Influence of photopolymerization on propagation properties of photonic crystal fiber infiltrated with a liquid crystal mixture

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Abstract—In this paper we analyze the influence of the photopolymerization process on propagation properties of photonic crystal fiber infiltrated with liquid crystal doped with a mixture of reactive monomer and photoinitiator. The obtained results showed changes in the photonic band gap of the fiber due to a refractive index change of the liquid crystal mixture caused by the polymerization process. Moreover, the research demonstrated the possibility of preserving the desired molecular orientation of liquid crystal initially stabilized by placing the sample in an external electric field. This was achieved by simultaneously irradiating the sample and controlling the orientation of liquid crystal molecules with the electric field. The spectral analysis of the polymerized sample showed no visible difference in propagation spectra when the electric field was turned off after the process was finished.

Liquid crystals (LCs), due to their unique electro-optical properties, are widely used in modern optical technology [1]. They exhibit the properties of both liquids and crystals as LC molecules have rotational freedom around their long axis while having an ordered arrangement of their centers of mass [2]. Liquid crystals are optically anisotropic substances. The direction and value of their anisotropy can be changed under the influence of an external electric or magnetic field as well as temperature [3–5]. To modify the properties of LCs, such as switching times, threshold voltage or phase transition temperature, various types of dopants can be introduced [6–7]. Currently, a lot of research is focused on creating composites consisting of LCs and monomers used to fix the orientation of LC molecules [8–9]. The polymerization of LCs gives many possibilities such as creating complex photonic structures or stabilizing blue phase LCs to room temperature to create LCDs with properties superior to the ones made with nematics [10].

In this paper, we present the influence of the photopolymerization process on propagation properties of photonic crystal fiber (PCF) infiltrated with a liquid crystal mixture based on a nematic LC [11]. Wavelengths propagating in PCF's core are greatly influenced by refractive index values of materials of which a cladding is constructed. Slight variations of the refractive index cause changes in the propagation spectrum, which allows to observe refractive index changes caused by polymerization of the LC mixture.

Liquid crystal mixture used in the research consisted of a nematic LC 6CHBT ($n_o = 1.5$, $n_e = 1.7$ [12]) doped with reactive monomer (RM) Bisphenol A dimethacrylate (Sigma Aldrich, >98%, CAS: 3253-39-2) and photoinitiator (PI) 4,4'-Bis(diethylamino)benzophenone (Sigma Aldrich, ≥99%, CAS: 90-93-7). The RM+PI dopant concentration was 2%, with RM:PI proportions being 9:1. The mixture was placed in an ultrasonic bath and mixed for 30 minutes in the temperature above the phase transition of the LC to make sure that the compounds were dispersed evenly. Then, it was introduced into a silica PCF shown in Fig. 1 (solid core with a 8.5μm diameter and air holes, separated by 5.9μm and arranged in 8 rings surrounding the center of the fiber, with a 3.5μm diameter) with capillary forces. To examine the propagation properties of PCF with an LC mixture, a broad – spectrum light source (Micropack HL-2000) and a spectrometer (Ocean Optics USB4000) were used. The PCF's end, filled with LC mixture, was placed between two ITO-coated glass plates to determine the changes in electro-optical behavior of the sample. The PCF part was connected directly to the light source and the part filled with an LC mixture was connected face-to-face to the fiber probe going out of the spectrometer.

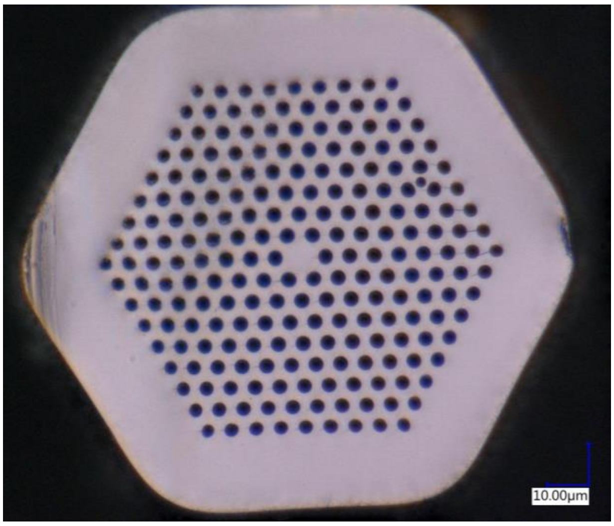

Fig. 1. PCF (made by UMCS Lublin) used in the experiments.

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Firstly, the propagation spectra were observed in a non-polymerized sample with and without the influence of the external electric field and saved as reference. After that, the electric field was turned off so that the LC molecules were oriented planarly and the sample was irradiated several times with LED (λ=395nm, P=7mW). The spectra were examined after each irradiation and the comparison of the sample's electro-optical behavior before and after photopolymerization is demonstrated in Fig. 2.

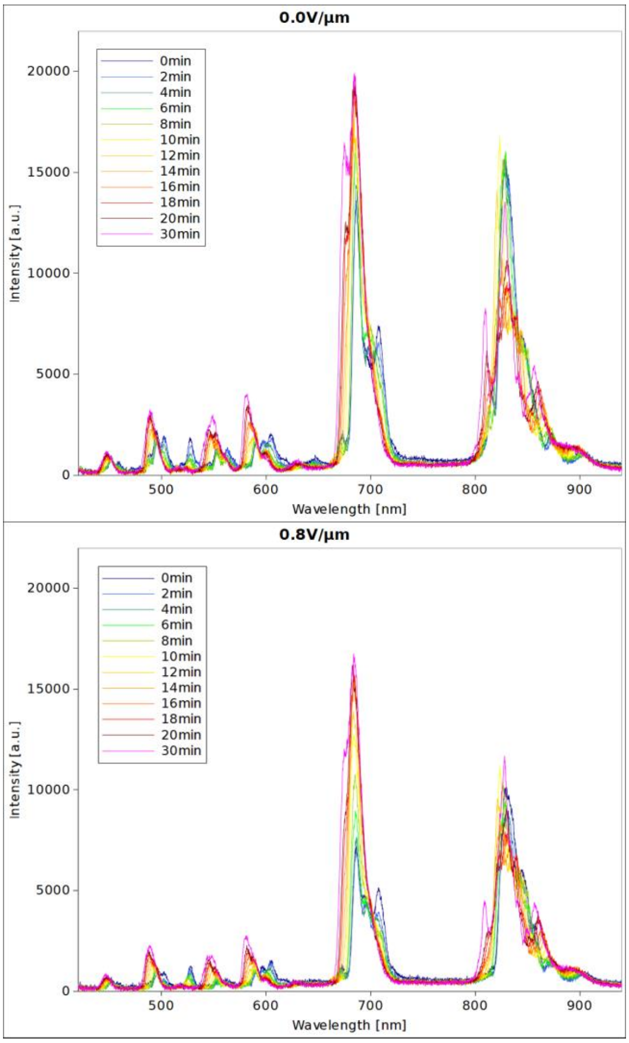

Fig. 2. Comparison of propagation spectra after different times of photopolymerization in a planar orientation of the LC. Spectra on the top are observed with no electric field and the bottom ones are observed in 0.8V/µm.

For better visualization of the results, some of the propagation spectra (660–720nm) were enlarged and shown in Fig. 3.

The shape of the spectrum after photopolymerization changed, as compared to the reference one - the positions of the peaks shifted toward shorter wavelengths and their width increased. Moreover, the overall band gap peaks' intensity also increased. It can be noticed that for longer irradiation times these changes were more prominent (Fig. 2, Fig. 3). Based on that, it can be concluded that polymerization changed the overall refractive index of the LC mixture and this change increased when the polymer network became stronger.

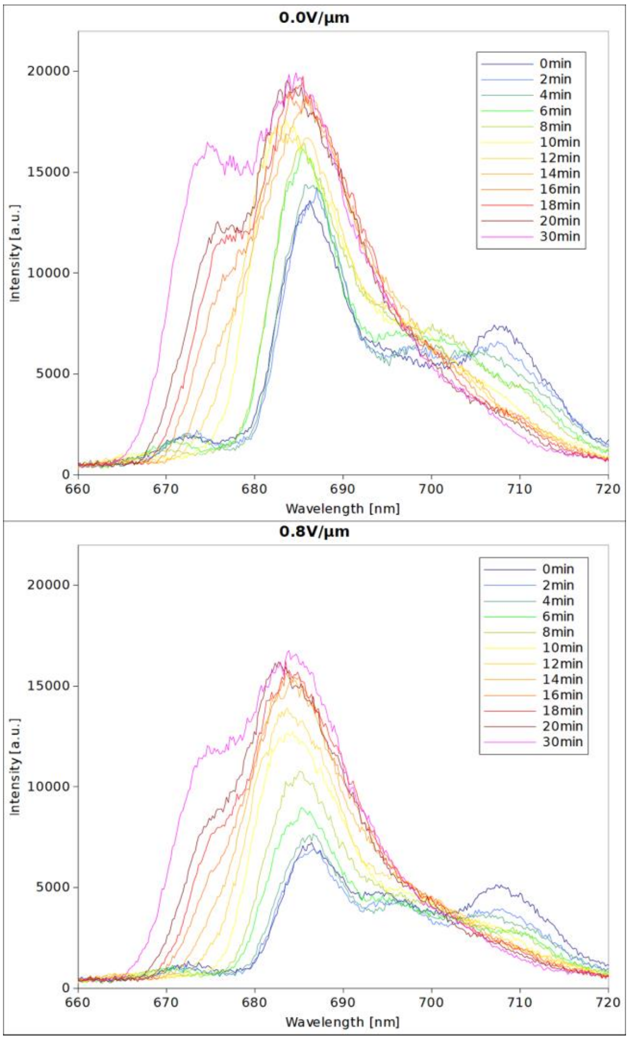

Fig. 3. Changes in the main peak of the spectra shown in Fig. 2 in a range from 660nm to 720nm.

Next, the orientation of LC molecules in the sample was set with the external electric field and the photopolymerization process was used to preserve it. During the preparation process, the electro-optical behaviour of the non-polymerized sample was analyzed to determine the voltage necessary for reorientation of LC molecules to a homeotropic orientation.

Later, the LC mixture was irradiated in series as in the previous experiment for a selected value of electric field (1.7V/µm), for which new clear band gaps were observed. That value was chosen to be above the reorientation threshold of the molecules to the homeotropic position (around 0.9V/µm) to make sure that the electric field counteracted changes in the molecular orientation that could be caused by heating of the LC mixture during the photopolymerization process. Comparison of the spectra before and after various irradiation times are shown in Fig. 4.

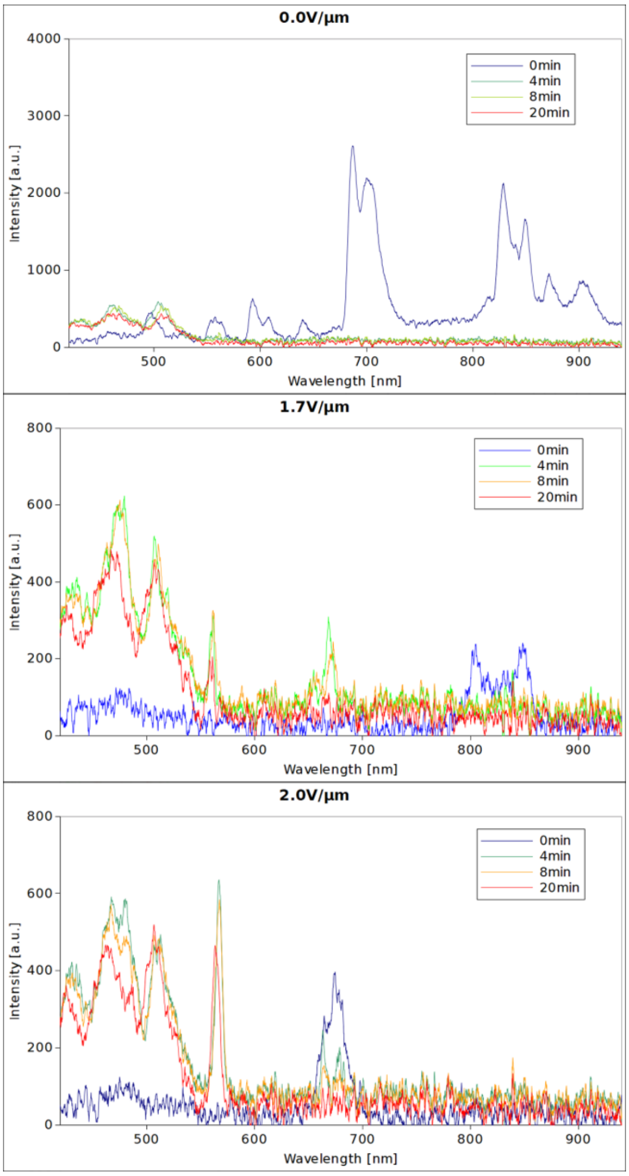

Fig. 4. Comparison of propagation spectra after different times of photopolymerization in a homeotropic orientation of the LC. Spectra on the top are observed with no electric field and the middle and bottom ones are observed in 1.7V/µm and 2/µm respectively.

The results demonstrated in Fig. 4 proved that it was possible to stabilize the molecular orientation of the LC that was previously controlled with an external electric field - the shape of the spectrum of the polymerized sample stayed the same after switching off the electric field. However, the location of the peak observed for 1.7V/µm shifted towards shorter wavelengths compared to the non-polymerized sample due to a refractive index change of the LC mixture. Additionally, irradiating the sample longer than 4 minutes did not introduce significant changes in the spectrum, which suggests that the polymer network did not get much stronger after that.

In conclusion, the research showed that photopolymerization of the LC mixture caused changes of its refractive indices. This resulted in shifting the positions and changing the height of the peaks observed in the propagation spectrum of PCF. After 20 minutes of irradiation in a planar orientation of the LC, the main peak's position shifted by around 4nm towards shorter wavelengths (from 687nm to 683nm) and its intensity increased by 45%. Similar changes were observed for the other peaks. Moreover, it was possible to stabilize the LC molecules in a specific orientation and by doing so preserving another set of band gaps achieved by a slight change in the values of refractive indices and mostly by a new molecular orientation.

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