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DYNAMICALLY TUNABLE BIREFRINGENCE IN PHOTONIC LIQUID CRYSTAL FIBERS

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Abstract − The paper discusses polarization phenomena occurring in highly birefringent (HB) solid-core photonic liquid crystal fibers (PLCFs) based on the commercially-available HB *Blazephotonics* photonic crystal fiber (PCF) and a high-index-glass PCF manufactured by the Institute of Electronics Materials Technology ITME (Poland), both infiltrated with liquid crystals (LCs). We report on the latest experimental polarization characteristics of the host PCFs filled with prototype guest nematic LCs characterized by either extremely low (of the order ~ 0.05) or medium (of the order ~ 0.2) material birefringence. Due to anisotropic properties of the microstructrured PLCFs switching between different guiding mechanisms due to electrically and/or temperature-induced dynamically tuned birefringence has been demonstrated. These results hold great potential for both fiber-optic sensing and in-fiber polarization mode dispersion control and compensation.

Keywords: polarization, birefringence, photonic crystal fiber, liquid crystal

1. INTRODUCTION

Optical fibers exhibit particular polarization properties [1, 2]. Contrary to ordinary plane waves in bulk media which amplitudes are constant in the wave plane, guided electromagnetic fields in optical fiber waveguides are called inhomogenous plane waves since their amplitudes are not stable any more within the plane wave and the fields are characterized, in most cases, by non-transverse components. In the description of polarization phenomena in optical fibers there are generally two approaches. The first one treats an optical fiber as an optical waveguide in which light can be guided in the form of waveguide modes. This approach identifies basic polarization eigenmodes of a fiber and relates them to the polarization state of the guided light. Changes in output polarization are described in terms of polarization-mode coupling due to birefringence changes acting as perturbations along the fiber. Another approach treats an optical fiber like any other optical device, which transmits light and the fiber, can be divided into separated sections behaving like polarization state shifters. Here, polarization evolution in a fiber can be described by one of the three general formalisms: by the Jones formalism, by the Stokes-Mueller formalism, or by the Poincaré's sphere representation.

Anisotropic optical fibers have been extensively investigated for over the last two decades [1]. This includes also an elliptical liquid crystal-core fiber infiltrated with a nematic liquid crystal (LC) mixture characterized by extremely low values of refractive indices that can exhibits single-polarization behavior at a certain temperature range [3]. Recently, there has been a great interest in microstructured photonic crystals fibers and particularly in yet more advanced micro-structures known as photonic liquid crystal fibers [4]. The photonic liquid crystal fiber consisting of a PCF filled with a LC benefits from a combination of a passive PCF host structure and an "active" LC guest material being responsible for diversity of new and uncommon properties.

2. EXPERIMENTAL SETUP AND MATERIALS

To investigate polarization phenomena we used two different fibers: a commercially available highly-birefringent *Blazephotonics* PM-1550-01 photonic crystal fiber (HB PCF, see Fig.1a) and a high index glass PCF made by Institute of Electronics Materials Technology ITME (Poland) (Fig.1b) that served as the hosts fibers to be infiltrated with liquid crystals. The geometrical parameters of the HB PCF are as follows: pitch (spacing between neighboring holes) Λ = 4.4 μm, large holes diameter d_H = 4.5 μm, small holes diameter d = 2.2 μm, and diameter of the holey region D = 40 μm. The PLCF manufactured on the basis of the *Blazephotonics* PM-1550-01 fiber had only two large holes infiltrated with liquid crystals. The geometrical parameters of the second fiber (made by ITME) are as follows: pitch (spacing between neighboring holes) Λ = 7.6 μm, holes diameter d = 5.2 μm, and diameter of the fiber D = 125.4 μm.

The experimental setup for investigation of propagation and polarization properties of the PLCFs is shown in Fig. 2. In the case of the *Blazephotonics* PCF we used a ~50 cm long photonic crystal "host" fiber in which only a short section (L_{PLCF}~10÷30 mm) was filled with the guest nematic LC by using capillary forces. By temperature-induced collapsing in a conventional fusion splicing machine we were able to infiltrate selectively two large holes on both sides of the PCF core with the LC. After filling with the LC the whole collapsed region of the PCF was cut off. In the second case we used a 16 cm long high index glass-based photonic crystal "host" fiber also infiltrated (capillary forces) with the guest nematic LC.

The input light from a tunable laser source (*Tunics Plus CL*) operating at third optical window (spectral range 1500÷1640 nm) was coupled into an empty section of the HB PCF. The terminal section of the PCF filled with LC i.e. the PLCF under investigation was placed between electrodes. The electrodes were plugged to a high-voltage source, which allowed for controlling both voltage from 0V to 1000V and frequency from 200 Hz to 2 kHz. The output optical signal coming out of the PLCF was analyzed by the measurement apparatus that included a modular PAT 9000B polarimeter (*Tektronix*). The PLCFs were thermally controlled by a temperature stabilization device.

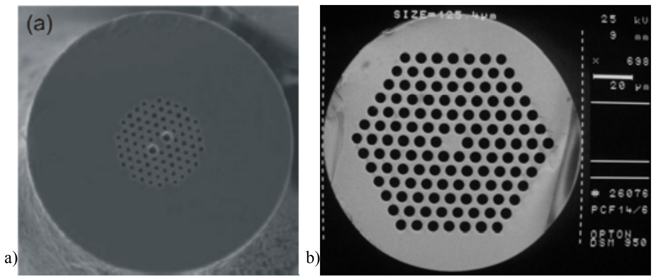

Fig. 1. Cross section of the *Blazephotonics* PM-1550-01 HB fiber (a) and high index glass based PCF made by ITME (b).

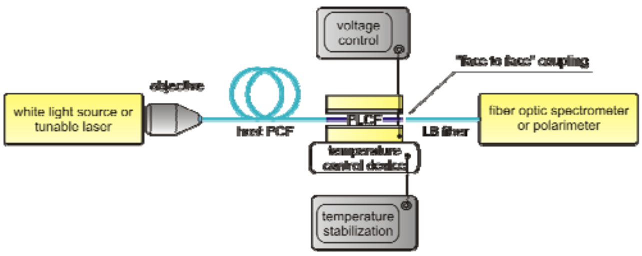

Fig. 2. Experimental setup for investigation propagation and polarization properties of the PLCF.

As guest materials, we used nematic liquid crystals that were characterized by different optical anisotropic properties: extremely low, and medium material birefringences. Low-birefringence prototype LC mixtures 1110 and 1550 were manufactured at Military University of Technology (MUT) in Warsaw, Poland. Temperature dependences of their refractive indices (at 589 nm) are shown in Fig. 3a. Main difference between 1110 and 1550 mixtures is clearing temperature, which are 40.6°C and 78°C respectively. Those LC mixtures are especially interesting for silica glass fibers infilling, as their ordinary refractive index in specific temperature ranges is lower than refractive index of silica glass. A typical nematic liquid crystal PCB (4'-n-pentyl-4-cyanobiphenyl) was chosen as the material with medium birefringence. Thermal characteristics of refractive indices for PCB at the wavelength λ=589 nm are shown in Fig. 3b.

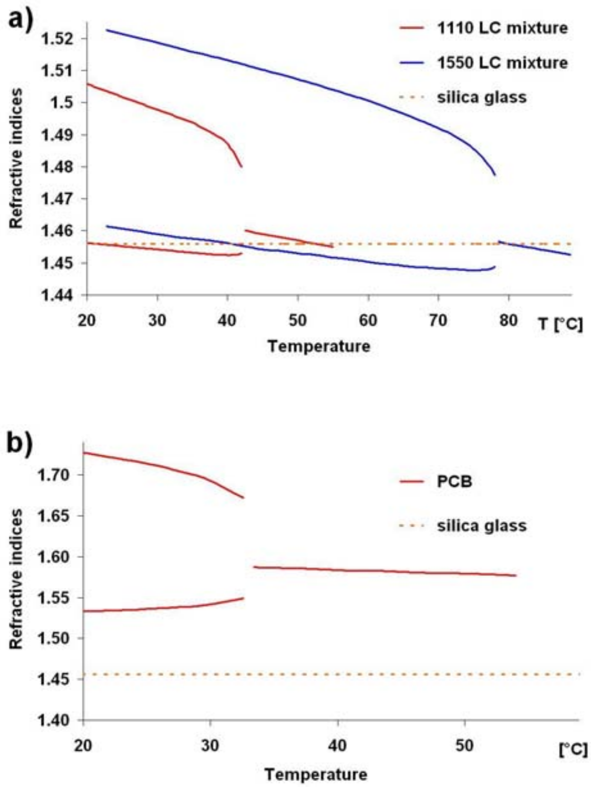

Fig. 3. Refractive indices as a function of temperature for LC mixtures: with low-birefringence 1110 and 1550 (top) and for PCB (bottom).

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 by the electric field as follows:

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

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

However $\Delta\delta\varphi\,(\Delta E)$ 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:

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

3. POLARIZATION PROPERTIES

A photonic crystal fiber infiltrated with a liquid crystal significantly changes its guiding properties. Any change in the refractive index value of the LC within the holes allows for significant changes in the modal field and therefore also in optical properties of the fiber. Recently [5,6], we have observed generally a planar LC molecular alignment within the holes. If two large holes only of the HB *Blazephotonics* PCF are infiltrated with the 1110 (or1550) LC mixture, their refractive index n_H can be smaller than the refractive index of the fused silica ($n_H < n_{silica}$) and the light in the fiber solid core propagates by the modified Total Internal Refraction (mTIR) mechanism. However, if $n_H > n_{silica}$, the fundamental mode splits into two "new" LC cores; hence switching from a single-core fiber to a two-core fiber is possible. Simultaneously, for the $n_H > n_{silica}$ regime higher order modes can be still guided in the "old" solid core. This suggests that a higher order mode in the PLCF was guided.

Experimental results of polarization properties of the PLCFs in which only selected micro holes were filled with nematic liquid crystals were presented elsewhere [5] suggest that the shape of the propagation mode profile was changed. It means that birefringence axes rotate. The "fast" axis of the PCF corresponds to the "slow" axis of the PLCF.

Any change in the value of refractive index of a nematic liquid crystal (NLC) within the large holes allows for significant changes in the modal field and therefore also in optical properties of the fiber. Assuming the value of the NLC refractive index within the holes in the range 1.42 - 1.55 we have numerically calculated effective refractive indices n_{eff} of the modes propagating in the PLCF. The effective refractive index denotes the refractive index of the light "seen" by a selected fiber mode propagating in the PLCF. Each fiber mode is characterized by its own value of n_{eff} that directly connected to the mode propagation constant $\beta = kn_{eff}$ (k – wave number). For guided modes β is real and restricted to the range

$$k_{cl} \le \beta \le k_{co} \quad (3)$$

where $k_{cl} = 2\pi n_{cl}/\lambda$, $k_{co} = 2\pi n_{co}/\lambda$, n_{co} is the maximum refractive index of the core, and n_{cl} is the refractive index of the cladding.

The results demonstrate that the effective refractive index of the propagation modes increases with the refractive index of the holes and the refractive index of the NLC is larger than that of the fused silica of the core. It means that transition from single (n_{eff} = 1.43548) to double-core (n_{eff} = 1.45) propagation occurs and higher-modes propagation is possible. For LC mixture refractive index range in the PLCF the propagation of the higher order modes was obtained. From the application point of view temperature tuning of birefringence is not the best solution.

Additionally as was presented in our previous paper [6], this PLCF behaves as single polarization fiber under the influence of an external electrical field. In the off-voltage state the PLCF was almost insensitive to polarization due to the planar alignment of the molecules in the holes was obtained. In the high-voltage state, the PLCF becomes highly sensitive to the input linear polarization, as the reorientation of the LC molecules resulted in a significant anisotropy of the PLCF cross-section.

To reduce attenuation at the single-mode regime a high-index-glass PCF manufactured at the Institute of Electronics Materials Technology ITME (Poland) was proposed and infiltrated with a medium-birefringence LC. Typically in silica-based PLCFs, photonic band-gap (PBG) propagation is observed, since refractive indices of most LCs are higher than silica index [6, 7]. The losses of PBG modes are much higher than for index guided modes (see Fig. 4).

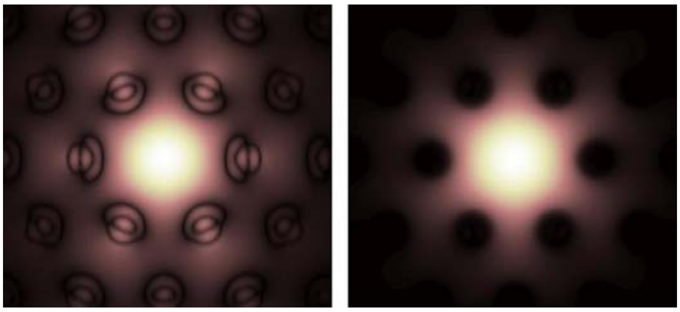

Fig. 4. Depending on LC refractive index n_{LC} PBG ($n_{LC} > n_{PCF}$ – left picture) or index-guided ($n_{LC} < n_{PCF}$ – right) modes can propagate in LC-filled PCF. Confinement losses of the index-guided mode are about six orders of magnitude lower than for the PBG mode.

Figure 5 presents evolution of the state of polarization (SOP) in the 16-cm long PLCF, in which 12-cm section was placed between two flat electrodes. A voltage increase caused reorientation of the LC molecules, and consequently an increase of the PLCF birefringence. The change in SOP observed for 330V corresponds to the continuous change in the phase birefringence of ~ $2 \cdot 10^{-5}$.

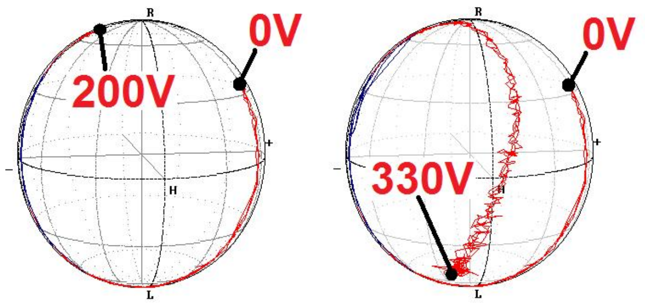

Fig. 5. SOP evolution in the high-index PCF filled with 5CB.

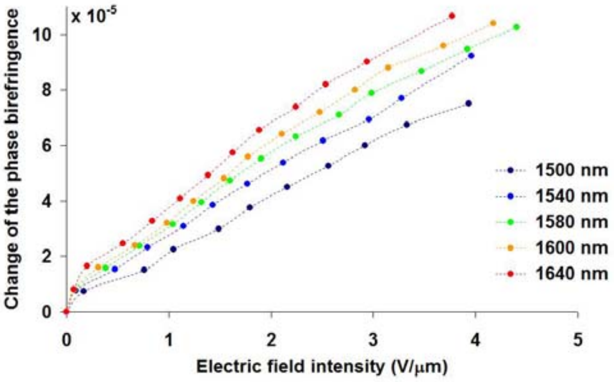

Fig. 6. phase birefringence as a function of the external electric field.

Figure 6 presents calculation results of the phase birefringence by using the formulae (1). The phase birefringent in an initially isotropic fiber is induced by electric field-induced reorientation of the LC molecules in the PCF holes.

4. CONCLUSIONS

Photonic liquid crystal fibers benefiting from a merge of passive photonic crystal fiber host structures with 'active' liquid crystal guest materials create a new challenge for both fiber optics and liquid crystal photonics. They introduce new levels of tunability to the photonic crystal fibers – the 'hot topic' of modern fiber photonics and boost performance of these fibers due to a diversity of new and uncommon propagation and polarization properties.

In particular, we have demonstrated the latest results on polarization properties of the PLCFs. It was demonstrated that the high change of the phase birefringence can be achieved in two ways: either by application of an external electric field, or by using an anisotropic host PCF to be infiltrated with LCs. It has also been shown that thermal birefringence tuning is possible in the PLCFs based on highly birefringent PCFs and on low-birefringence LC mixture.

Due to anisotropic properties of the microstructrured PLCFs switching between different guiding mechanisms as well as electrically and temperature-induced dynamically tunable birefringence have been demonstrated. These results hold great potential for both fiber-optic sensing and in-fiber polarization mode dispersion control and compensation.

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