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Electrically tunable chiral nematic liquid crystal photonic crystal fibers

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Liquid crystal photonic crystal fibers (LC-PCFs) are a new class of optical waveguides. We found that chiral nematic liquid crystals, infiltrated in photonic crystal fibers, allow an effective electrical control of such optical waveguides. An optical method for measurement of the bandwidth of the reflection spectral band (expressing the bandgap of the LC-PCF) is presented. We succeeded in achieving an effective driving of the helix axis alignment at a diversity of electric field magnitudes and frequencies.

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1. Introduction

Photonic crystal fibers (PCFs) are fibers with an internal periodic structure made of capillaries (forming a hexagonal lattice), filled with air. These fibers present a new class of optical waveguides.

The hexagonally ordered holes actually provide the wave guidance in different ways [1-3]. On the one hand, PCFs can act to depress the average cladding refractive index, so that light escaping the core has to tunnel through an equivalent low-index layer. On the other hand, being arranged in a regular 'photonic' lattice they can provide destructive interference for a certain wavelength region and "forbid" the light propagation in the cladding. Therefore, there are two different mechanisms for PCF performance: the index-guiding effect (similar to the one in classical optical fibers) [4,5] and the photonic bandgap (PBG) effect [6,7].

Recently, the possibility of an active control of optical waveguiding of the PCFs has attracted a lot of interest, especially by making use of liquid crystals (LCs) [8]. Such active control is possible because of the very existence of the air holes in the PCF; introducing LC material into these air holes can strongly influence the light propagation. Thus one realizes Liquid Crystal Photonic Band Gap Fibers (LC-PBGF). Depending on the refractive index of the LC, the guiding effect of the fiber can possibly be changed from guiding based on modified total internal reflection (mTIR), to guiding based on the PBG.

Electrical tunable fiber devices were achieved using external applied electric fields to reorient the LC [9,10]. This resulted in a high anisotropy in the cross-section of the PCF.

For the effective using of LC-PCF, as a hopeful alternative to both conventional and PCFs, two basic operations must be done: the infiltration of the PCF with the LC and in turn a stabilization and detection of the alignment of the confined LC.

Our goal is to select LC substances with suitable material constants, like refractive indices, dielectric permittivity, electroconductivity, chirality etc, in order to realize an effective tunable optical waveguide. We used a chiral LC for an effective electric driving of the PCFs.

2. Materials and liquid crystal infiltration

The chiral nematic (N^*) LC was realized by the mixing of 3.5 weight % cholesteryl benzoate (CB) (displaying a cholesteric phase) with E7 LC. The mixture has two phase transitions: solid $\rightarrow N^*$ with temperature $T_{SN*} = -20°C$ and $N^* \rightarrow$ isotropic with temperature $T_{N*I} = 69°C$. The extraordinary and ordinary refraction indices of E7 are $n_e = 1.737$ and $n_o = 1.5185$ at 633 nm and 20°C. The dielectric anisotropy of E7 (ε_a) is ≈ 13. We expect the birefringence to be $\Delta n = n_e - n_o$ and the dielectric anisotropy ε_a of the mixture to be close to those of E7.

The N^* LC was infiltrated into the PCF using pressure infiltration [11,12].

The cross section of the used PCF structure is shown in Fig. 1.

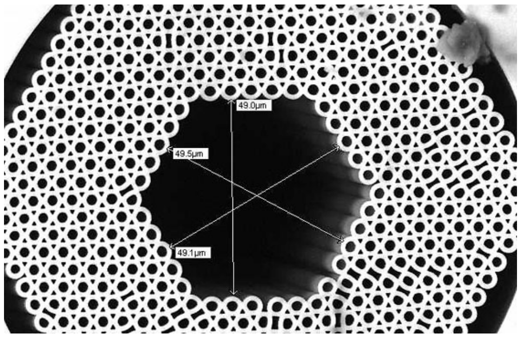

Fig. 1. Optical micrograph of the end facet of the PCF. The PCF's outer diameter is ~ 13.3 µm, and the inner one is ~ 3 µm. The inner core diameter is ~ 49.2 µm.

3. Analysis of the electro-optical properties of capillaries infiltrated with chiral LC

Generally, chiral LCs self organize to give a macroscopic helical structure that exhibits a PBG, provided that the circularly polarized incident light with wavelength of the order of the helical pitch could be (depending on its handedness-right or left) transmitted or reflected respectively. The simplest LC phase to form a PBG structure for the reflected circular polarized mode is the N^* phase, where the director ***n*** (the average molecular orientation) precesses orthogonally and continuously around a single direction, giving a helical structure (Fig. 2). One full rotation of ***n*** around the helix axis describes the pitch of the helix, although the structure repeats itself over a distance equal to half the pitch (the period) because of the inversion symmetry of ***n***: ***n***=–***n***. Since the periodicity exists in only one direction (i.e. along the helix axis), the PBG also only exists in the same unique direction.

The optical properties of the chiral medium are modulated with a spatial period $L = p/2 = \pi/q_o$ (q_o – wave vector).

This may, in principle give rise to Bragg reflections, provided that $2L=m\lambda$ (m – integer). Experimentally, one does observe one Bragg reflection (m = 1). The higher order reflections (m= 2, 3,…) are forbidden for normal incidence. In the case of oblique incidences all orders (m=1,2,3,..) are observable.

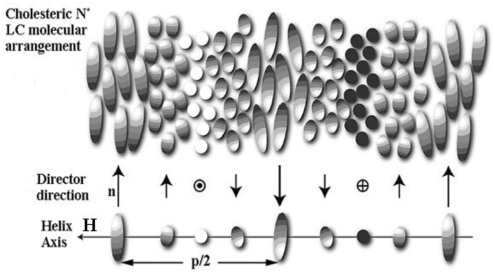

*Fig. 2. Schematic of the molecular configuration of one full pitch p of a chiral nematic LC, showing the director **n** and the helix axis H.*

Linearly polarized light that is incident parallel to the helix axis of N^* can be considered as two circularly polarized waves with opposite handedness. A PBG occurs for the circular polarized mode that matches the rotation sense of the helix when the wavelength is of the order of the pitch. For the other circular polarized mode with opposite sense handedness, the light is transmitted.

For the transmission at arbitrary wavelengths (normal incidence) the Mauguin limit is important. In this limit ($\lambda << p\Delta \boldsymbol{n}$) the uniaxiality is still correct.

Measurement of the transmission (or reflection) spectrum defines the PBG, where the decrease (or increase) in light intensity indicates the range of wavelengths forbidden to propagate. The bandwidth of the reflection band $\Delta\lambda$ is proportional to both the helix pitch p and the birefringence Δn ($\Delta\lambda = \Delta n.p$).

The chiral smectics C (S_{C*}) are more interesting LCs, since their relaxation times are very short (≈50 μs). The S_{C*} materials exhibit a helical structure and consequently an uni-dimensional PBG. We will use these materials in our future investigations.

In order to realize electric driving, we inserted the LC-PCF between two glass substrates covered with an ITO semitransparent layer (serving as an electrode). By polarized microscopy analysis, we determined the helix (H) alignment (with respect to the fiber single hole axis) in the case of planar orientation. The chiral LC mixture, because of its large value of ε_a, displayed strong dielectric reorientation (a Freedericksz's transition). The dielectric reorientation expressed the helix axis H (director ***n***) rotation around the fiber axis. In this way, we succeeded in achieving effective control of the H alignment at a diversity of electric field magnitudes and frequencies.

In order to achieve microtextural polarization analysis of the LC-PCF, we measured the intensity I^{tr} of the transmitted light, by means of a photodiode in various optical configurations (i.e. of the mutual orientation of the polarizer **P**, the analyzer **A** and the 'easy' LC direction imposed by capillary flow during the LC infiltration). We used the case **A⊥P**, (**n**^**P**) = 45°, where the transmitted light intensity is a maximum (see [13,14]) as indicated in Fig. 3. This figure presents the polarized micrograph of the mixture inside a PCF hole.

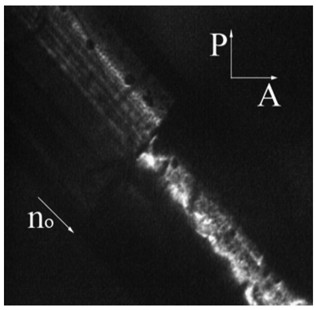

Fig. 3 The polarized micrograph of the infiltrated capillaries.

We realized the planar homogeneous orientation (coaxial with the fiber axis) using the method of the capillary infiltration. In this case, we observed a cholesteric texture consisting of cells surrounded by oily streaks (bundles [15]). By applying an a.c. or d.c. electric field, we observed the cells to change colour from green to red. This indicates that the helix axis direction is rotated by the electric field. We indicated two kinds of helix alignment imposed by the electric field: perpendicular or oblique with respect to the fiber axis. In the case of homeotropical initial orientation of the chiral mixture (***n*** is perpendicular to the fiber capillary axis) we observed a striped texture typical for the cholesteric substance. This texture indicates that the H direction is coaxial with the fiber axis orientation. Applying the electric field we observed that the texture colour changes and the stripe period (L) increases. We interpret this effect as a H rotation from parallel to oblique, with respect to the fibre axis. We measured the pitch p values versus the electric field magnitude and frequency. We also estimated the reflection light bandwidth Δλ, taking account of the restriction that the electric field magnitude has to be lower than that which provokes the electric coherence length $\xi=(K_{22}/\varepsilon_a)^{1/2}/E$ (K_{22} – twist elastic constant). This restriction is important, since above a critical field E_c $p \to \infty$ and we obtain a $N^* \to N$ structure transition. Thus, we can control the electric field dependence of the bandwidth of the reflection band Δλ. At a fixed temperature (65°C), we estimated Δλ ≈ 400 nm (for Δn = 0.2 and p ≈ 2 μm).

In Fig. 4 we indicate the threshold (H rotation onset) frequency trend in the planar case. We found the minimum (2.3 V for 2 kHz) of the electric voltage that ensures suitable driving.

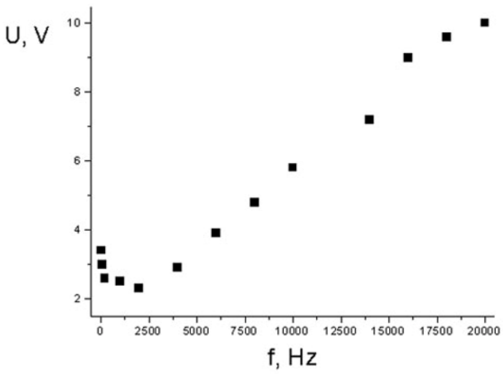

Fig. 4. The frequency threshold for the H rotation characteristic at a planar orientation of the mixture.

4. Conclusion

We have indicated that the chiral nematic LC is an effective medium for the realization of electrically controllable LC-PCFs. The minimum of the applied electric voltage, ensuring suitable driving, was determined. We estimated the reflection light bandwidth expressing the bandgap of the photonic crystal fibers. An electric driving of the helix axis alignment was achieved.

Acknowledgements

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