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Directional Electric Field Sensitivity of a Liquid Crystal Infiltrated Photonic Crystal Fiber.

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Directional electric field sensitivity of a liquid crystal infiltrated photonic crystal fiber

S. Mathews, G. Farrell and Y. Semenova

Abstract— The directional sensitivity of nematic liquid crystal infiltrated polarization maintaining photonic crystal fiber to an externally applied electric field is evaluated for two dimensional electric field sensing. Selectively infiltrated and infiltration length optimized polarization maintaining photonic crystal fiber is used as a probe. Using a polarimetric scheme the polarized transmission properties of the infiltrated fiber are evaluated in terms of the orientation of the fiber polarization axis in an electric field. It is shown that the sensor has varying sensitivity to electric fields oriented at different angles with respect to the fiber polarization axis. The proposed low cost, all-fiber sensor can be used for two-dimensional directional electric field sensing.

Index Terms— Electric field sensing, liquid crystal infiltration, polarization maintaining photonic crystal fiber, selective infiltration, polarimetric sensing scheme.

I. INTRODUCTION

INFILTRATION of liquid crystals (LC) into photonic crystal fibers (PCF) has attracted much attention recently for application in a variety of in-fiber tunable devices [1-3]. After LC infiltration the propagation properties of the PCF become highly dependent on the external electric field, a property which can also be utilized for electric field sensing.

Fiber optic based electric field sensing has been demonstrated using a number of approaches. The major advantage of fiber optic based electric field sensing is that true dielectric isolation is possible in the presence of high electric fields or voltages. Furthermore, unlike conventional metallic electrode based sensors, fiber optic based electric field sensors minimally disturb the unknown electric field. Most of the demonstrations to date have involved the measurement of the intensity of an electric field. However in many applications it is also necessary to measure the direction of an electric field. Directionally sensitive electric field sensors allow for the measurement of electric field components and can be used for electric field mapping. In [4] a technique employing a GaAs crystal integrated with an optical fiber for the detection of electric field components was demonstrated. Electric field

mapping using a sensor based on an electro-optic crystal has also been demonstrated in [5, 6], where the symmetry properties of the electro-optical crystal were utilized. These approaches involve the integration of fibers and electro-optical crystals and therefore have a number of disadvantages such as high coupling losses, high cost, limited mechanical reliability and are difficult to mass produce.

In this paper we demonstrate for the first time a true all-fiber sensor involving the application of a nematic liquid crystal (NLC) infiltrated photonic crystal fiber as a directional electric field sensor. A section less than 1mm long of a selectively infiltrated polarization maintaining photonic crystal fiber (PMPCF) is used as the sensor head, allowing for a very compact and all-fiber sensor head and ease of integration with coupling fibers. The elliptical core geometry of the PMPCF along with selective LC infiltration imparts the PMPCF with a high variable birefringence on the application of an electric field. The length of the infiltrated section of the PCF, subjected to electric field, is initially optimised to have a monotonically varying polarized transmission response with electric field intensity change at 1550 nm. A study of the polarized transmission of the NLC filled PMPCF at different orientations of its polarization axis with respect to electric field direction is performed and presented here to evaluate the sensitivity to the direction of an electric field.

II. BACKGROUND

The birefringence tunability of PCF was demonstrated by selective infiltration of polymer by C. Kerbage et al [7]. On selective infiltration of the two large holes of the PMPCF (Figure 1(a)), the birefringence of the fiber is set by the refractive indices of the NLC mixture, which vary as the NLC molecules reorientate on the application of electric field. The overlap of the core mode of the PMPCF with the infiltrated LC in the two large holes allows for the fiber to exhibit a large variable birefringence on the application of external electric field.

The phase retardance for the light propagating through the infiltrated PCF is given as, $\Phi = (\Phi_0 + \Phi_E)$ (1), where Φ_0 is the inherent phase retardance due to the infiltrated PMPCF in the absence of the field. The electric field induced phase retardance of the fiber is $\Phi_E = \kappa_0 \Delta N L$, where κ_0 is the wavevector, ΔN is the electric field induced phase birefringence which is a direct measure of the projection of the average molecular orientation along the PCF polarization axis

(Figure 1) and L is the length of the infiltrated section subjected to an electric field. The direct measurement of ΔN , which is a function of the effective refractive indices of the modes of the infiltrated PCF, is difficult. It is convenient therefore to express the field induced phase retardance as $\Phi_E = (\pi\Delta E/E_\pi)$, with E_π being the sensor characterization term which is inversely proportional to the infiltration length L . Linearly polarized light with the direction of polarisation at 45° with respect to the PCF polarization axis, suffers a retardance given by equation (1) and the transmitted intensity through an analyser at 45° with respect to n_y (and parallel to the input polarizer) is given as $I = I_0/2 \{ 1 + \sin(\Phi_0 + (\pi\Delta E/E_\pi)) \}$ (2). A smaller value of E_π suggests that the sensor has a higher sensitivity to electric field.

III. DIRECTIONAL E-FIELD SENSITIVITY OF THE PROBE

The sensor probe consists of a less than 1mm long selectively infiltrated section of a PMPCF. Figure 1(b) shows the infiltrated PCF orientation with respect to the electric field direction. The angle between the electric field direction and the fiber polarisation axis (n_y) is θ . Figure 1 (c) shows the schematic of the large diameter holes of the PCF with the average orientation of the LC molecules (NLC director) on the application of electric field. Within each hole, as the molecules orient along the field direction, the NLC director component in the direction of the field is given by $n_E = n_e \sin\phi$ as shown in figure 1(d), with ϕ being the angle between the fiber propagation direction (z) and the NLC director and n_e is the extraordinary refractive index of the NLC. As the NLC molecules reorient along the electric field direction (increase in ϕ) the component n_E increases in magnitude. Linearly polarized light with polarisation direction at 45° with respect to the PCF axis (n_y) in this case will undergo increasing retardance with an increase in electric field intensity for a fixed length of the infiltrated section within the electrodes. For a fixed electric field intensity, on rotation (increase in angle θ), the component of n_E along n_y ($n_E \cos\theta$) decreases as θ increases from 0° to 90° , so in this case the phase retardance experienced by the light decreases. It should be mentioned that using the explanation above, an increase in θ from 90° to 180° will produce the same retardance as θ going from 90° to 0° . As a result the polarized transmission response of the infiltrated PMPCF with polarization axis of the PMPCF rotated from 90° to 180° , with respect to the electric field direction, will be the same as when rotation is from 90° to 0° .

The fiber used for our experiments is commercially available PM-1550-01 (cross-sectional image shown in figure 1(a)). The two large holes have a diameter of ~ 4.5 microns. A nematic NLC mixture MLC-7012 (Merck) is chosen for this study, as it shows a 45° splayed alignment, observed experimentally in a 5 micron silica capillary using a polarizing microscope. Splay aligned LC mixtures within PCF holes are known to have a low electric field threshold for LC molecular reorientation [8]. Selective infiltration of the two large holes is achieved by

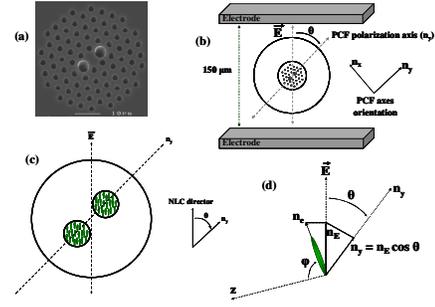


Fig. 1. (a) Scanning electron microscope image of the PM-1550-01, (b) Infiltrated PCF polarization axis orientation and electric field direction, (c) Large holes of PMPCF with NLC molecular alignment on application of electric field, and (d) Average molecular orientation and it's projection on the electric field direction and PCF polarization axis.

collapsing the smaller holes at the cleaved fiber end using a standard fusion splicer with controlled arc discharges [9].

The experimental set-up used for the study is shown in figure 2. The electric field is applied in the form of a sinusoidally varying positive polarity waveform at 1 kHz frequency, using a combination of high voltage (1000 V) power supply modulated by a standard waveform generator. The length of the infiltrated section within the electrodes is initially adjusted to have a phase change of $\sim \pi/2$ for the entire applied electric field range from 0 to 4.0 kVrms/mm. Precise control of the length of infiltration during the infiltration process is difficult to achieve. Therefore for this study mechanical translation of the infiltrated section with respect to the electrodes is used as a more practical alternative to allow the infiltration length exposed to an electric field to be set with the required precision.

In order to study the sensitivity of the infiltrated PMPCF to the direction of an electric field a polarimetric scheme [10] is employed. The infiltrated fiber section is mounted on a precision fiber rotator so that the infiltrated end can be rotated within the fixed electrodes to study the effect of change in fiber orientation with respect to electric field.

IV. EVALUATION OF DIRECTIONAL E-FIELD SENSITIVITY

Figure 3(a) below shows the polarized transmission response of the selectively infiltrated fiber at 1550 nm for different orientation angles of the PCF polarization axis with respect to the electric field direction. As can be observed from the plots the polarized transmittance through the fiber decreases monotonically with the electric field intensity for

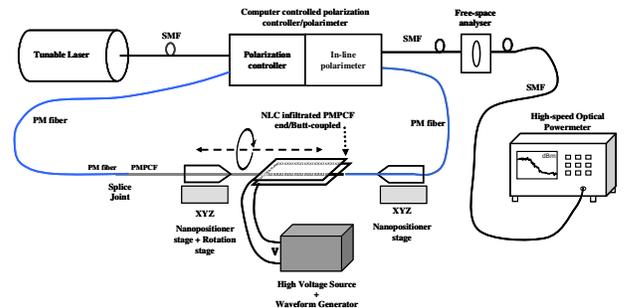


Fig. 2. Experimental set-up to study the directional sensitivity of NLC infiltrated PMPCF.

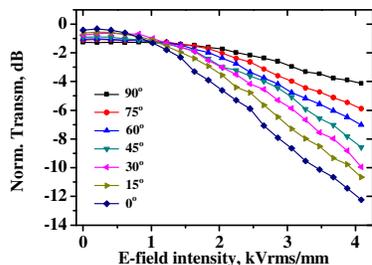


Fig. 3. Polarized transmission response at 1550 nm for different orientations of the PCF polarization axis with respect to electric field direction with increasing electric field intensity.

each orientation angle. For each case of the orientation of the PCF polarization axis the $n_e \cos\theta$ component increases with electric field intensity, resulting in higher phase retardance of the propagating light and hence a decrease in the polarized transmission is observed. From figure 3 it can also be observed that as the electric field intensity increases, there is an increase in the difference between transmitted power at $\theta = 0^\circ$ and at $\theta = 90^\circ$. It is also observed that the slope of the transmission response with electric field intensity reduces with an increase in θ from 0° to 90° as the fiber is rotated, in the electric field range from 1.0 to 4.0 kVrms/mm. A sinusoidal fitting based on (2) on the polarized transmission response at $\theta = 0^\circ$ and at $\theta = 90^\circ$ yields an estimate of the E_π values as ~ 7.02 kVrms/mm and ~ 4.82 kVrms/mm respectively. The sensor has a higher sensitivity to electric fields oriented parallel to the PCF polarization axis. The sensitivity decreases as the θ is increased and is found to be lowest when the polarization axis is orientated orthogonally to the electric field direction. Figure 4 shows the angular dependence of the transmitted power versus orientation of the PCF polarisation axis at a fixed electric field intensity of 3.67 kVrms/mm. A linear fit performed on the data gives an estimate of the angular sensitivity of the PMPCF orientation with respect to the electric field as ~ -0.07 dB/degree at a fixed electric field intensity of 3.67 kVrms/mm. It should be noted that when the data in Figure 4 is plotted with a linear intensity scale, the relationship is non-linear as expected from Equation 2. A dB intensity scale is used in order to provide an estimate of the angular sensitivity of the device. As explained in section III, at a fixed value of the electric field intensity the $n_e \cos\theta$ component decreases in magnitude as θ is increased from 0° to 90° (rotation of PCF). Correspondingly the phase retardance suffered by the light decreases thereby increasing the polarized transmittance. For a fixed electric field intensity the sensor allows for the determination of the direction of the externally applied electric field from the polarized transmission response.

V. CONCLUSIONS

We have demonstrated and evaluated the directional sensitivity of a nematic liquid crystal infiltrated polarization maintaining PCF in an electric field for sensing of electric field components, where the infiltration length has been optimized. A probe, which consists of a section of a selectively infiltrated

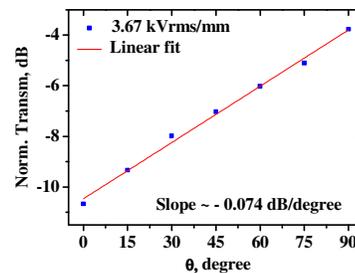


Fig. 4. Angular dependence of transmission on the orientation of the PCF polarisation axis with regard to the direction of electric field at an electric field intensity of 3.67 kVrms/mm, shown here with the linear fit

PMPCF less than 1 mm long, is optimized to have a monotonically varying transmission response for a particular electric field range by adjusting the length of the infiltrated section subjected to electric field. A study performed on the orientation of the polarization axis of the PMPCF with respect to electric field direction demonstrates that the sensor probe has higher sensitivity to electric field component aligned along the PMPCF polarization axis. The sensor allows for the determination of the direction of an electric field at fixed electric field intensities, thereby allowing for the measurement of the components of an externally applied electric field. Such PMPCF structures can be used for the fabrication of all-fiber directional electric field sensors for the measurement of two-dimensional electric field components and for electric field mapping.

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