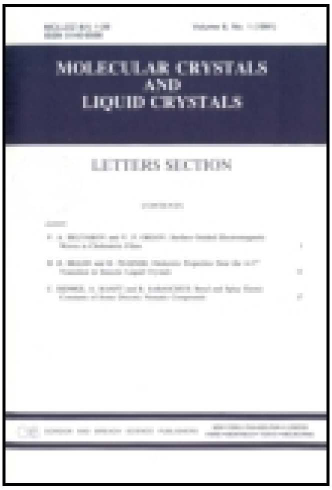

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

Liquid Crystals and Polymer-Based Photonic Crystal Fibers

T. R. Woliński[a], K. Mileńko[a], M. M. Tefelska[a], K. A. Rutkowska[a], A. W. Domański[a], S. Ertman[a], K. Orzechowski[a], M. Sierakowski[a], O. Chojnowska[b] & R. Dąbrowski[b]

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

[b] Military University of Technology, Warsaw, Poland

Published online: 30 Sep 2014.

To cite this article: T. R. Woliński, K. Mileńko, M. M. Tefelska, K. A. Rutkowska, A. W. Domański, S. Ertman, K. Orzechowski, M. Sierakowski, O. Chojnowska & R. Dąbrowski (2014) Liquid Crystals and Polymer-Based Photonic Crystal Fibers, Molecular Crystals and Liquid Crystals, 594:1, 55-62, DOI: 10.1080/15421406.2014.917471

To link to this article: http://dx.doi.org/10.1080/15421406.2014.917471

Mol. Cryst. Liq. Cryst., Vol. 594: pp. 55–62, 2014

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421406.2014.917471

Liquid Crystals and Polymer-Based Photonic Crystal Fibers

T. R. WOLIŃSKI,[1,*] K. MILEŃKO,[1] M. M. TEFELSKA,[1] K. A. RUTKOWSKA,[1] A. W. DOMAŃSKI,[1] S. ERTMAN,[1] K. ORZECHOWSKI,[1] M. SIERAKOWSKI,[1] O. CHOJNOWSKA,[2] AND R. DĄBROWSKI[2]

[1]Faculty of Physics, Warsaw University of Technology, Warszawa, Poland
[2]Military University of Technology, Warsaw, Poland

Experimental results of polymer photonic liquid crystal fibers based on commercially available (Kiriama) PMMA and cyclo-olefin polymer (Zeonex 480R) microstructured polymer fibers infiltrated with nematic liquid crystals (2CHBT/8CHBT and PCB) are presented and thermally-tuned photonic band-gap propagation mechanism is observed. These preliminary results suggest, that polymers binding to liquid crystals much easier than silica, can offer new opportunities while using polymer-based photonic crystal fibers.

Keywords Polymer photonic liquid crystal fibers

1. Introduction

Over the past decade photonic crystal fibers (PCFs) have attracted an increasing scientific interest due to a great number of potential applications. Optical wave guiding in a PCF is governed by one of two principal mechanisms responsible for light trapping within the core: a classical propagation effect based on the modified total internal reflection (mTIR or index guiding) and the photonic band gap (PBG) effect, which occurs if the refractive index of the core is lower than the mean refractive index of the cladding region. Infiltrating the air-holes with liquid crystals (LCs) induces highly-tunable photonic structures, called photonic liquid crystal fibers (PLCFs) [1–3].

Recently more attention has been directed towards microstructured polymer optical fibers (mPOFs) [4]. Plastic materials as polymethyl methacrylate (PMMA) as well as polycarbonate (PC) are very interesting optical materials with high mechanical strength and white light transmittance. Among the key advantages of mPOFs are their high flexibility and greater resistance to mechanical stress than in the case of silica glass fibers. Thanks to that it is possible to create a variety of microstructured polymer photonic structures and in particular those with a large refractive index contrast between the core and the cladding.

*Address correspondence to T. R. Woliński, Faculty of Physics, Warsaw University of Technology, Koszykowa 75, 00-662 Warszawa, Poland. E-mail: wolinski@if.pw.edu.pl

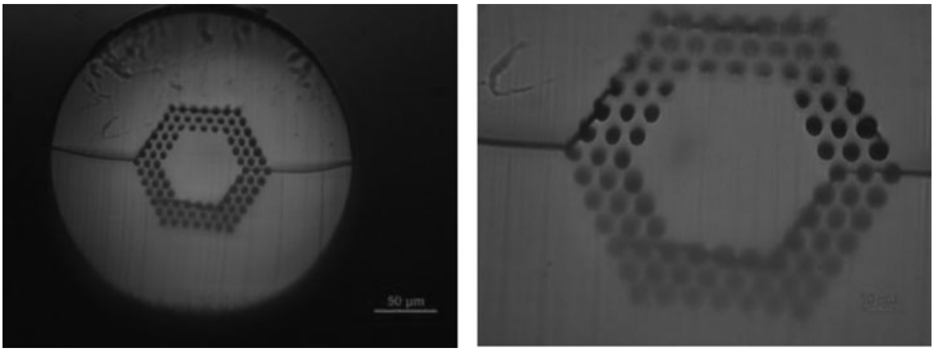

Figure 1. Custom-designed microstructured polymer optical fiber made of Zeonex 480R and fabricated by Kiriama Pty. Ltd. [11].

Liquid crystal and polymer-based photonic crystal fibers constitute a new solution based on unique properties of liquid crystals and mPOFs opening up new areas in innovative sensing and photonic devices applications. Compared with their silica-based microstructured fibers, it is easier to fabricate exotic mPOFs by extrusion or drilling at low temperature; their nonlinearity is potentially stronger, the range of available polymers that may be drawn is more diverse and the biocompatibility of polymers is often better. Liquid crystals due to their attractive properties i.e., the high birefringence, high electro-optic and thermo-optic effects are a very good candidate for mPOF infiltration to obtain tunable all-in-fiber innovative photonic devices for sensing and security applications [3].

In this paper, we present experimental results of commercially available mPOFs (Kiriama) with PMMA and cyclo-olefin polymer (Zeonex 480R) infiltrated with nematic liquid crystals (2CHBT/8CHBT and PCB) to obtain temperature-induced PBG propagation mechanism. These preliminary results suggest, that polymers binding to liquid crystals much easier than silica, can offer new opportunities while using polymer-based photonic crystal fibers.

2. Materials

2.1 Microstructured Polymer Optical Fibers

Research activities on microstructured optical fibers made out of polymers started in 2001 [4] as a consequence of PCFs technology development. This originates mainly due possibilities brought by the difference in material properties between polymers and silica glass [5]. In this paper two microstructured polymer optical fibers fabricated by Kiriama Pty. Ltd. (Sydney, Australia) were combined with liquid crystals. One of them (shown in Fig. 1), specially designed and made on a particular request, has a large core to obtain good core- guiding propagation. Analogous type of optical fiber made of a silica glass has been already tested, yielding to the exceptionally low attenuation when infiltrated with liquid crystal [6]. In the case analyzed here, rods and capillaries used to form mPOF of interest have been made of the cyclo-olefin polymer called Zeonex [7, 8]. Specific type of this optical material, namely 480R, is characterized by the high mechanical strength and while light transmittance of about 92% (for a thickness of 3 mm and within the spectral band of 360–800 nm) [8]. In addition, Zeonex 480R is characterized by low water and moisture absorption, good chemical, UV light and high heat resistance. Refractive index for the

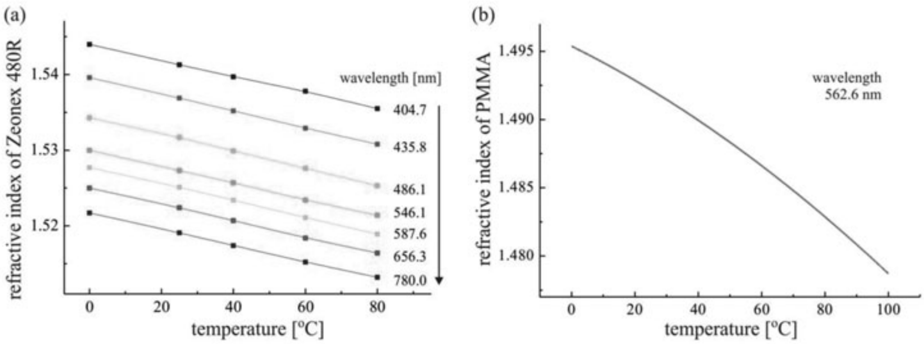

Figure 2. Temperature dependence of refractive index for (a) Zeonex 480R [5] and (b) PMMA material [11].

sodium D spectral line (589 nm) is equal to 1.525 at 25°C [7,8].Temperature dependence of refractive index is presented in Fig. 2(a). Zeonex is anticipated to possess relatively low loss in the THz region. Report on the fabrication and characterization of a suspended-core mPOF made of Zeonex polymer using THz time domain spectroscopy is shown in Ref. [9]. Moreover, Zeonex can be combined with other polymers. Specifically, Zeonex 480R and PMMA (described below) are compatible materials in terms of processing temperature and dilatation coefficients controlled in the fiber drawing process and thus can be successfully applied for co-drawing applications. All-solid mPOF formed by Zeonex submicron cores hexagonally arranged in a PMMA cladding allowed for a single mode operation in a broad spectral range down to the visible [10].

The outer- and the core- diameters of the manufactured fiber are equal to 225 μm and 55 μm, respectively. The diameter of the single hole varies in the range of 5.3–5.8 μm, while the lattice constant, $\Lambda = 8.0$–8.4 μm (Fig. 1).

Second of the analyzed fibers was commercially available G3-340 high-bandwidth micro- structured polymer optical fiber made of PMMA, with a highly multimode operation in the visible spectral range (Fig. 3). PMMA is an acrylic glass with a refractive

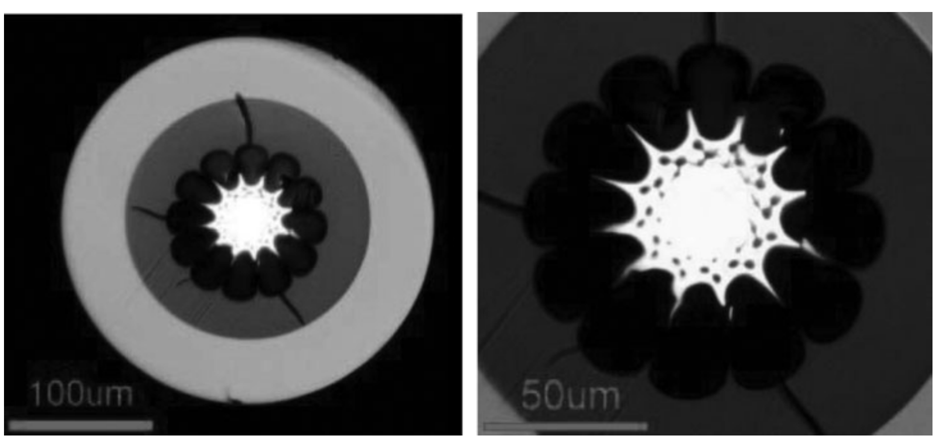

Figure 3. G3-340 microstructured polymer optical fiber (pictures taken from the Kiriama datasheet [11]).

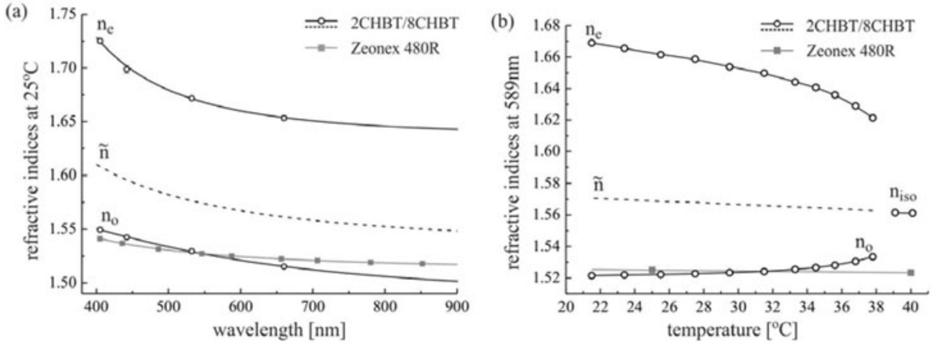

Figure 4. Dispersion curves for a 2CHBT/8CHBT LC mixture at 25°C (a) and its refractive indices at the wavelength of 589 nm as a function of temperature (b), where no is ordinary and ne is extraordinary refractive index in the nematic phase, niso is refractive index in the isotropic phase. Average refractive index (dashed lines), defined as $\tilde{n} = (2no + ne)/3$, can be assumed when a random orientation of LC molecules within mPOF structure is considered. Dispersion characteristics of the 2CHBT/8CHBT LC mixture were obtained by fitting three- parameters Cauchy functions to experimental data (marked with hollow circles) measured with use of the thin prism method described in Ref. [15]. Refractive indices of the LC mixture in a function of temperature have been measured for sodium D spectral line with use of a refractometer. Refractive indices of Zeonex 480R are also shown in a)-b) for comparison [7, 8].

index of 1.491 at 589 nm and is characterized by white light transmittance of 93% (for a thickness of 3 mm and within the spectral band of 380–780 nm [7,8]). The temperature dependence of the refractive index for PMMA (at the wavelength of 562.2 nm) is presented in Fig. 2(b). It is worth to note that first microstructured polymer optical fibers were made of PMMA [4]. Moreover, based on the endlessly single-mode PCF design, they allowed for first demonstration of a single- mode operation in a non-silica PCF. After that, despite other commercially available polymers being applied, PMMA still remains in extensive use for mPOFs fabrication. A methodology suitable for the fabrication of a wide range of mPOFs out of PMMA for different applications is described in [2, 9]. Highly birefringent PMMA-based mPOFs have been proposed to be applied for sensing applications [10].

In the case of commercially available G3-340 mPOF (Fig. 3), the outer- and the core diameters are equal to 250 μm and 40 μm, respectively. The core and the inner cladding of the fiber were made of PMMA, while the outer jacket was made of polycarbonate (PC).

2.2 Liquid Crystals

Two liquid crystalline materials synthesized at the Military University of Technology (MUT), Warsaw (Poland) have been applied in this work.

First of them was a nematic LC mixture consisting of 4-(trans-4′-octylcyclohexyl) isothiocyanatobenzene and 4-(trans-4′-ethylcyclohexyl) isothiocyanatobenzene (2CHBT/8CHBT) in the weight ratio of 4:1. The ordinary refractive index of 2CHBT/8CHBT LC mixture was specially designed to be applied in mPOF made of Zeonex 480R material, in a way that it crosses curve describing refractive index of Zeonex as a function of temperature (Fig. 5b).

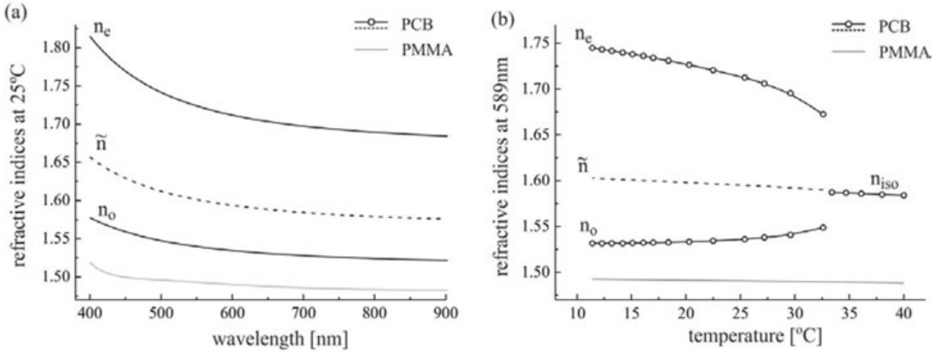

Figure 5. Dispersion curves of PCB liquid crystal (a) [13] and temperature dependence of its refractive indices (b). The latter measured at the MUT by means of refractometer. Analogous characteristic for PMMA material are shown in both panels for comparison [8, 14, 17].

Second liquid crystal was a well known nematic pentylo-cyano-biphenyl, PCB. The refractive indices for a temperature of 25°C in the function of wavelength, as well as their temperature dependence for the sodium D spectral line are presented in Fig. 5.

3. Experimental Set-up and Results

The experimental setup consists of a halogen lamp (Ocean Optics Mikropack) as a light source, a microscope with a digital camera as a detector, and a Peltier module as a thermal control. The latter can be successfully applied to heat the required section of the fiber, and thus to thermally tune propagation properties of the polymer PLCF.

The mPOF made of Zeonex was infiltrated with the 2CHBT/8CHBT mixture by using two different methods. In the first of them one end of the fiber was placed in a container with LC so that the liquid flows into the air channels by capillary forces. In the second method, the additional high pressure has been added to push the liquid into mPOF channels. Figure 6 shows the microscopic picture of the employed mPOF illuminated with a white light. When the fiber is empty, a part of light is confined in the core but its substantial portion propagates in the cladding (Fig. 6a). This happens since the fiber is made of single

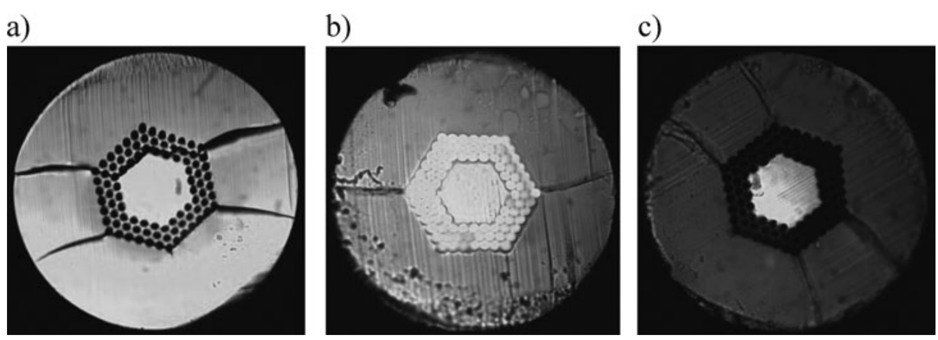

Figure 6. a) Microscopic picture of the polymer micro-structured fiber illuminated with a white light; mPOF infiltrated with 2CHBT/8CHBT LC mixture: b) short length of infiltration, c) relatively long length of infiltration.

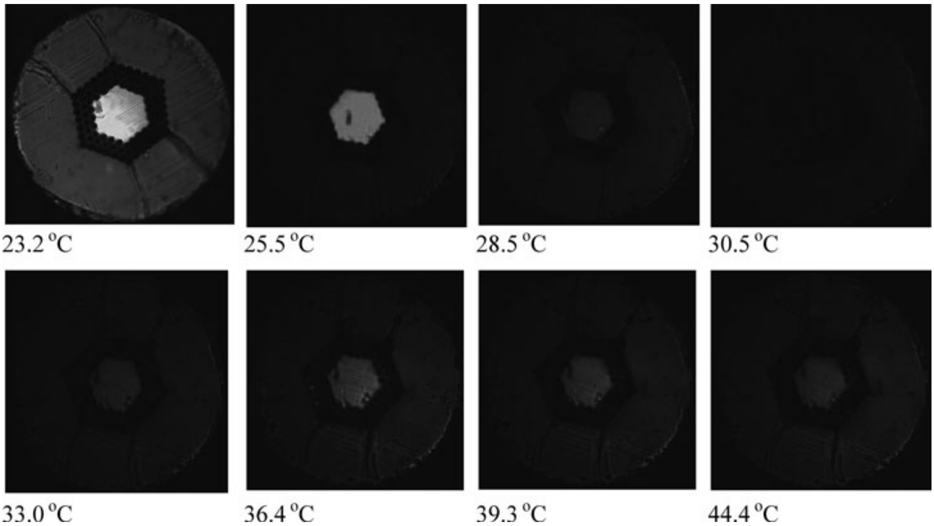

Figure 7. Thermal tuning of the light propagation in the Pol-PLCF infiltrated with the use of capillary forces.

material and has no outer coating. When only a short length of the fiber (3 cm) is infiltrated with the LC, light is guided mostly in the fiber core but it propagates also in the air channels filled with the liquid crystal (Fig. 6b). Long infiltration length (7 cm) provides strong light confinement in the fiber core (Fig. 6c).

After the long section of the fiber has been filled with the use of capillary forces, the infiltrated part of the fiber was placed on the Peltier module and then heated. The thermal tuning of the light propagation in the polymer PLCF was observed at the output facet of the polymer PLCF, for the thermal range from 23.2°C to 44.4°C as it is shown in Fig. 7. In the room temperature, propagation of a white light in the fiber core has been observed, indicating thus that the light is guided due to the modified total internal reflection. This suggests that the liquid crystal alignment within the air channels is due to the flow-induced planar (homogenous) orientation (i.e. ordinary refractive index of LC can be assumed). While rising temperature, the refractive index of LC increases and refractive index of Zeonex 480R decreases. It causes in turn formation of the photonic band gap effect, in which only red part of the visible light spectrum is supported.

When high pressure has been applied in order to infiltrate mPOF, a green light propagating in the fiber has been observed (Fig. 8), indicating that the photonic band gap effect has been obtained again. It suggests that applied method of infiltration does not provide the planar orientation of LC in mPOF (as it was a case for infiltration by the capillary forces) and average refractive index of LC mixture should be considered. Rising temperature causes the band gap to shift and the change in the color of propagating light is observed. For the temperature close to 30°C the propagation in the fiber core ceases due to refractive indices of LC and Zeonex approaching each other.

In the next experiments the G3-340 mPOF was infiltrated with PCB liquid crystal by using capillary forces and the length of the infiltrated section of the fiber was 6 cm. The picture of the output facet of the fiber, illuminated with the white light is shown in Fig. 9. We observed a mode in the core surrounded by a ring of point light sources, with a different wavelengths from green to red. We believe that observed effects are due to the

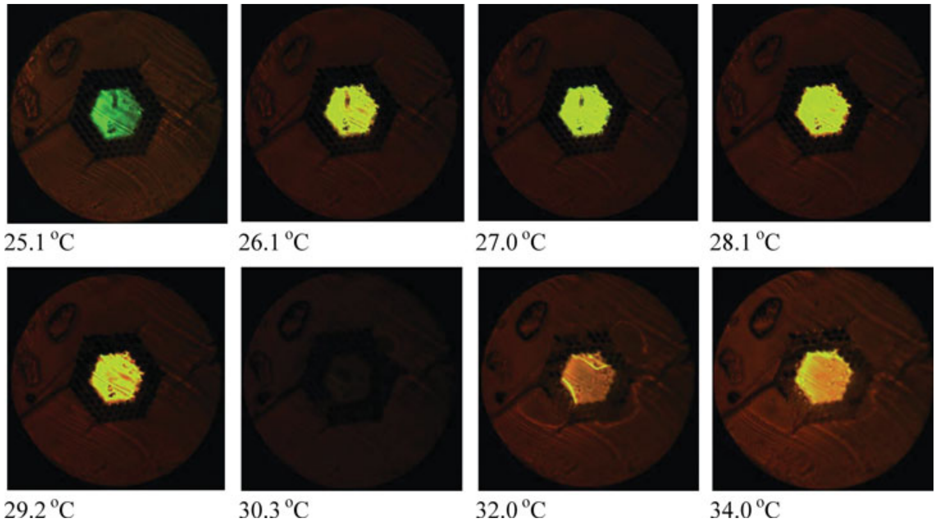

Figure 8. Thermal tuning of the light propagation in the Pol-PLCF infiltrated with the use of the high pressure.

small air holes present in the fiber core (Fig. 3). These small holes (in additions to the big ones located in the cladding area) seemed to be also infiltrated with LC. Therefore they form small waveguides arranged around the fiber core, close to its edge. After three days, the phenomenon has been still visible but the liquid crystal reacting with PMMA material causes the bridges supporting fiber core to be dissolved (photo in the right-hand side in Fig. 9). Identical experimental procedure repeated many times, have ended up with the same conclusions.

In the next stage of performed experiments, the fabricated sample has been placed on the Peltier module and heated. Rising temperature increases the reaction speed between the fiber and liquid crystal. At high temperatures the bridges made of PMMA are resolved and the fiber core is no longer supported, although it still guides the light with high intensity.

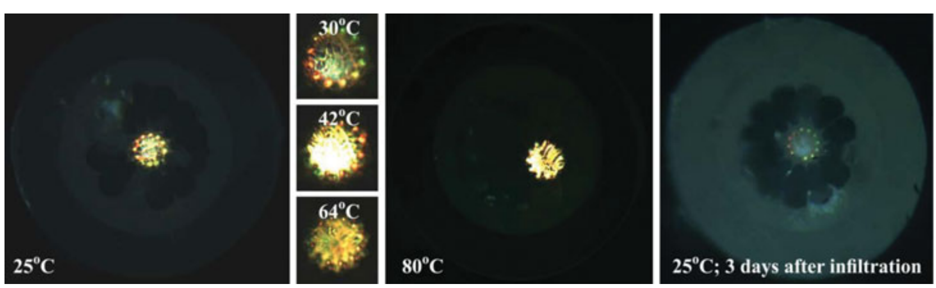

Figure 9. Microscopic pictures of mPOF G3-340 infiltrated with PCB liquid crystal and illuminated with the white light. Thermal tuning of the light propagation, as well as temporal stability of Pol-PLCF sample has been tested. Please note that the sample under the aging tests (picture on the right-hand side) has not been heated.

4. Conclusions

Liquid crystal infiltration of the polymer -based photonic crystal fiber provides a tunable confinement of the light in the fiber core. Depending on the infiltration method the light propagation governed by the modified total internal reflection or photonic band gap effect can be achieved. Moreover, the change in external temperature causes the formation and shift of the photonic band gaps. It is important to note that liquid crystal can strongly (and destructively) react with polymers, therefore designing and fabrication of a special host and guest materials is required. Preliminary results presented in this paper are not always stable and therefore more experimental and theoretical investigations are required that will be performed in the near future.

Acknowledgment

This work was supported by the Polish National Science Centre (NCN) under the grant no. 2011/01/B/ST7/05015.

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