Tunable properties of Liquid Crystal filled Photonic Crystal Fibers

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ABSTRACT

The electronic tunability of ferroelectric liquid crystal filled photonic crystal fibers is experimentally demonstrated in the wavelength range of 1500 nm – 1600 nm. The tunability is achieved by applying electric field onto the ferroelectric liquid crystal infiltrated photonic crystal fiber. Tuning of the fiber propagation properties is achieved due to re-orientation of ferroelectric liquid crystal molecules on the application of the applied electric field. Such fibers could find applications in the fabrication of fast, low loss, cost effective and highly efficient in-fiber tunable devices to be used in the telecom wavelength range.

Keywords: Liquid Crystals, In-fiber tunable devices, Photonics Crystal Fibers, Liquid Crystal Infiltration

1. INTRODUCTION

Photonic Crystal Fibers (PCFs) have been under intense study recently since they offer a promising alternative to conventional fibers for a wide range of applications in telecommunications and sensing. The typical air-hole lattice structure of photonic crystal fibers provides the advantage of the tailoring of their propagation properties, which can be utilized for the fabrication of in-fiber tunable devices. In general, PCFs guide light either by total internal reflection (TIR) or photonic bandgap (PBG) effect, depending on the fiber structure. For the TIR-guiding fibers, the refractive index of the core is higher than that of the cladding. Therefore the guiding mechanisms are similar to conventional fibers. In the case of PBG fiber, light of certain wavelength band is confined in the low-index core by full two dimensional photonic bandgap effect [1]. The propagation parameters of the PCF can be fine tuned when the air-holes are filled with external-field dependent materials. Exploiting the highly extended access provided to the light guidance through PCFs, researchers have previously demonstrated various in-fiber tunable devices by infiltrating them with high-index liquids, polymers [2, 3].

One of the most interesting materials for filling the air-hole of a PCF are liquid crystals due to the fact that these are materials with high optical anisotropy strongly dependent on external factors. Liquid crystals are much favored optoelectronic materials on account of easy tunability of their properties with pressure, temperature, electric fields and magnetic fields. The refractive indices of these materials can be easily modified either by temperature or by external fields. Photonic crystal fibers infiltrated with liquid crystals have emerged as a new class of optical fibers commonly called Photonic liquid crystal fibers (PLCFs) [4]. Researchers have shown the capability of the PLCFs to function as optical sensors for these external parameters when infiltrated with liquid crystals [5]. PLCFs are one of the most promising candidates for the fabrication of in-fiber tunable devices. Different types of PCFs infiltrated with nematic liquid crystals have been studied and their electronic and temperature tunability have been demonstrated [6, 7]. Nematic liquid crystals are characterized by relatively slow tuning speeds (~ milliseconds) and furthermore, thermal tuning can be employed for applications where smooth and slow changes are required. By comparison to nematic liquid crystals, ferroelectric liquid crystals (FLC) possess fast switching speeds, excellent electro-optic response, larger switchable birefringences and better phase stability upon repeated electronic switching [8]. Infiltration of FLC materials into PCFs could lead to the fabrication of fast in-fiber tunable devices, by employing the electronic tunability of such devices.

In this paper, we demonstrate the electronic tunability of ferroelectric liquid crystal infiltrated PCFs. We have employed hollow-core and solid-core PCFs to study the electronic tunability, by infiltrating them with FLC materials. The tunability is studied in the wavelength range of 1500 nm – 1600 nm. With the FLC infiltrated solid core PCF, a linear response of the spectral shift with change in voltage is obtained and a tunable range of ~ 20 nm is achieved.

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2. ELECTRONIC TUNABILITY OF PLCF

Solid core PCFs infiltrated with liquid crystals could be classified as microstructured waveguides consisting of high-index inclusions that surround a low-index core, given the relatively higher effective refractive index (>1.5) of liquid crystal materials when compared to that of silica (~ 1.48). In this case the guidance of light is governed by the photonic bandgaps presented by the cross-sectional geometry of the PLCFs [2]. The application of external electric onto the PLCF causes the molecular director reorientation in the infiltrated region which changes the effective refractive index of the cladding region. The change in the cladding refractive index causes shift in the photonic bandgaps, whereby the wavelength dependent guidance of the light can be tuned.
Hollow core PCFs are PBG fibers, with the core refractive index relatively lower than the cladding effective refractive index. Complete infiltration (core and cladding region) of hollow core fibers with liquid crystal leads to a lower effective refractive index in the cladding region when compared to the core, where the guidance again is due to total internal reflection. Selective infiltrating the core of the hollow-core PCF creates a large refractive index contrast between the core and the cladding region. Application of the electric field in this case causes the change in refractive index of the core, and facilitates the tuning of the propagation properties of the PLCF.

3. EXPERIMENT AND SET-UP

We infiltrated two different kinds of PCFs with ferroelectric liquid crystal materials. The PCFs used are PM-1550-01 and HC-1550, both commercially available from Crystal Fibers A/S. The PM-1550-01 is a polarization maintaining (PM) PCF, with a solid core having two large holes of diameter 4.5 μm and small holes of diameter 2.2 μm with a pitch Λ (inter-hole spacing) of 4.4 μm. The HC-1550-02 is a hollow core PCF with a core diameter of 10.9 μm and a pitch of Λ of 3.8 μm. The HC-1550-02 has a larger holey region (diameter ~ 70 μm) when compared to that of PM-1550-01 (diameter ~ 40 μm).

In order to create a large refractive index contrast between the core and the cladding regions, we developed a technique to selectively infiltrate the hollow core PCF (HC-1550-02) with ferroelectric liquid crystals, using a conventional fusion splicer. The smaller holes in the PCF cladding were collapsed using the fusion splicer and the collapsed region was cleaved off after the infiltration. The fusion current and fusion time was optimized [9] with the fusion splicer, in order to achieve the collapse of the holes in the cladding region only, keeping the hollow core open. The infiltration of FLC material into the PCFs was carried out by immersing the cleaved end of the fiber into the FLC material kept at a temperature between 80 – 90 °C. The FLC molecules get drawn into the PCF, due to capillary forces. The quality of infiltration in the PLCFs was inspected using polarization microscopy (GX XPL 3200 polarization microscope) before performing the electronic tunability studies.

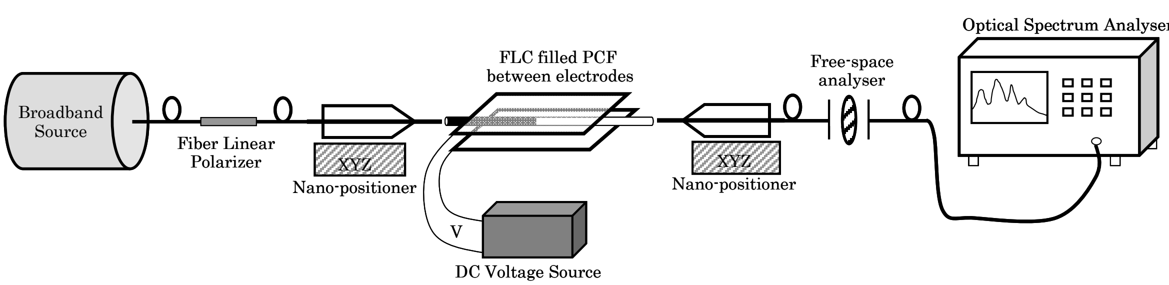

Fig. 1. Schematic diagram of the experimental setup for studying the electronic tunability of the FLC infiltrated PCF.

The ferroelectric liquid crystal material used for our experiments is FELIX 019/000 (AZ Electronics). The material has a Smectic C phase in the temperature range from 2 – 60 °C, with a tilt angle of ~ 38°. The ordinary (n_o) and extra-ordinary (n_e) refractive indices of the material are 1.487 and 1.651 respectively, measured at 30 °C at 589.3 nm. Our experiments were performed at room temperature. A 5.0 cm length section of both the PCFs infiltrated with the FLC material were used for the experiment. The PLCFs were placed between two electrodes to allow the application of an electric field perpendicular to the fiber axis. The experimental setup used for studying the electronic tunability of the PLCFs is as shown in fig 1. Light from the broadband source (Superlum Diodes Ltd.; 1490-1640 nm) was coupled into a fiber linear polarizer and then coupled into the infiltrated end of the PLCF. The output from the other end of the PLCF is coupled through a free space analyzer (Infrared Polarizer) and inputted to an optical spectrum analyzer. The coupling of light at the input end and the collection from the output end of the PLCFs was achieved using a 3-stage XYZ-nano-positioner waveguide stage (resolution - 0.1 µm). The coupling loss was circa 1.5 – 2.0 dB with fiber butt-coupling using the nano-positioner. The polarized transmission spectrum of both the PLCFs was recorded for a voltage range from 0 V – 150 V DC.

4. RESULTS AND DISCUSSIONS

The length of infiltration of the FLC material into the PCFs was estimated as ~ 1.3 cm for the PM-1550-01 and ~ 1.0 cm for the HC-1550. The observations in crossed polarizers suggests that the alignment of the FLC molecules in the infiltrated region to be largely along the axis of the fiber. The observations with the partially infiltrated HC-1550 PLCF show that the core and some holes in the cladding region still get infiltrated. The collapsing of the holes in the cladding region is not fully achieved with the fusion splicer and further optimization is required. Figure 2 shows the photographs of the partially and fully infiltrated PLCFs taken using a digital microscope under crossed polarizers with the axis of the PLCF aligned at an angle of 45° with respect to the polarizer axis for both the PM-1550-01 (2.a) and HC-1550-02 (2.b).

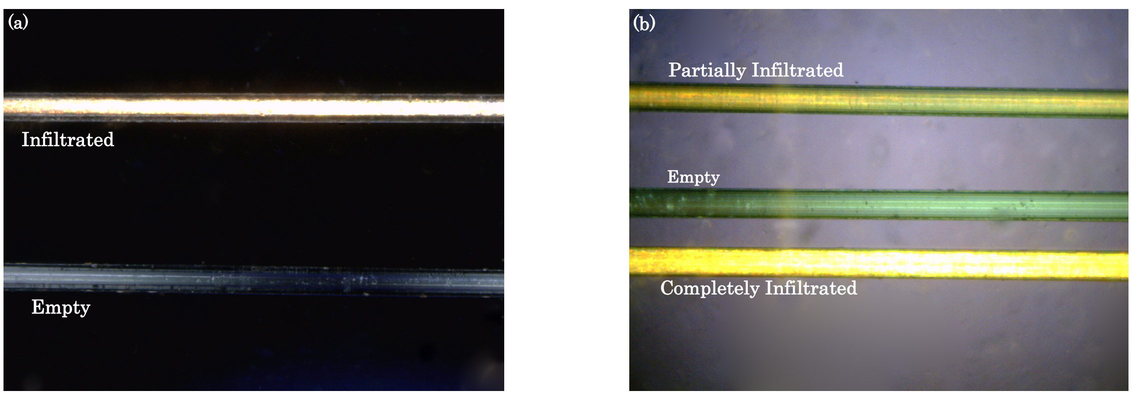

Fig. 2. Snapshots of the PLCF taken under crossed polarizers. a) Empty and infiltrated sections of PM-1550-01, b) Empty, partially infiltrated and fully infiltrated sections of HC-1550-02.

The transmission spectrum for the fully infiltrated HC-1550 PLCF showed very low power output, probably due to the low refractive index contrast between the core and the cladding region as both regions were infiltrated with FLC material. The PLCF showed no response to the applied electric field in this case. Polarized transmission spectrum for the partially infiltrated HC-1550 PLCF for different voltages is as shown in figure 3. We observed a drop in the output power from the PLCF with increase in voltage from 0 V – 50 V DC. For voltages above 50 V DC, very low output power from the PLCF was obtained, suggesting that the propagation properties of the PLCF get disturbed at these voltages.

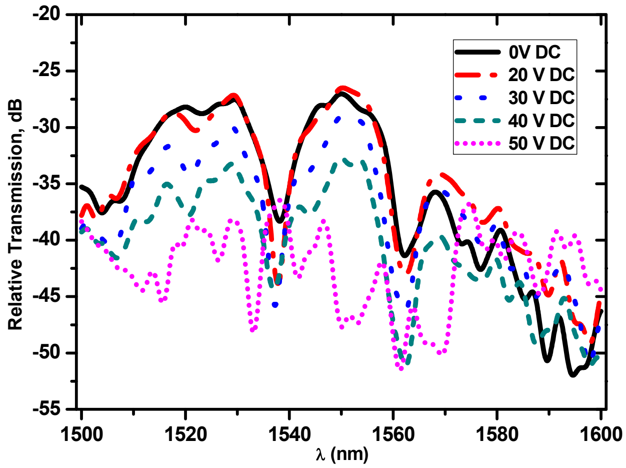

Fig. 3. Polarized Transmission spectrum of FELIX 019/000, partially infiltrated HC – 1550 at different voltages.

The polarized transmission spectrum of the fully infiltrated PM-1550-01 PLCF, obtained for different voltages showed transmission minimum (notch) at around 1550 nm, which is a characteristic of PBG guidance. No change in the transmission spectrum was observed for voltages from 0 V – 60 V DC, suggesting that at these voltages the reorientation of the FLC molecules does not take place and the propagation is governed by the ordinary refractive index of the FLC within the holes of the PCF. For voltages from 60 V to 110 V DC, a shift of the transmission minimum towards the lower wavelengths is observed with an increase in voltage, as shown in Figure 4. An overall shift of ~ 22 nm from 1554 nm (60 V) to 1532 nm (110 V) was observed. The spectral profile shows the features of a notch-type filter which could be tuned with the application of the electric field. The shift of the transmission notch for the voltage range from 60 V – 110 V shows a linear response, as shown in Figure 5. The reorientation effect of the FLC molecules takes place above ~ 60 V and at these voltages the PBG positions depend on the FLC extraordinary refractive index.

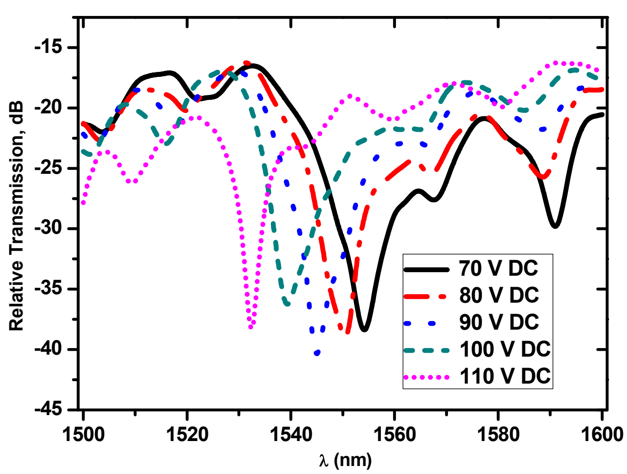

Fig. 4. Polarized Transmission spectrum of FELIX 019/000 infiltrated PM-1550-01 at different voltages.

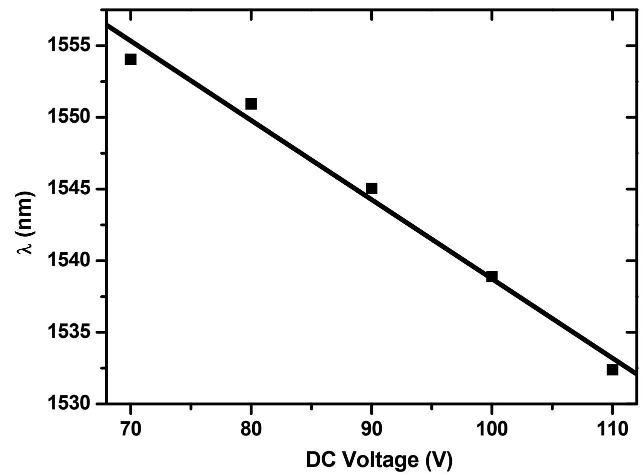

Fig. 5. Electronic tunability of the spectral minimum (notch) of the PM-1550-01 PLCF.

Further increase in the voltage up to 150 V resulted in no shift in the spectrum, with the transmission minima remaining centered at 1532 nm. The FLC material may have attained the maximum tilt angle and further reorientation does not take place with increase in voltage.

The tunable notch filter-like behavior shown by the PM-1550-01 PLCF, in this wavelength range could find application in the spectral shaping of the cavity of a modelocked fiber laser, in tunable dispersion control within and outside the cavity and also for amplified spontaneous emission (ASE) filtering and gain flattening of erbium doped fiber amplifiers. Further investigations are currently underway, in order to understand the spectral behavior as shown by the partially infiltrated HC-1550-02 PLCF and to obtain better tunability with hollow core FLC infiltrated PCFs, in terms of maintaining the spectral features with minimum loss in output power, with change in the applied voltage.

5. CONCLUSION

We have demonstrated the electronic tunability of ferroelectric liquid crystal infiltrated Photonic crystal fibers in the wavelength range of 1500 nm – 1600 nm. We studied the tunability of selectively infiltrated hollow core and fully infiltrated solid core photonic crystal fibers. The partially infiltrated hollow core photonic crystal fiber was found to respond to the applied electric field in the voltage range from 20 V – 50 V, with a decrease in the output power with increase in voltage. The transmission profile of the fully infiltrated solid core photonic crystal fiber shows a tunable notch-filter like behavior in the wavelength range from 1532 nm – 1554 nm in the voltage range from 60 V – 110 V DC and the shift in the transmission minimum with the change in the applied voltage is found to be linear. Our results could pave the way for the fabrication of fast in-fiber tunable devices to be used in the telecom wavelength range. Specifically, a device based on the ferroelectric liquid crystal infiltrated polarization maintain photonic crystal fiber (PM-1550-01) could find application in the fabrication of an all-in-fiber tunable notch filter for the spectral shaping of the cavity for fiber lasers and for the ASE filtering of fiber amplifiers.

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