMSOL, Multiphysics). The values of

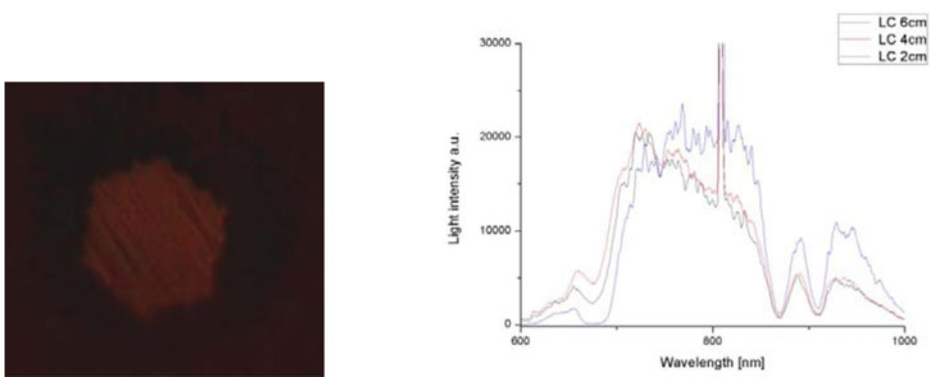

Figure 6. Propagation (left) and spectrum (right) of the PC-1 mPOF filled with 6CHBT, with supercontinuum as a light source.

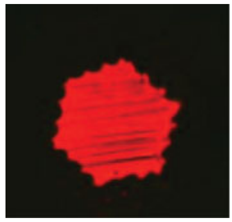

Figure 7. Propagation in the PC-1 mPOF filled with 5CB, with a supercontinuum as a light source.

refractive indices taken for simulations have been approximated with the use of the material characteristics presented in Fig. 3a. To imitate the most possible orientation of the NLC molecules within air-channels, a diagonal form of electric permittivity tensor for NLC has been used with the values of: ${n_o}^2$, ${n_o}^2$, ${n_e}^2$ for planar and $\tilde{n}^2$, $\tilde{n}^2$, $\tilde{n}^2$ for random orientation, where n_o, n_e and $\tilde{n} = 2n_o/3 + n_e/3$ are the ordinary, extraordinary and average refractive index, respectively. Fig. 4 shows the effective refractive index of the fundamental core mode in the PC-2 mPOF infiltrated with MBBA NLC as a function of wavelength (at room temperature) for two different molecular arrangements. For planar orientation (Fig. 4a), mTIR-guiding is observed for the wavelengths shorter than ∼420 nm, for which the ordinary refractive index of NLC is lower than that of the PC. For longer wavelengths, as well as for random orientation (i.e. when an average refractive index of NLC is considered; Fig. 4b) there are no core-guided modes for some specific wavelengths, which corresponds to the gaps in the transmission spectrum (as characteristic for the PBG-guiding mechanism appearing when the refractive index of the core is lower than an effective refractive index of the cladding region).

4. Experimental Results

In the first part of the experiment, empty samples of PC-based mPOFs were tested with different light sources. The experimental setup consisted of a light source and a microscope with a digital camera as a detector. Initially, we examined PC-1 fibers with a halogen lamp as a light source. Strong propagation in the core was observed with a small amount of light

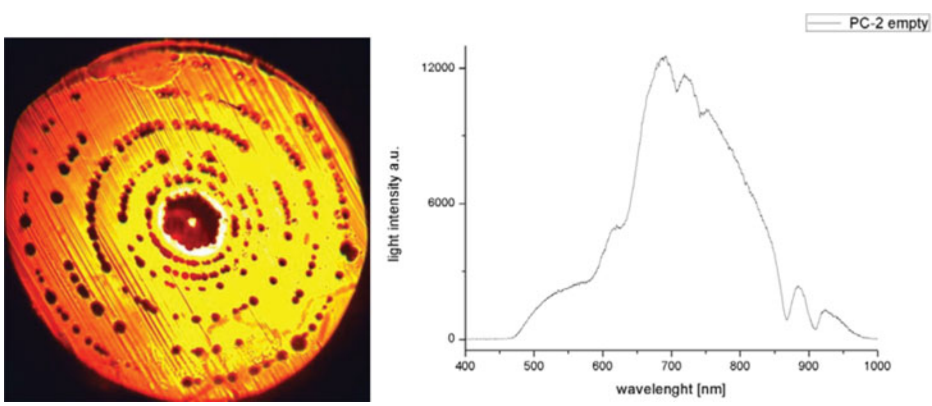

Figure 8. Propagation (left) and spectrum (right) of the empty PC-2 mPOF with a halogen lamp as a light source.

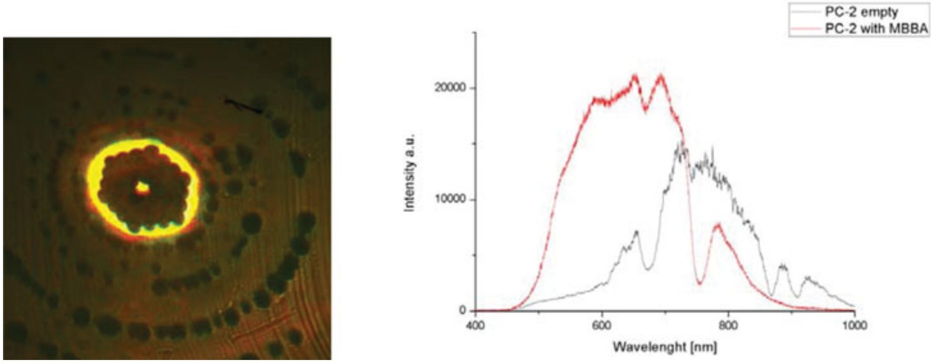

Figure 9. Propagation in the PC-2 mPOF filled with MBBA (a halogen lamp used as a source) (a); Comparison of the spectrum of an empty PC-2 (black) and one filled with MBBA (red). The spectrum of the LC infiltrated mPOF is shifted compared to the spectrum of an empty fiber, probably due to the presence of a light ring (b)

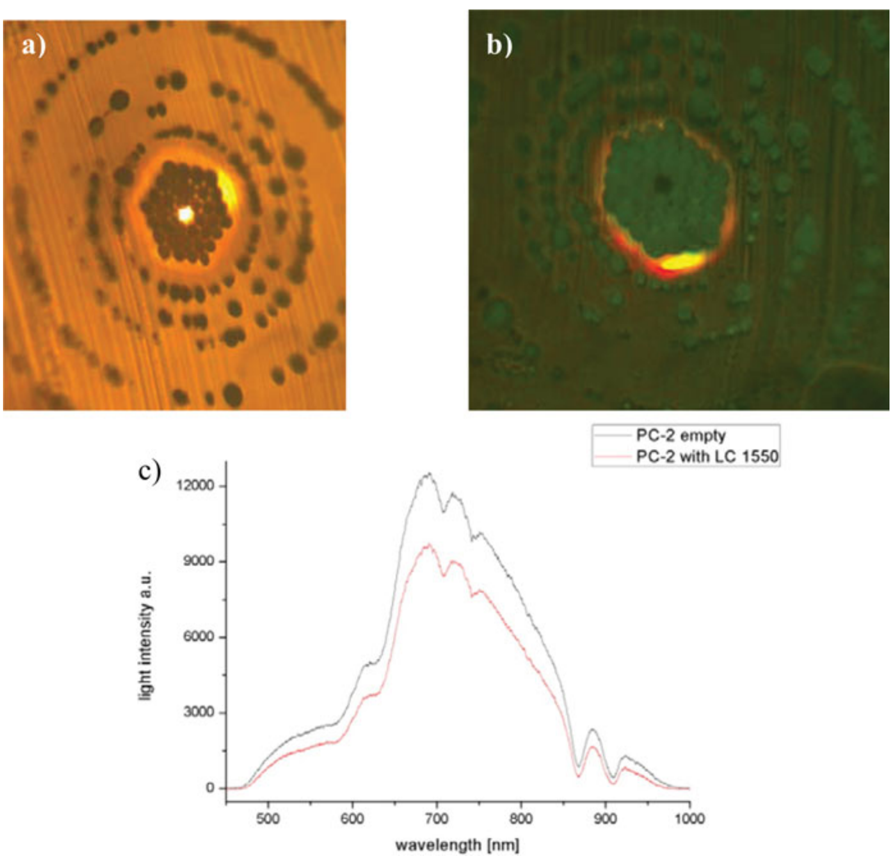

Figure 10. Propagation in an empty PC-2 fiber (a), Propagation in the PC-2 mPOF filled with 1550 LC (b), Spectrum comparison of an empty PC-2 (black) and one filled with LC (red) (c).

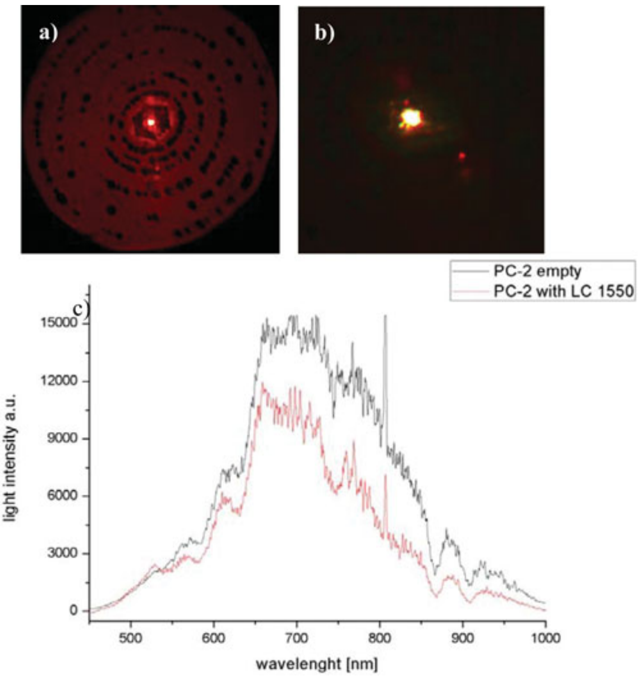

Figure 11. Propagation in empty the PC-2 fiber supercontinuum as a light source (a), Propagation in the PC-2 mPOF filled with 1550 LC (b). Spectrum comparison of an empty PC-2 (black) and one filled with LC (red) (c).

propagation in the cladding (Fig. 5). Similar results were obtained when the light source was replaced by a He-Ne laser operating at 633 nm.

For the PC-1 mPOFinfiltrated with 6CHBT we used supercontinuum as a light source, since the halogen lamp power was too weak to observe the whole spectrum. The length of the sample was about 48 cm with a 10-cm LC infiltrated part. During the measurement the LC infiltrated part was being reduced resulting in an increase of output power (Fig. 6).

When 5CB was used as mPOF infiltration, very strong propagation within the fiber core was observed, see Fig. 7. Unfortunately, after few minutes 5CB reacted with the polymer and, consequently, dissolved its structure.

In the second part of the experiment a small-core PC-2 mPOF was investigated. As previously, the first step was to examine propagation in the empty fiber without LC infiltration. When a halogen lamp was used as a light source, strong propagation could be observed, although a large part of light escaped to the cladding (Fig. 8).

An alternative and more efficient method of light injection to the mPOF utilized the face-to-face method by means of a single-mode SM600 fiber. Due to a small diameter of the SM600 fiber core, the light could propagate only in the core of the PC fiber. This method was also used with supercontinuum as a light source.

The second part of the experiment consisted in infiltrating mPOF PC-2 with LC. One end of the PC fiber was placed in a bottle with a LC and, with additional help of high pressure, fluid flowed into the air channels. Depending on the LC used different effects were observed.

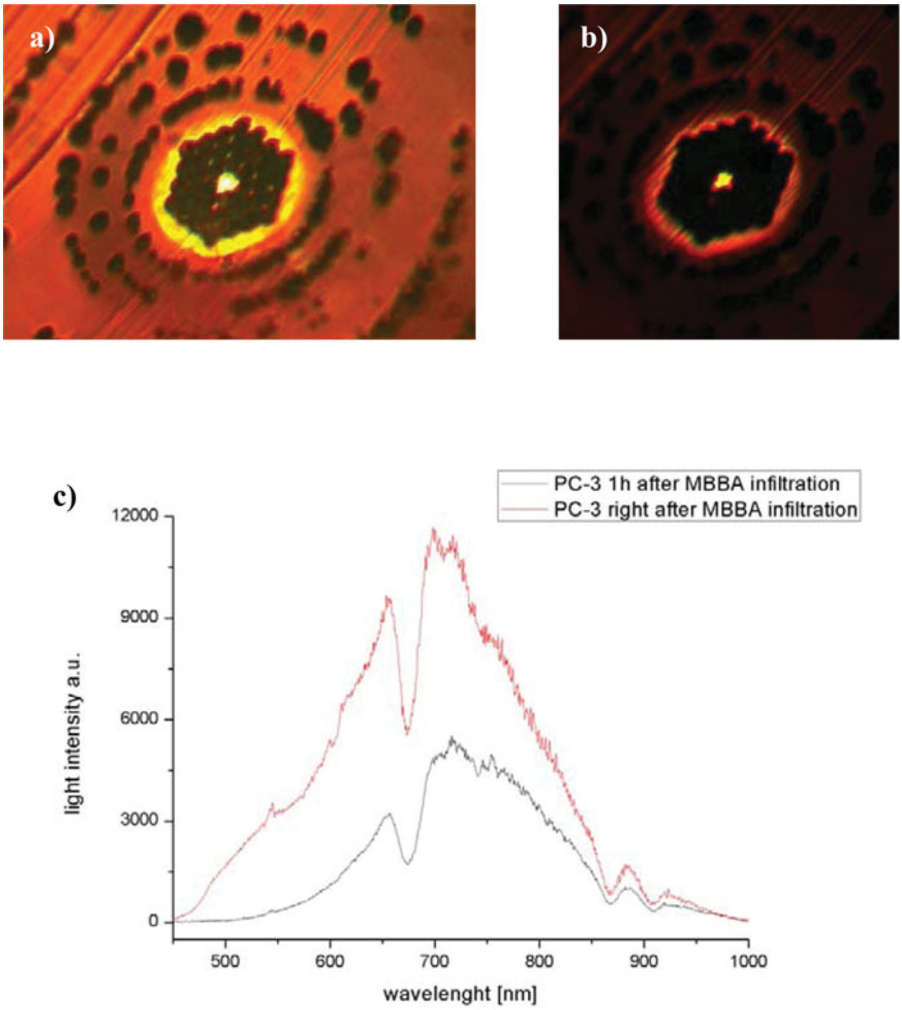

Figure 12. Propagation of the irradiated PC-3 mPOF right after MBBA infiltration (a), one hour after MBBA infiltration (b); output spectrum with a halogen lamp as a light source (c): the red line shows light intensity right after infiltration and the black line - one hour later. Around 675 nm, we observed strong light attenuation that might be attributed to a long length of the fiber - with shorter fibers the attenuation is significantly weaker.

The most interesting effects were observed with MBBA due to higher (than PC) values of both refractive indices, which allowed to obtain very well localized propagation within the PC core. Additionally, around the core a light ring was observed probably due to the effect of cladding modes trapping inside the fiber (Fig. 9). The main disadvantage of MBBA is its polarity, which might be responsible for dissolving the PC fiber structure.

To eliminate this defect, we used LC with positive dielectric anisotropy as, e.g. a low-birefringence 1550 nematic LC mixture. Due to lower 1550 LC refractive indices, light propagation within the core was due to the mTIR effect. To reduce the diameter of the beam, the incoming light was injected by using the SM600 fiber. When a halogen lamp was used as a light source, we were unable to obtain core propagation but, instead, a light ring (similary to to Fig. 9) from the trapped cladding modes was created. The comparison of propagation and spectrum of an empty fiber and mPOF filled with LC is presented in Fig. 10.

When supercontinuum was used as light source, propagation within the fiber core appeared, although it was sometimes accompanied by a light ring around the microstructure. The comparison of propagation and spectrum of the empty fiber and the fiber filled with LC is presented in Fig. 11.

As it was demonstrated, more promising results were observed in the PC-2 fiber filled with polar materials. Unfortunately, the destructive effects of these polar LCs on polymer (PC) structure prevent obtaining stable light propagation within LC infiltrated PC-2 mPOFs. To overcome this limitation, we exposed the PC mPOF to radiation in order to straighten the crosslinking of fiber molecules. The process of irradiation was made in the Central Laboratory for Radiological Protection (Warsaw, Poland). Selected samples were exposed to X-ray irradiation made with a voltage of 150kV and a current of 10mA. The exposure was done with the use of a substitution method in a calculated point of the space with positioning lasers. With this method, the reference value of KERMA (kinetic energy released per mass unit) in the air was determined as 0.0556 Gy/s. The next step was to put the samples in a previously measured point and irradiate with an exposition time of about 6360 s. The value of KERMA in the air was monitored during every exposition to ensure no change in its level. As a result of this irradiation process, mPOF became more immune to the influence of polar LCs. These irradiated PC-2 fibers are further recalled as PC-3 fibers.

After irradiation, the PC fibers were filled with MBBA and investigated by using different light sources. Similar effects as in the case of PC-2 were observed, but in this particular case the polar LC did not dissolve the polymer structure. However, after about one hour we observed proceeding loss of output power and after two hours propagation disappeared due to structure decomposition (Fig. 12). Despite that, the irradiation process enabled to extend PC fiber usefulness from 15 minutes to almost 2 hours.

5. Conclusions

Both experimental and theoretical studies of polymer photonic crystal fibers made of polycarbonate and infiltrated with liquid crystals have been presented. Depending on the sign of dielectric anisotropy of the liquid crystal, different results can be obtained. Liquid crystals with positive dielectric anisotropy allow obtaining light guiding due to the mTIR mechanism, but due to the low refractive index value of the liquid crystal, localized propagation within the core was not always possible to obtain. However, liquid crystals with negative dielectric anisotropy, allowed to achieve well-localized and strong propagation within the fiber core. Unfortunately, these liquid crystals can destructively react with the polycarbonate microstructure. To overcome this destructive effect, the PC fiber should be initially exposed to X-ray radiation. It allows to straighten the crosslinking of fiber molecules and minimize the destructive effect of polar LC. Another solution is to use an additional guest material inside the fiber to protect the structure.

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