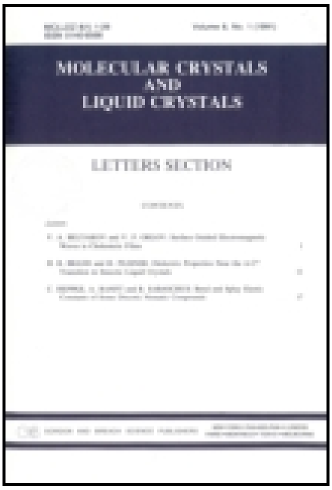

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

Numerical Analysis of the Phase Birefringence of the Photonic Crystal Fibers Selectively Filled with Liquid Crystal

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Published online: 30 Sep 2014.

Mol. Cryst. Liq. Cryst., Vol. 596: pp. 5–11, 2014

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421406.2014.918239

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In this work, we present the theoretical investigation of the phase birefringence in a multi-component-glasses photonic crystal fiber, selectively infiltrated with various nematic liquid crystals. We compare the influence of different PCF infiltration patterns on the fiber phase birefringence. The ability to continuously tune birefringence up or down, depending on the direction of LC molecules tilt is also presented.

Keywords Optical fibers; tunable birefringence; numerical design

1. Introduction

Photonic crystal fibers (PCFs) are a special type of optical fibers, that are widely used in telecommunication and sensing. The structure of the photonic crystal fiber allows for the air channels to be infiltrated with liquid crystal (LC) material, in this way we obtain a new class of fibers called photonic liquid crystal fibers (PLCF) [1]. The PLCFs give the possibility to dynamically tune their polarization properties due to external fields-induced reorientation of LC molecules. The tunable single polarization operation [2] and tunable birefringence [3, 4] has been previously presented. So far research was focused on silica glass-based PCF filled with LCs. However, the refractive indices of a great majority of LCs are higher than the silica glass refractive index (~1.46) and thus in silica-glass PCFs filled with LCs, light is generally propagating due to the photonic band-gap phenomenon. Due to high scattering of the LCs and deep penetration of the mode into the LC-filled holes the attenuations in these PLCFs are in the order of a few or even a few tens dB/cm. In this paper we present a new approach for tunable PLCFs by selective infiltration of the multi-component glasses photonic crystal fiber. The selective infiltration of the PCFs in the sense that only selected fiber air channels are filled with a desired liquid crystal, gives possibility to generate devices with new properties [5]. In particular such selective infiltration causes the formation of initial phase birefringence in the fiber [6].

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2. Materials

2.1 Photonic Crystal Fiber

Employed in calculations the PCF14(6) fiber is a specially designed photonic crystal fiber manufactured at the Institute of Electronics Materials Technology ITME, Warsaw (Poland) (its cross-section is shown in Fig. 1a,b). The fiber diameter is 125.4 μm and it consists of six rings of holes with diameters of 5.2 μm and pitch equal to 7.6 μm. The PCF is made by the stack-and- draw technique from the lead-bismuthgallate (Pb-Bi-Ga)-based glass designated as PBG08 [7]. The PBG08 glass has a very high refractive index ($\sim$1.95).

2.2 Liquid Crystal

The liquid crystal material used in this work was 5CB and it was fabricated at the Military University of Technology (MUT), Warsaw (Poland). The 5CB nematic LC is commonly-used and well-characterized: thermal characteristics of its both refractive indices are well known (Fig. 1c), as well as its dispersion [8] The material birefringence of the 5CB is Δn $\approx$0.18.

To analyze the influence of different liquid crystal we considered typical refractive indices of LCs, ordinary equal to 1.52 and extraordinary in the range of 1.52–1.8.

2.3 Photonic Liquid Crystal Fiber (Selective Infiltration)

When a photonic crystal fiber is infiltrated with a liquid crystal by capillary forces the alignment of the LCs molecules in the fiber air holes is generally planar and induced by flow (Fig. 2a) [9]. In this work we focus on the selective infiltration of photonic crystal fiber, when only selected micro-holes are filled whereas other remains empty (or filled with air). This infiltration can be achieved by precise covering of the chosen parts of the PCF with glue and placing this end of the PCF into the container with a liquid crystal [10]. After infiltration, the part of the PCF with the glue should be cleaved.

In this work we have considered two different infiltration patterns: half (Fig. 2a) and bow tie (Fig. 2b) infiltrations.

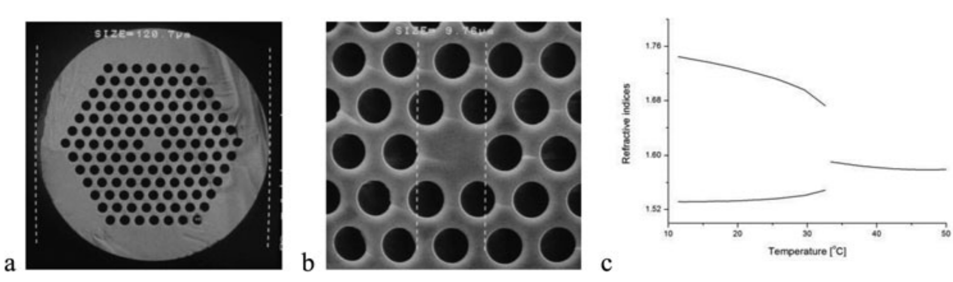

Figure 1. a, b) Microscopic picture of employed photonic crystal fiber, c) refractive indices as a function of temperature of the 5CB liquid crystal.

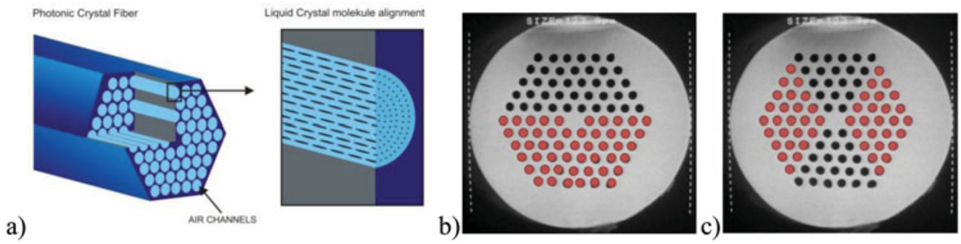

Figure 2. a) Schematic representation of the liquid crystal molecules alignment in the photonic crystal fiber air channels; Schematic representation of selective infiltration patterns (red dots): b) half, c) bow tie.

3. Theoretical Analysis

To calculate modal properties of the PCF14(6) selectively filled with the 5CB nematic LC we used full-vector finite element method (FEM) with perfectly matching layers (PML) [11]. To investigate the influence of the LC molecules reorientation induced by a transverse electric field, a simplified theoretical model was used [11]. In this model an anisotropy of a LC has been taken into account by defining diagonal tensor for dielectric permittivity $\varepsilon = [\varepsilon_{xx},\varepsilon_{yy},\varepsilon_{zz}]$, which components are presented in Fig. 3. We assume that without an electric field all the LC molecules are parallel to the fiber axis (Fig. 4a). Our previous calculations evolving full dielectric permittivity tensor and LC reorientations with arising electric field [12] showed, that the simplified theoretical model with the diagonal tensor gives results which are in a good agreement with the strict model, however significantly shorter time was needed for computations.

The numerical calculations was performed for wavelength range from 1000 to 1800 nm and dispersion of both fiber and LC were taken into account. At the same time we carried

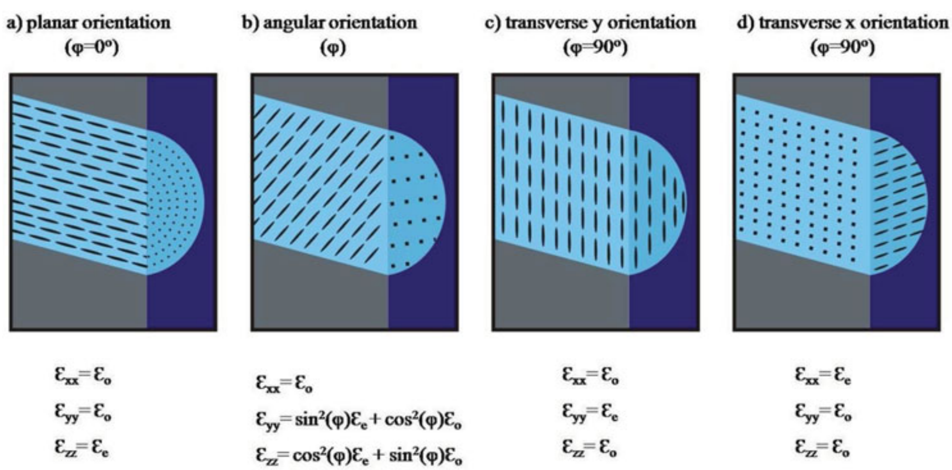

Figure 3. LC molecules orientations and corresponding components of dielectric permittivity tensor $\varepsilon = [\varepsilon_{xx},\varepsilon_{yy},\varepsilon_{zz}]$: a) planar, b) tilted, c) transverse y, d) transverse x.

out calculations for tilt angles from 0°, 15°, 30°, 45°, 60°, 75°, and 90° for two transverse orientations x and y.

3.1 "Bow Tie" PLCF

Firstly we have calculated the phase birefringence as a function of molecules tilt angle, in two cases: when the molecules change their orientation from planar to transverse x and transverse y direction (Fig. 3c,d). The result for wavelength equal to 1550 nm is presented in Figure 4a. We can see that the PLCF with planar liquid crystal alignement (for molecules tilt angle 0°) has phase birefringence equal to $1.8 \cdot 10^{-5}$. The change of tilt angle from 0° to 90° causes the increase of phase birefringence for transverse reorientation in x-direction up to $4 \cdot 10^{-5}$. However for the transverse reorientation in y-direction phase birefringence decreases, it reaches 0 for 52° of tilt angle and $-1.5 \cdot 10^{-5}$ for 90°. The change of phase birefringence as a function of wavelength, for tilt angle 0°, 90° x and 90° y is presented in Figure 4b. When the molecules have planar orientation the phase birefringence changes from $0.5 \cdot 10^{-5}$ to $2.9 \cdot 10^{-5}$ in a considered wavelength range. In the transverse "orientation x" the phase birefringence increases for higher wavelengths, from $1 \cdot 10^{-5}$ for 1000 [nm] to $6.4 \cdot 10^{-5}$ for 1800 [nm]. In the case of reorientation in y-direction the phase birefringence decreases for higher wavelengths, from $-0.4 \cdot 10^{-5}$ for 1000 [nm] to $-2.4 \cdot 10^{-5}$ for 1800 [nm]. This result shows great similarities to the selectively filled PLCF in which only one row of micro-holes in the middle of the fiber was infiltrated with LC [6].

3.2 Half Infiltrated PLCF

For the half infiltrated fiber the initial phase birefringence at wavelength 1550 nm is $0.9 \cdot 10{-}5$ (Fig. 5a). When the tilt molecules changes from 0° to 90° for the reorientation in x-direction, the phase birefringence increases to $6.3 \cdot 10^{-5}$. In the case of the reorientation in y-direction, the phase birefringence decreases for increasing tilt angle. For the tilt angle 27° phase birefringence is equal to zero, and $5.1 \cdot 10^{-5}$ for tilt angle 90°. The phase birefringence as a function of wavelength for the half infiltrated fiber is presented in Fig. 5b . For the planar orientation the phase birefringence changes from $0.3 \cdot 10^{-5}$ to $1.4 \cdot 10^{-5}$. In the case of orientation "transverse x" the phase birefringence starts from $1.6 \cdot 10^{-5}$ at 1000 nm wavelength and goes to $10.1 \cdot 10^{-5}$ at 1800 nm. The phase birefringence in the

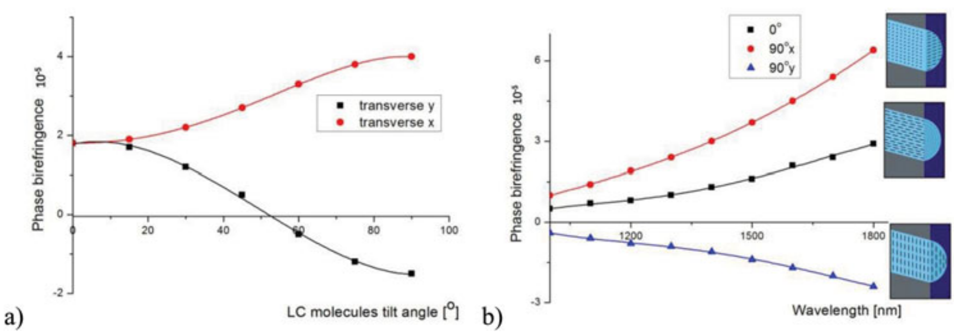

Figure 4. a) Phase birefringence of transverse reorientations in x- and y-direction in a function of LC molecules tilt angle (@1550 nm); b) Phase birefringence for tilt angle 0°, 90° x and 90° y as a function of wavelength.

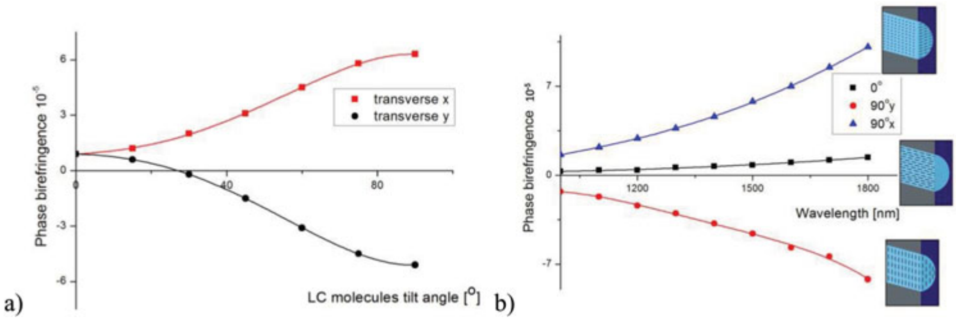

Figure 5. a) Phase birefringence of transverse reorientations in x- and y- direction in a function of LC molecules tilt angle in degrees (@1550 nm); b) Phase birefringence for tilt angle 0°, 90° x and 90° y as a function of wavelength.

90 tilt angle for the "transverse y" orientation ranges from $-1.3 \cdot 10^{-5}$ to $-8.2 \cdot 10^{-5}$ in considered wavelength range.

When we compare this results with fully infiltrated PCF14(6) with 5CB previously presented [13], where for planar alignment corresponding to 0° tilt angle, phase birefringence was equal to 0, we can see that presented in this paper types of the selective infiltrations causes the formation of initial phase birefringence and by changing the LC molecules tilt angle we can achieve zero, plus or minus phase birefringence.

3.3 *Different Liquid Crystals*

To calculate the influence of the different liquid crystals we fixed ordinary refractive index to 1.52 and changed the extraordinary refractive index in the range of 1.52 to 1.8. The calculations were carried out for the molecules tilt of 90° for "transverse x" and "transverse y" orientations, at 1550 wavelength. The result for the bow tie infiltration pattern is presented in Fig. 6a. We can see that the phase birefringence changes from $1.3 \cdot 10^{-5}$ to $9.5 \cdot 10^{-5}$ for "transverse x" orientation, and from $1.3 \cdot 10^{-5}$ to $-7.3 \cdot 10^{-5}$ for "transverse y" orientation. For the half infiltrated fiber we obtained higher change in birefringence up to $18.1 \cdot 10^{-5}$ and down to $-17.1 \cdot 10^{-5}$.

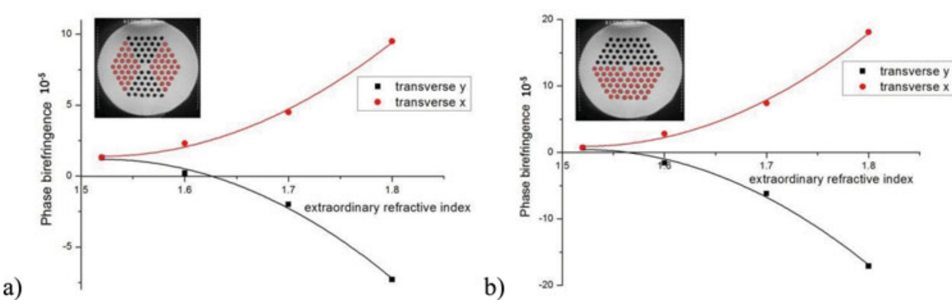

Figure 6. Phase birefringence as a function of extraordinary refractive index of LC molecules: a) bow tie b) half infiltration patterns (@1550 nm).

4. Conclusions

In this paper we have presented the numerical analysis of the phase birefringence in selectively infiltrated high-index glass photonic crystal fiber. We have proposed two different infiltration patterns. In the case of 5CB LC we report the presence of initial phase birefringence, in the range of $0.9 \cdot 10^{-5}$ to $1.8 \cdot 10^{-5}$ at 1500 nm. The highest birefringence was observed for half infiltration equal to $10.1 \cdot 10^{-5}$ and in this structure we can achieve the tuning of the phase birefringence up to $10.1 \cdot 10^{-5}$ or down to $-8.2 \cdot 10^{-5}$ depending on the direction of electric field.

The result for bow tie infiltration pattern shows great similarities with one row infiltration pattern. This suggest that the biggest influence on the phase birefringence have the air channels closest to the fiber core. The phase birefringence for different liquid crystals was also presented. The higher the extraordinary refractive index of the LC (or in other words closer to the index of the host fiber) result in the bigger phase birefringence tuning range.

In both types of analyzed fibers selectively infiltrated with LC the direction of the external electric field in a respect to fiber axis influences the phase birefringence of the fiber. This feature could be used in all-fiber sensors of the electric field to detect not only intensity, but also the direction of the field, i.e. a fiber totally filled with LC can be used for measurements of the intensity since a selectively filled fiber can be used for determination of the direction.

Acknowledgments

This work was supported by the National Centre for Research and Development in frame of the project LIDER/05/208/L3-11/NCiBR/2012 and by the European Union in the framework of European Social Fund through the Warsaw University of Technology Development Programme, realized by Center for Advanced Studies.

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