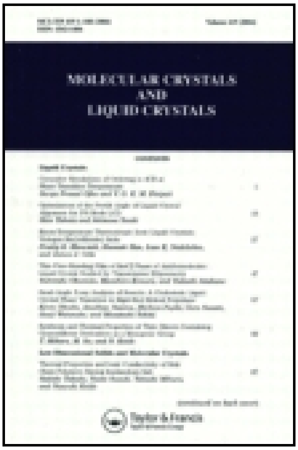

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Tunable Broadband In-Fiber Polarizer Based on Photonic Liquid Crystal Fiber

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In this paper a tunable broad-band polarizer based on the photonic crystal fiber (PCF) filled with liquid crystal (LC) is presented. Host PCF is made of glass with 1.518 refractive index and ordinary refractive index of the LCs is lower than glass index. Numerical simulations have proven that by changing LC orientation from planar to transverse a broad-band single-polarization guidance is possible: for planar orientation of LC molecules both polarizations are index-guided, whereas for transverse orientation only one polarization is index-guided. Also some initial experimental results are included showing that polarization dependent losses and phase birefringence can be tuned with transverse electric field.

Keywords: fiber optics; liquid crystals; photonic crystal fibers; polarization

1. INTRODUCTION

In the last few years a lot of research activities all over the world have been focused on Photonic Crystal Fibers (PCFs) with array of micro holes running along the axial direction. By changing position and diameters of the micro holes tailoring of many optical properties is possible in such fibers. Extraordinary performance (not possible in traditional fibers) has been recently achieved in PCFs, including

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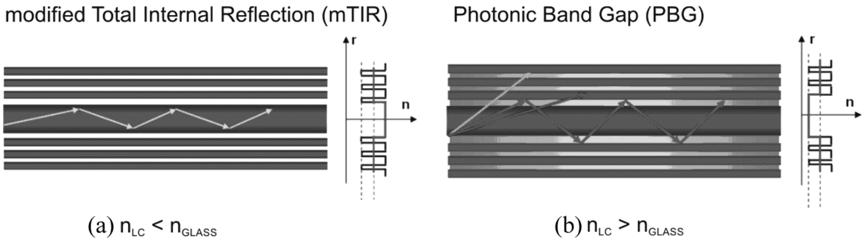


FIGURE 1 Guiding mechanism in LC filled PCFs.

single-mode behavior over many wavelengths, useful nonlinear properties and thermally independent birefringence [1].

Another way to change properties of the PCFs is to fill their holes with various materials. Infilling with substances which refractive indices could be modified by external factors opens up a possibility to create a new class of tunable all-in-fiber optical devices. Liquid Crystals (LCs) are particularly interesting for this purpose. PCFs infiltrated with LCs create a new class of optical fibers called Photonic Liquid Crystal Fibers (PLCFs).

Generally, there are two principal mechanisms which govern light propagation in the PLCFs. If refractive index of the filling liquid crystal is lower than index of the PCF glass, all wavelengths are guided within the core by the so-called modified Total Internal Reflection (mTIR – Fig. 1a). However if refractive index of LC is higher than glass index, only selected wavelengths can by guided due to the Photonic Band Gap (PBG) phenomenon.

Recently, thermally- and electrically-induced as well as all-optical tuning have been successfully demonstrated in the PLCFs [2–5]. Dynamic and temperature-induced switching between both: PBG and mTIR guiding mechanisms was demonstrated in [6], where in certain temperatures ranges the ordinary refractive index of the LC was either higher or lower than the silica glass index. It must be mentioned that usually PBG propagation is characterized by much higher losses than these observed in mTIR guidance.

2. IDEA OF THE BROADBAND TUNABLE PLCF-BASED POLARIZER

Tunable polarizers based on LC-filled silica PCFs have been already discussed [7–11]. Principle of operation of these devices relied on electrically-induced LC molecules reorientation: without electric field molecules were aligned mainly along fiber axis and both polarizations were guided. When a transverse electric field was applied to the fiber, LC molecules were reoriented and only one polarization was guided (Fig. 2).

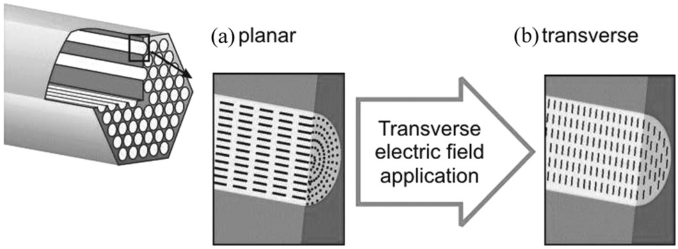


FIGURE 2 Planar and transverse LC molecular alignment.

Molecular alignment can be not only controlled by electric field, but also by using special aligning films on the micro-holes surface [12]. The main disadvantage of recently demonstrated polarizer based on silica PCF was that it worked only for selected wavelengths guided due to the PBG effect. In the silica-based PLCF, only PBG guiding is possible since refractive indices of most LCs are higher than the refractive index of the silica glass ($\sim$1.46). Besides that, the operating band of any silica-based PCF polarizer is limited to the PBG edges, there is also issue of significant losses resulted from PBG guidance.

In this work we propose a broadband tunable polarizer based on the PCF manufactured of glass with an increased refractive index value. Filling such a fiber with the LCs whose ordinary refractive indices are lower than the glass index allows for every wavelength to be guided by the mTIR mechanism. If LC molecules are oriented along the fiber Z-axis (planar orientation – Fig. 2a) both polarizations will be guided by the mTIR mechanism. However, if LC molecules are reoriented with E-field along Y-axis (transverse orientation – Fig. 2b), only the X-polarized mode will be guided by the mTIR mechanism. For the light polarized along Y-axis, the effective refractive index of the cladding will be higher than the refractive index of the fiber core and mTIR guidance will be no longer possible (assuming that the extraordinary refractive index of LC is higher than the glass index).

In this work we have decided to use a prototype PCF9C-6a micro-structured fiber fabricated at the Institute of Electronic Materials Technology (Warsaw). This fiber is made of the glass which refractive index is equal to 1.518 (at $\lambda = 589\,\text{nm}$). The PCF9C-6a fiber is a PCF with rectangular matrix of micro holes of the diameters between 450 and 550 nm. Its lattice constants in X and Y directions are 2.3 and 2.4 µm, respectively (Fig. 3).

To create a tunable polarizer the PCF9C-6a fiber should be filled with LCs whose ordinary refractive index is lower than 1.518. We have chosen two LC mixtures: 1550 and 1743 manufactured at Military

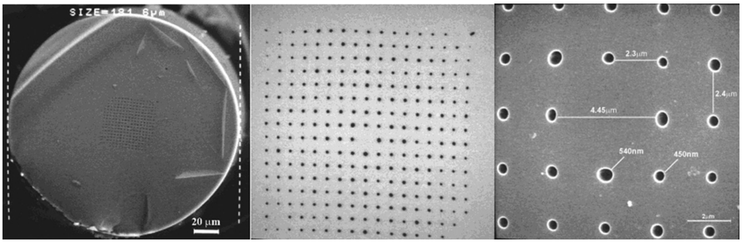


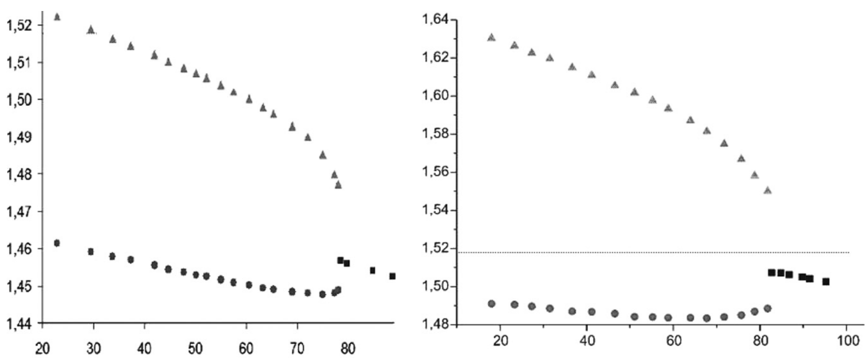
FIGURE 3 Cross-section of the PCF9C-6a microstructured fiber.

University of Technology (Warsaw). Thermal characteristics of their refractive indices are shown in Figure 4.

Numerical simulations based on the full-vector Finite Element Method (FEM) [13] proved that this choice of the PCF and both LC mixtures was fully justified.

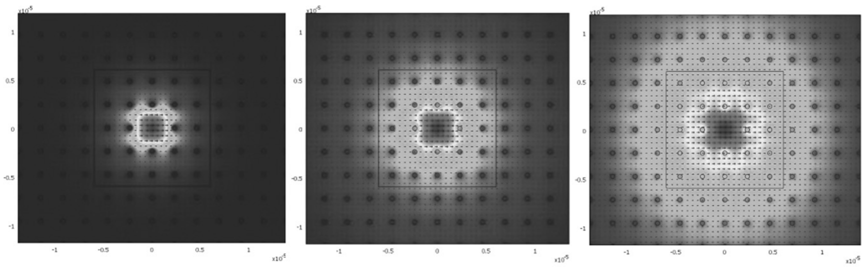
In the FEM simulations both planar and transverse molecular alignments were taken into account by defining a diagonal permittivity tensor of the micro-holes ε_{holes} (for planar orientation $\varepsilon_{holes} = \text{diag}\,[\varepsilon_o, \varepsilon_o, \varepsilon_e]$ and for transverse $\varepsilon_{holes} = \text{diag}\,[\varepsilon_o, \varepsilon_e, \varepsilon_o]$, where ε_o, ε_e are ordinary and extraordinary permittivities of the LC).

Figure 5 shows mode profiles of an empty PCF9C-6a fiber and of the same fiber filled with both LCs. It is evident that for the empty fiber the guided optical field is well located in the core area, but after LC infiltration this mode area is getting bigger. This behavior is a result of decreasing contrast between PCF and micro-holes refractive indices–the smaller indices contrast leads to the larger mode area and hence



(a) (b)

FIGURE 4 Thermal characteristics of used LC mixtures: (a) 1550 (b) 1743 (gray dotted line indicates the refractive index of the host PCF).



(a) empty PCF (b) PCF filled with 1550 (c) PCF filled with 1743

FIGURE 5 Simulated fundamental mode profiles at temperature 25°C for empty PCF9C-6a, and filled with 1550 and 1743 LC mixtures. It can be noticed that if contrast between core and holes indices is getting smaller the mode area is getting bigger, and thus modal losses are increasing.

optical field confinement in the core is weaker, thus modal losses also increase with decreasing contrast between refractive indices.

Table 1 compares calculated losses of the empty PCF9C-6a and of the fiber filled with both LCs of both: planar and transverse molecular orientations. As it was expected, a change in orientation (from planar to transverse) leads to single-polarization propagation. Since losses of the LC infiltrated PCFs are relatively high, short sections of the PLCF should be used as to construct a tunable polarizer.

TABLE 1 Calculated Losses of an Empty PCF9C-6a and Filled with 1550 and 1743 LC

Results @600 nm	Mode polarization	Effective index	Losses
Empty PCF9C-6a fiber	X – mode LP11x	1.516082	$2.8 \cdot 10^{-3}$ dB/m
	Y – mode LP11y	1.516081	$5.0 \cdot 10^{-3}$ dB/m
PCF9C-6a fiber filled with 1550 LC (planar molecules orientation)	X – mode LP11x	1.516814	9 dB/m
	Y – mode LP11y	1.516814	12 dB/m
PCF9C-6a fiber filled with 1550 LC (transverse molecules orientation)	X – mode LP11x	1.51681	10 dB/m
	Y – mode LP11y	no propagation of Y polarized modes in the core	
PCF9C-6a fiber filled with 1743 LC (planar molecules orientation)	X – mode LP11x	1.517211	37 dB/m
	Y – mode LP11y	1.517212	56 dB/m
PCF9C-6a fiber filled with 1743 LC (transverse molecules orientation)	X – mode LP11x	1.517209	38 dB/m
	Y – mode LP11y	no propagation of Y polarized modes in the core	

3. EXPERIMENT

3.1. Sample Preparation

Initially, the PCF9C-6a fiber was filled with a LC. Due to the small diameters of the micro-holes (~500 nm) the filling process was very slow – about 10 cm of the fiber required ~24 hours for infiltration. Capillary forces-induced filling was assisted by high pressure air: one end of the fiber was immersed in the hermetically sealed container with the LC mixture while high pressure air was pumped to the container.

Next, about 30–40 mm long sections of the LC filled PCF were capillary connected with two pieces of a standard single mode (SM) fiber. Finally, the capillary with the PLCF was placed between two flat electrodes (Fig. 6) and a distance between these electrodes limited by the capillary outer diameter was equal to 250 μm. A high-voltage amplifier connected to the electrodes allowed for continuous change of voltage from 0 to 1500 V, with frequency from 500 Hz to 10 kHz (voltage tuning was limited to 1000 V due to the electric discharges, so that maximum intensity of the electric field between 250 μm spaced electrodes was limited to 4 V/μm). Moreover, during measurements temperature of the electrodes was controlled by two Peltier modules.

A tunable laser (*Tunics Plus*) was used as a light source and changes in the output signal were analyzed by the *PAT9000B* polarimeter.

3.2. PCF9C-6a Filled with 1743

Measurements of the PLCF filled with the 1743 LC were somehow complicated because of significant attenuation of each of the samples. Losses originated from two main factors: first, the PLCF itself has quite big attenuation (see Table 1); and second, the mode profile of the PLCF does not match to the SM fiber mode profile and thus capillary connections induce considerable decrease in the output optical power. Few samples filled with the 1743 LC were measured and total

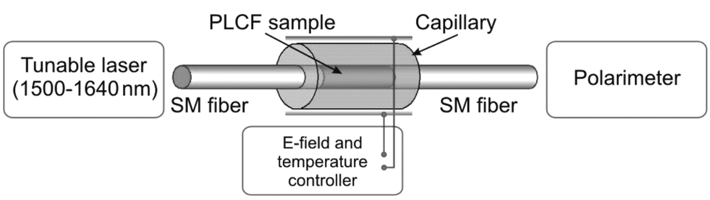


FIGURE 6 Experimental setup.

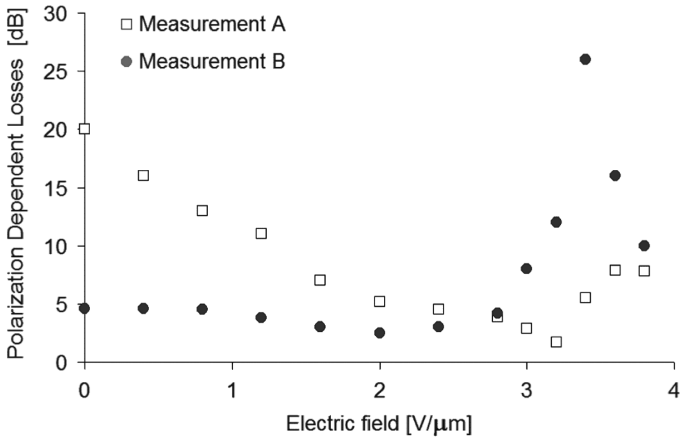
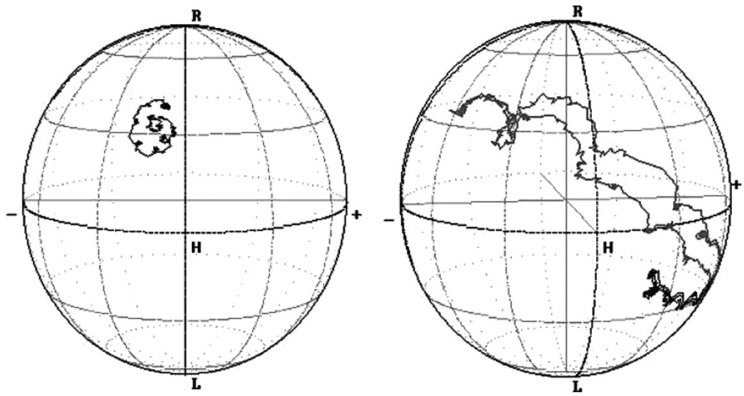


FIGURE 7 Examples of Polarization Dependent Losses tuning in the PCF9C-6a filled with 1743 (at temperature 25°C).

sample losses (between two ends of SM fibers) were estimated to be ~35 dB.

For all the PLCF samples filled with the 1743 LC an increase of the applied electric field resulted in changes in Polarization Dependent Losses (PDL). However these changes were very unstable and unrepeatable. Figure 7 shows exemplary PDL tuning with the electric field. For one sample, an increase of the electric field caused a fall of PDL (white rectangles), whereas for another sample, an initially low level of PDL reached the value of 27 dB when the field intensity was 3.5 V/μm (red circles). In an ideal model of a tunable in-fiber polarizer in the planar configuration (no field) PDL should be equal to 0 dB, whereas for the transverse configuration (high field intensities) it should be as high as possible. Practically, only few samples had low PDL without field and increasing PDL with arising voltage. This could be explained by an asymmetry in the PCF9C-6a microstructure—not only lattice constants are slightly different in x- and y-direction but there are also considerable fluctuations in the micro-holes diameters (see Fig. 3). This asymmetry may cause that even in the empty fiber significant PDL could occur. LCs infiltration may increase PDL, since molecular orientation may differ from one hole to another, especially if significant fluctuations of the holes diameters are present.

Non-zero PDL in the LC-filled PCF means that the effect of electric tuning may depend on the direction of the E-field: in some cases molecular reorientation may increase PDL, and in other may decrease it



(a) (b)

FIGURE 8 Examples of State of Polarization tuning (at temperature 25°C) in the PCF9C-6a filled with 1743 in two different samples: (a) small spiral changes (quite repeatable); (b) significant changes (with hysteresis).

(in second case, reoriented LC molecules "compensates" PCF asymmetry). Such dependence was observed experimentally: when samples were rotated axially between electrodes, the PDL tuning was different (Fig. 7).

Liquid crystal reorientation introduces changes not only in PDL, but also in the state of polarization (SOP) at the end of the sample. It is natural, because together with LC reorientation both effective indices of x- and y-polarized modes are being continuously changed, and eventually birefringence is also being continuously modified. Figure 8 shows examples of the SOP changes recorded on the Poincare spheres—similarly to PDL tuning, SOP changes also strongly depended on the field direction.

3.3. PCF9C-6a Filled with 1550

In the samples filled with the 1550 LC mixture total losses (between both ends of the SM fibers) were estimated to 20 dB and were lower than for the 1743 LC-filled samples because of two reasons: attenuation of the PLCF was smaller (see Table 1); and the mode area was smaller and better matched to the SM mode profile (however still capillary connection losses were significant).

Unfortunately in the 1550 LC-filled samples no noteworthy changes in the PDL value were observed when the electric field was increasing. There was still non-zero PDL without the electric field, however an increase in voltage has not resulted in the PDL changes.

More interesting effects were observed when SOP changes have been analyzed since continuous and stable changes of SOP were possible. An example of the SOP tuning in the 1550 LC-filled PLCF sample is shown in Figure 9. It's worth to notice that SOP changes strongly depended on the electric field frequency. The largest tuning was observed where the field frequency was equal to 7.5 kHz. Figure 9e shows that increasing voltage at this frequency resulted in almost circular trace on the Poincare sphere. It means that continuous phase changes between two polarization components of the guided mode were electrically induced (if the full circle would be marked it would be adequate to 2π phase change).

The phase difference between two orthogonally polarized components of the fundamental mode after propagation trough the highly birefringent fiber can be expressed as:

$$\delta\varphi = \frac{2\pi}{\lambda} BL \tag{1}$$

where B is the phase birefringence of the fiber and L is the length of the fiber. When the electric field is increasing only the phase birefringence of the PLCF is changing, so the phase difference will be modified

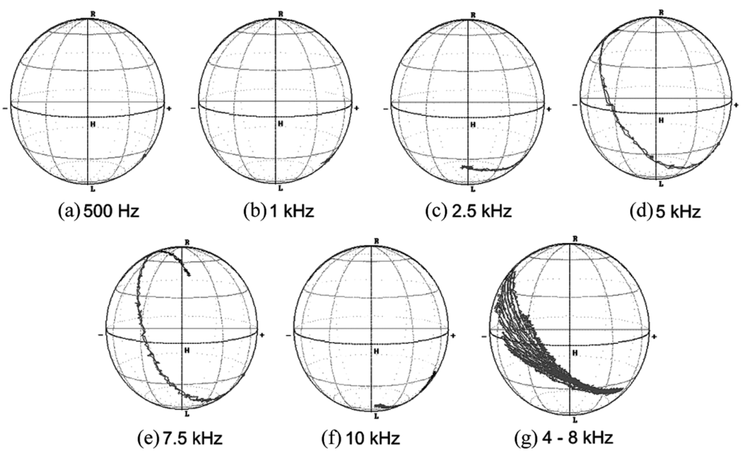


FIGURE 9 State of Polarization tuning in the PCF9C-6a filled with 1550. For each frequency electric field intensity was changed from 0 to 4 V/μm – largest tuning was observed at 7.5 kHz.

by the electric field as follows:

$$\Delta\delta\varphi(\Delta E) = \delta\varphi(E_2) - \delta\varphi(E_1) = \frac{2\pi}{\lambda}B(E_2)L - \frac{2\pi}{\lambda}B(E_1)L = \frac{2\pi}{\lambda}L\Delta B(\Delta E) \tag{2}$$

where ΔE signifies an increase of electric field from the values E_1 to E_2.

However $\Delta\delta\varphi$ (ΔE) can be easily measured from the Poincare sphere traces and thus the change of the PLCF phase birefringence ΔB can calculated by using following formula:

$$\Delta B(\Delta E) = \frac{\Delta\delta\varphi(\Delta E)}{2\pi}\frac{\lambda}{L} \tag{3}$$

It was already mentioned that for the 1550 LC-filled samples the largest tuning effect was observed when the electric field frequency was equal to 7.5 kHz. The graphs presented in Figure 9 was obtained for 34 mm length of the PLCF (tunable laser was set to 1570 nm). An increase of the electric field from 0 V/μm to 4 V/μm resulted in the $\sim 1.3 \cdot \pi$ phase change (Fig. 9e). In this case modification of the phase birefringence (calculated by using Eq. (3) was equal to $3 \cdot 10^{-5}$.

Another very interesting effect is presented in Figure 9g where few traces for different frequencies (from 4 to 8 kHz) were recorded. Here not only the arc length is being changed, but also an angular shift occurs (this effect was stable and repeatable). This behavior suggests that not only the threshold voltage is frequency dependent, but also LC molecules reorientation in slightly different at each frequency. This effect could be exploited in perspective tunable polarization controllers, in which any change in the electric field intensity and frequency would allow for any arbitrary SOP at the output.

3.4. Long Term Stability

In the context of potential applications long term stability is always a very important issue. Unfortunately, the PCF9C-6a fiber filled with both LCs was very sensitive for thermal fluctuations (example on Fig. 10). It is possibly caused by an asymmetry in the fiber microstructure which leaded to a non-zero birefringence. Both liquid crystal refractive indices strongly depend on temperature (see Fig. 4), so even small changes in temperature may significantly influence the PLCF birefringence. Strong sensitivity on temperature was observed experimentally when samples were heated – significant and uncontrollable changes in SOP were observed on Poincare sphere.

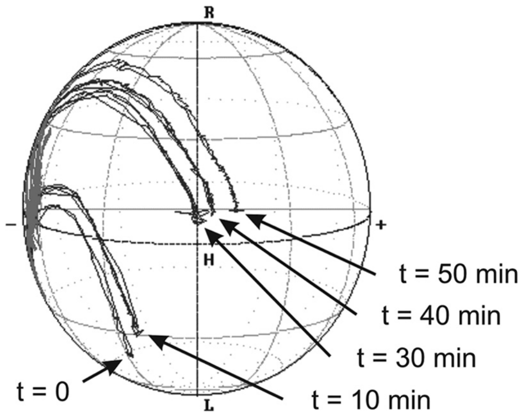


FIGURE 10 State of Polarization tuning in the PCF9C-6a filled with 1550 measured with some time intervals – due to the thermal fluctuations long term stability of SOP is low.

4. CONCLUSIONS

In this paper a broad-band tunable polarizer based on the PCF made of glass with 1.518 refractive index was proposed. Numerical simulations have proven that by changing LC orientation from planar to transverse we can obtain a single-polarization guidance. Unfortunately correlation between numerical predictions and experimental results is only qualitative. Although PDL tuning was observed in the 1743 LC-filled sample, the effect was very unstable and unrepeatable probably due to an asymmetry in the host PCF microstructure. Differences between theoretical predictions and experiment can be explained by two main factors. First is that the host PCF was not ideal (non-zero birefringence) and second is that the LCs mixtures used in experiment was relatively hard to reorient with electric field (relatively high threshold for the Fredericks transition).

However, it seems that a construction of a tunable broad-band polarizer is still possible if the host PCF structure will be further optimized. Low birefringence should be a main requirement for such a PCF, which means that its microstructure must be highly symmetrical. If the PCF refractive index would be around 1.65, a greater set of LC materials could be used, allowing for better control with the electric field. Also if the micro holes diameter would be larger (around 3–5 μm), the electric tuning should be more effective – in a smaller holes much higher voltages are needed for LC reorientation due to stronger impact of surface anchoring.

Tuning of SOP and a possibility to introduce a continuous change of phase birefringence observed in the PLCF samples filled with the 1550 LC suggest that the PLCFs could be potentially used not only as tunable polarizers, but also as effective polarization controllers or polarization mode dispersion compensators. Further experiments and optimizations procedures are still in progress.

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