

Tunable properties of light propagation in photonic liquid crystal fibers

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Tunable properties of light propagation in photonic crystal fibers filled with liquid crystals, called photonic liquid crystal fibers (PLCFs) are presented. The propagation properties of PLCFs strongly depend on contrast between refractive indices of the solid core (pure silica glass) and liquid crystals (LCs) filling the holes of the fiber. Due to relatively strong thermo-optical effect, we can change the refractive index of the LC by changing its temperature. Numerical analysis of light propagation in PLCF, based on two simulation methods, such as finite difference (FD) and multipole method (MM) is presented. The numerical results obtained are in good agreement with our earlier experimental results presented elsewhere [1].

Keywords: liquid crystals, photonic band gap, optical fibers, photonic crystal fibers.

1. Introduction

Photonic crystal fibers have appeared as a new class of optical fibers which has revealed many interesting features successfully applied also to the sensing domain. A typical PCF consists of pure silica with a periodic distribution of air holes in the cladding. In PCFs, light can be guided either by effective index mechanism related to the modified total internal reflection (TIR) or through light confinement by the photonic band gap (PBG) phenomenon. The size and the location of the air holes allow for tailoring PCF parameters in a very wide range opening up possibilities for various applications. Moreover, propagation parameters of a PCF can be fine tuned when the air-holes are filled with different gases, liquids or solid materials (e.g., polymers).

The most interesting materials for filling the PCFs air-holes are liquid crystals due to the fact that these are materials with high optical anisotropy strongly dependent on external fields. In this way, we obtain a novel class of active optical fibers that can be called photonic liquid crystal fibers (PLCFs) [1–3]. As it was recently demonstrated [1–5], the PLCFs are very promising for a wide range of applications, such as variable optical attenuators, tunable filters, switches, sensors, and other devices applied to sensing and optical transmission systems. True understanding of LCs behaviour and molecular orientation inside very small capillaries is very important for understanding light propagation mechanisms in such structures. Moreover, methods for filling such thin capillaries are not trivial at all. The choice of the filling method resulting in a minimum amount of molecular orientation defects can be very crucial for the reliability of any potential PLCF-based devices.

The paper deals with the effect of the molecular orientation, by assuming effective refractive index value of the LC-inclusions n_{eff}^{LC} in the first stage of the numerical simulations. This assumption is also valorized with the preliminary experimental results as well as with those of Refs. 3, 4, and 5. In our analysis, the temperature dependence of the LC refractive index is considered. We assume that contrary to the electric field induced reorientation effect which has a threshold character, temperature causes smooth changes in the effective LC refractive index. In our analysis, the linear character of temperature influence of the effective LC refractive index changes is considered [10,11].

The analytical solution of the guided modes can be found only for selected types of optical fibers. For more complex waveguides such as PCFs, various numerical methods have been proposed. Many modelling techniques have been applied for PCF numerical characterization, including the plane wave expansion method (PWM), the multipole method (MM), the finite difference method (FDM) and others. In this paper, the propagation constants of guiding modes are numerically calculated with different techniques based on the multipole method (MM) (which also serves to calculate the confinement losses) as well as the finite difference scalar and vectorial methods. The experimental verifications of the mode solvers used are also briefly discussed.

2. Numerical simulation

Two methods were used to simulate light propagation in a PCF filled with a nematic LC. These are the finite difference and the multipole methods. The finite difference method [6] has the advantage of relatively simple formulation and numerical implementation. Most of conventional

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optical waveguides are designed to propagate well-confined guided modes with ideal real-valued propagation constants, calculation of leaky properties of waveguide modes having complex propagation constants has become more important due to recent intensive study on the confinement losses of photonic crystal fibers. Though finite-difference algorithms exist that can be applied to waveguides of arbitrary cross section, through stair casing and other approximations, it is known that high accuracy can only be achieved by the appropriate choice of equations for the particular problem geometry. Moreover, with FDM, the propagated modes are easily to find. In the multipole method [7,8], each dielectric boundary in the system is treated as a source of radiating fields. In current implementations for circular inclusions, the method achieves high accuracy and rapid convergence, with modest computational resources. Systems with large numbers of inclusions can be modelled, and for structures with discrete rotational symmetries the computational overhead is further reduced by exploitation of the symmetry properties of the modes. Disadvantage of multipole method is difficult in recognizing of propagated modes among many others obtained results. The numerical methods (FD and MM) mentioned above were chosen as complementary simulation tools allowing effective analysis of the propagation effects in the PLCF.

In our consideration, the silica glass index guiding photonic crystal fiber was used. The solid core surrounded by three rings was studied numerically. The main parameters of the PCF are the diameter $d = 4.8 \mu\text{m}$ and the hole's spacing $\Lambda = 6.5 \mu\text{m}$ (Fig. 1). Air holes of the PCF cladding region are filled with LC. In such a structure, the guiding conditions of the PLCF depend on the effective refractive index of the LC that can be easily tuned by the temperature or electromagnetic field.

Large variety of LC allows getting the mixture in which its refractive indices (ordinary and/or extraordinary) can be above or below the silica glass index for different temperature regions. Parameters of a prototype nematic liquid crystalline mixture (cat. no. 1550) manufactured at the Military University of Technology in Warsaw [5,9] was used in our theoretical investigations. The 1550 LC-mixture is composed of alkyl 4-trans-(4-trans-alkylcyclohexyl) cyclohexylcarbonates [5 (Table 2)]. Using LC-mixture is low birefringent liquid crystal with the phase transition temperature around 78°C . In the numerical simulation, we considered the PCF filled with a mixture with optical parameters corresponding to 1550 LC-mixture. For our analysis, the liquid crystal considered as a filling material can be characterized by the effective refractive index $n_{\text{eff}}^{\text{LC}}$ (Fig. 2) which is assumed as an average of the ordinary and extraordinary LC refractive indices [10,11]. The filling material which was used in the simulations and the experimental verification has the high thermo-optic coefficient $dn/dT \cong -7 \times 10^{-4} / ^\circ\text{C}$, which is 2–3 orders of magnitude higher than that silica glass (10^{-7} – 10^{-6}) [12]. Thus, we assumed that propagation properties of the photonic liquid

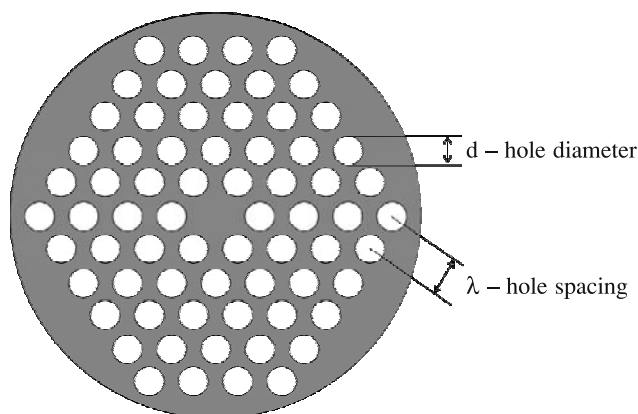


Fig. 1. Cross-section of the photonic crystal fiber (PCF) used as a host structure for LC-infiltration.

crystal fiber are mainly modified by temperature changes of the liquid crystalline material.

The analysis presented in the paper concerns a photonic liquid crystal fiber (PLCF) created by infiltrating one type of a PCF (Fig. 1), generally with 1550 nematic LC mixture discussed above. In such a structure, contrast between refractive index of the fiber core and the effective index of the cladding region determines the guiding conditions, which influence propagation constant, confinement losses and many others. The indices contrast can change with temperature. In our experimental investigation, the unpolarized white light source was used, that is why for numerical analysis we chose the wavelength range from 500 to 800 nm.

As it was demonstrated and discussed elsewhere [1], a solid-core index guiding photonic crystal fiber after filling with LC exhibits totally different propagation behaviour. While in the “empty” PCF, the light propagates by the modified total internal reflection mechanism, the same PCF filled with liquid crystalline materials may guide the light by the photonic band gap (PBG) effect for $n_{\text{eff}}^{\text{LC}} > n_{\text{SiO}_2}$ (silica refractive index) or by the index guiding mechanism if $n_{\text{eff}}^{\text{LC}} < n_{\text{SiO}_2}$. In case of PBG guiding mechanism, we observed propagation only within the spectral band, which corresponds to the photonics band-gap appeared in the cladding composed of periodically distributed LC-inclu-

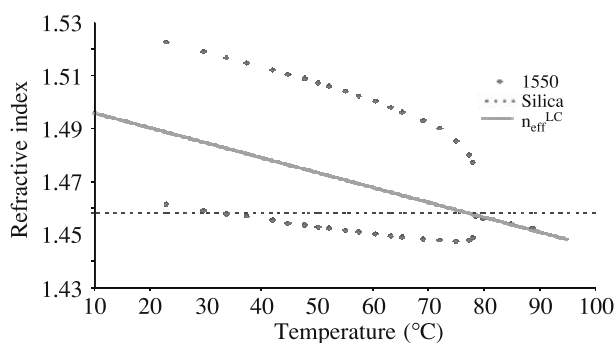


Fig. 2. Temperature dependence of the low-birefringence nematic LC effective refractive index (solid) and silica glass refractive index (dashed).

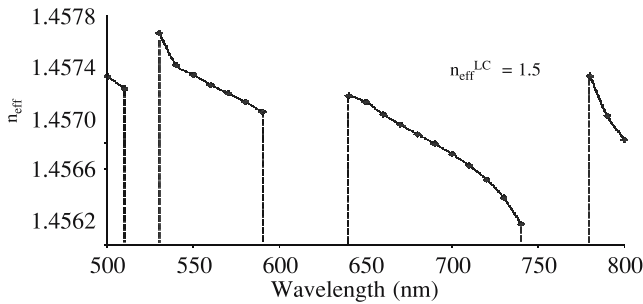


Fig. 3. Effective refractive index as a function of wavelength for fundamental mode propagating in the PCF filled with a nematic LC.

sions. When effective refractive index of LC is higher than that silica glass, the light is guided by the PBG mechanism, but with temperature the indices contrast diminishes and, consequently, the PBG effect disappears due to the matching between solid-core and cladding refractive indices. The transmitted spectrum fades out when the average refractive index of the cladding region is close to the silica core index. When the PLCF is heated further on, then propagation reappears, but now is governed by the TIR mechanism. In this way, the transition between both wave guiding mechanisms that are separated by a total lack of propagation is achieved. In our numerical simulations, we considered both TIR and PBG propagation effects.

The effective refractive index of the fundamental mode propagating by PBG effect in the PLCF as a function of wavelength is shown in Fig. 3. Every PBG shifts towards longer wavelengths with a decrease in the refractive index (Fig. 4). Moreover, the number of the PBGs increases with the refractive index as well as they become narrower (Fig. 5). Increasing refractive index contrast between the fiber core and the LC-inclusions induces stronger confinement of the light. For the effective LC refractive index, close to the silica glass index, a significant increase in the confinement losses is observed.

The simulation results concerning the light propagation, based on the TIR mechanism, are presented in Fig. 6–8. Effective refractive index of the fundamental mode propagating in the PLCF in function of wavelength is shown in

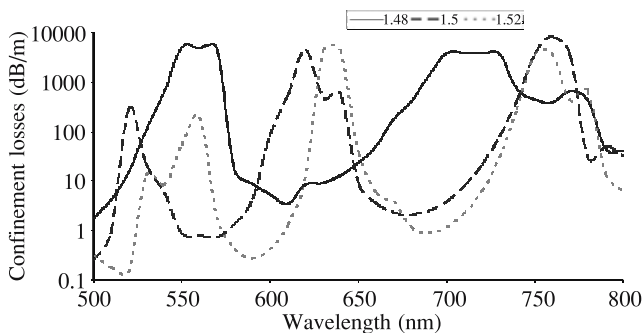


Fig. 4. Confinement losses dependence on wavelength for various LC-inclusions refractive indices close to the silica glass refractive index ($n_{\text{silica}} = 1.458$).

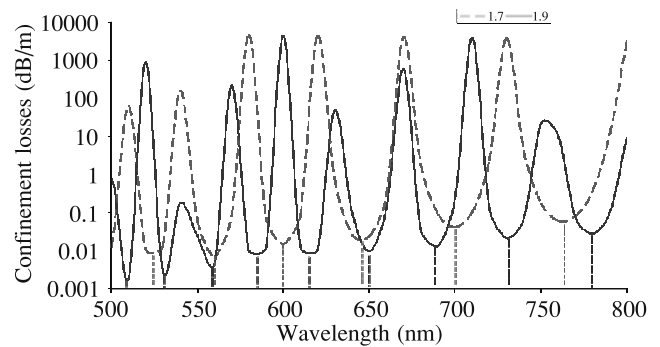


Fig. 5. Confinement losses as a function of the wavelength for LC refractive indices equal to 1.7, 1.8, and 1.9.

Fig. 6. The presented curves correspond to various refractive indices from 1.4 to 1.456, while the silica glass refractive index is considered to be constant and equal to 1.458.

In Fig. 7, the confinement losses vs. wavelength are shown for various effective LC refractive indices ($n_{\text{eff}}^{\text{LC}} = 1.450\text{--}1.456$). The threshold wavelength with respect to the confinement losses is observed. For shorter wavelengths, the losses are almost constant, while for the wavelengths longer than the threshold, the losses are increasing exponentially. For example, the curve corresponding to the LC effective refractive index $n_{\text{eff}}^{\text{LC}} = 1.452$ is flat for the wavelengths range 500–650 nm and then, after reaching the threshold value at 650 nm, the attenuation changes rapidly for 650–800 nm. The threshold moves towards the shorter wavelengths with an increase in the LC-inclusion effective refractive index. Depending on the structure and the filling material parameters, the broad-band or narrow-band variable optical attenuator (VOA) can be considered. In case of the index guiding mechanism in the PLCF for higher $n_{\text{eff}}^{\text{LC}}$ the broad band, VOA can be realized. However, in the case of smaller $n_{\text{eff}}^{\text{LC}}$, where threshold wavelength for confinement losses is present, the bandwidth of tunable attenuation is limited by the threshold wavelength. Moreover, in case

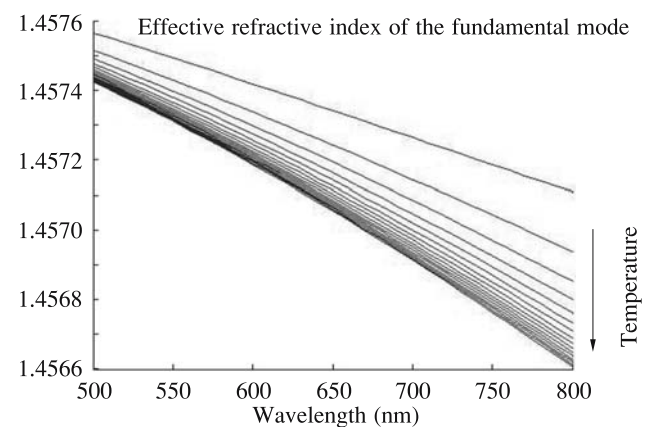


Fig. 6. Effective refractive index of the fundamental mode as a function of wavelength in the PCF filled with a nematic LC characterized by various effective refractive indices from 1.4 to 1.456 (refractive index of the silica glass is 1.458).

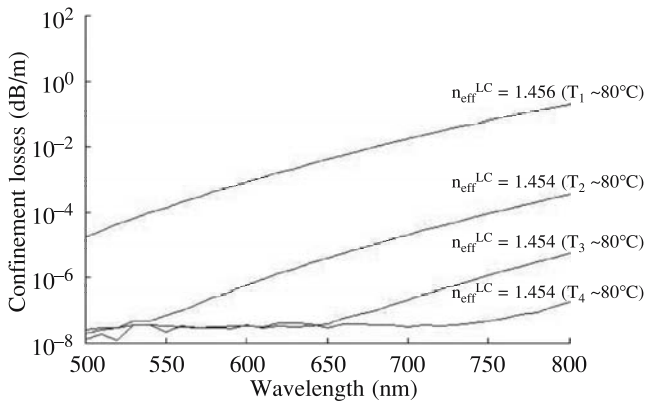


Fig. 7. Confinement losses in function of wavelength for various effective refractive indices of the LC-inclusions (refractive index in the range from 1.45 to 1.456).

of PBG guiding in the PLCF, a narrow-band VOA can be considered if the given narrow wavelength range is regarded.

Extremely large confinement losses modulation can be obtained for relatively small effective LC refractive index changes. The attenuation increase from 10^{-5} to 10^0 is caused by approximately 20°C temperature changes. The large number of the holes rings is the reason for the strong light confinement, and at the same time it allows broadening of the PLCF attenuation dynamics.

3. Experimental verification

The modification of propagation conditions by the thermo-optic effect of the PLCF is confirmed by experimental investigations that have been carried out at the Faculty of Physics, Warsaw University of Technology and published in details elsewhere [1,2]. The PLCF parameters used in both experimental and numerical analysis were the same.

In the experiment (Fig. 8), the visible light from broad band source was lead-in to the tested PLCF with the same “empty” PCF (without LC). The output signal was detected by the spectrometer. The PLCF was placed in the temperature controlling module, which allows small temperature changes.

The input light coupled to the PLCF was coming from the thermal depolarized white light source. There were neither polarizers nor analyzers used in the experiment. In consequence, polarization effects were not taken into account. Also, the assumption of effective refractive index of LC and perfect hexagonal symmetry of the fiber (non

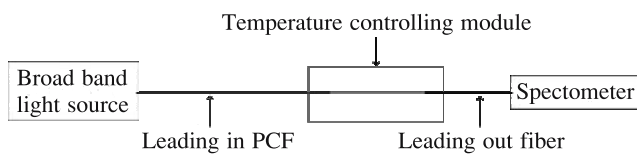


Fig. 8. Experimental setup for investigation of propagation properties of PLCF.

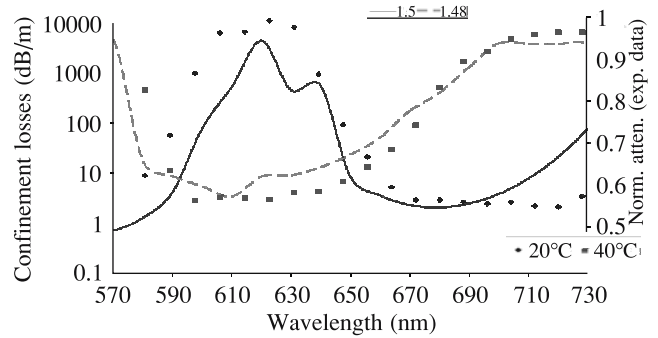


Fig. 9. Results of numerical simulations compared with experimental results presented elsewhere [1] for PBG guidance. Normalized attenuations are presented as a function of the wavelength for two temperatures around 20 and 40°C corresponding to $n_{eff}^{LC} \cong 1.48$ and 1.5, respectively.

birefringent fiber) structure allows us to neglect the polarization effects in simulations.

Spectral characteristics of PBG guiding mechanism are presented in Fig. 9, which shows a shift of PBG position influenced by temperature. That is why the evolution of the attenuation is not monotonic with temperature. Within the bandgap, the propagation losses are small and outside of the bandgap the losses are very high. Additionally, confinement losses depend on the refractive index contrast between LC and silica glass, which is again temperature dependent. The bands in which light can be guided, shift towards the shorter wavelengths with an increase in temperature. In the PBG regime, transition from strong confinement of light to high attenuation is obtained for temperature changes.

Further heating of the PLCF decreases the effective LC refractive index to the values lower than that of the silica glass. In this case, light propagation is based on the modified TIR mechanism. Normalized PLCF attenuation, as a function of the wavelength for various LC refractive indices was measured (Fig. 10). As one can see, the attenuation increase is caused by increase in the LC refractive index through decrease in temperature.

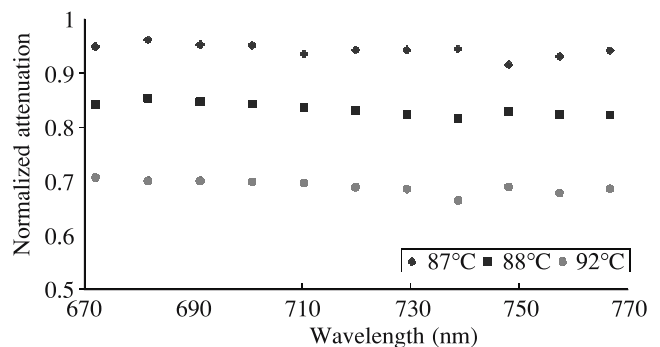


Fig. 10. Normalized attenuation in TIR regime as a function of wavelength for various temperatures: $\sim 87^\circ C \rightarrow n_{eff}^{LC} \cong 1.45$, $\sim 88^\circ C \rightarrow n_{eff}^{LC} \cong 1.449$, $\sim 92^\circ C \rightarrow n_{eff}^{LC} \cong 1.445$ (based on the experimental results reported in Ref. 1).

4. Conclusions

We have demonstrated the results of numerical simulations of PLCF propagation properties influenced by the thermo-optical effect of the nematic LC-inclusions. Both PBG and mTIR guiding mechanisms, that are typical for PCFs, were investigated. The presented numerical results are in a good qualitative agreement with the experimental data published elsewhere [1], what proves that the assumption of the effective refractive index of LC-inclusions n_{eff}^{LC} also proposed by Li *et al.* [10,11] is correct.

Moreover, the analyzed PLCF appears to be a great component of perspective optical all-fiber tunable devices. Potential applications of the tunable PLCF include variable optical attenuator, based on changes in confinement losses, tunable filters in which the photonics bandgaps are shifted with the effective refractive index of the LC changes, and also fiber-optic sensors and switches.

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