Liquid Crystal Devices for Optical Communications and Sensing Applications

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Liquid Crystal Devices for Optical Communications and Sensing Applications

A thesis presented for the Degree of Doctor of Philosophy

by

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Supervisors: Dr. Yuliya Semenova and Prof. Gerald Farrell

School of Electronic and Communications Engineering

College of Engineering & Built Environment

Dublin Institute of Technology

November 2011
To the much awaited new member in my family

To my Wife and my Parents
Abstract

This thesis is focussed on the design and development of liquid crystal based tunable photonic devices for applications in optical communications and optical sensing, with an emphasis on all-fiber device configuration. The infiltration of liquid crystals into photonic crystal fiber provides a suitable common platform to design and fabricate simple and compact all-fiber tunable photonic devices which can be easily integrated with optical fiber networks and sensing systems. Based on the infiltration of liquid crystals – materials with high dielectric anisotropy, into photonic crystal fibers a common platform is developed to address the need for electronically tunable photonic devices with a compact all-fiber device configuration. A ferroelectric liquid crystal based tunable filter is theoretically studied and experimentally demonstrated for applications in the demodulation of multiple Fiber Bragg Grating sensors. The electrical tunability of liquid crystal infiltrated photonic crystal fiber is employed for the development of all-fiber tunable photonic devices for a variety of applications in optical communication systems. A nematic liquid crystal infiltrated photonic crystal fiber based all-fiber broadband electronically controlled variable optical attenuator is demonstrated in the wavelength range from 1500 nm – 1600 nm. With smectic liquid crystal infiltration the electrical tuning of photonic bandgap is achieved and an all-fiber tunable notch filter for applications in optical communication is demonstrated. A novel technology for all-fiber based electric field sensing is developed with the use of nematic liquid crystal infiltrated photonic crystal fibers. A simple and compact all-fiber sensor head is demonstrated, which allows for the accurate measurement of electric field intensity, along with detection and measurement of electric field signal parameters such as frequency, amplitude and also the direction of the electric field. Studies performed on the transmission and reflection responses of the sensor, demonstrate the capability of the simple and compact all-fiber electric field sensor to operate in both in-line and end-point type configurations. The effect of the applied electric field frequency on the propagation properties of liquid crystal infiltrated photonic crystal fiber is studied in the range from 50 Hz to 1 kHz. With the use of a suitable fitting function on the time varying transmission response of the fiber, it is demonstrated that the parameters of the applied electric field such as frequency and amplitude can be measured. Selectively infiltrated photonic crystal fibers are studied in a polarimetric electric field sensing scheme and it is demonstrated that the optimization of the length of the infiltrated section of the photonic crystal fiber subjected to an electric field allows to obtain a linear transmission response for the sensor in a given electric field range. The directional electric field sensitivity of a liquid crystal infiltrated elliptical core photonic crystal fiber is studied and a true all-fiber directional electric field sensor is demonstrated which is capable of simultaneous detection and measurement of the amplitude and direction of an applied electric field.
Declaration

I certify that this thesis which I now submit for examination for the award of Doctor of Philosophy, is entirely my own work and has not been taken from the work of others, save and to the extent that such work has been cited and acknowledged within the text of my work.

This thesis was prepared according to the regulations for postgraduate study by research of the Dublin Institute of Technology and has not been submitted in whole or in part for another award in any other third level institution.

The work reported on in this thesis conforms to the principles and requirements of the DIT's guidelines for ethics in research. DIT has permission to keep, lend or copy this thesis in whole or in part, on condition that any such use of the material of the thesis be duly acknowledged.

Sunish James Mathews

11th Nov 2011
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I believe what shapes the frame of mind of a PhD student to indulge in the exhausting and yet the most fruitful years of one’s academic life, is the interaction with a few, but very important people. At this stage, having enjoyed the most fruitful years of my academic life, I have to look back and acknowledge the people who had shaped my mind so that I could complete the given task and proudly write these few words.

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Sunish James Mathews
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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AOTF</td>
<td>Acousto-Optic Tunable Filter</td>
</tr>
<tr>
<td>ARROW</td>
<td>Anti-Resonant Reflecting Optical Waveguide</td>
</tr>
<tr>
<td>ASE</td>
<td>Amplified Spontaneous Emission</td>
</tr>
<tr>
<td>DWDM</td>
<td>Dense Wavelength Division Multiplexing</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium Doped Fiber Amplifier</td>
</tr>
<tr>
<td>FBG</td>
<td>Fibre Bragg Grating</td>
</tr>
<tr>
<td>FLC</td>
<td>Ferroelectric Liquid Crystal</td>
</tr>
<tr>
<td>FP</td>
<td>Fabry-Perot</td>
</tr>
<tr>
<td>FPF</td>
<td>Fabry-Perot Filter</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width at Half Maximum</td>
</tr>
<tr>
<td>HB</td>
<td>Highly Birefringent</td>
</tr>
<tr>
<td>LC</td>
<td>Liquid Crystal</td>
</tr>
<tr>
<td>LCD</td>
<td>Liquid Crystal Display</td>
</tr>
<tr>
<td>LCPCF</td>
<td>Liquid Crystal infiltrated Photonic Crystal Fiber</td>
</tr>
<tr>
<td>LMA</td>
<td>Large Mode Area</td>
</tr>
<tr>
<td>LPG</td>
<td>Long Period Grating</td>
</tr>
<tr>
<td>MEMS</td>
<td>Micro- Electro -Mechanical System</td>
</tr>
<tr>
<td>m-TIR</td>
<td>Modified Total Internal Reflection</td>
</tr>
<tr>
<td>NLC</td>
<td>Nematic Liquid Crystal</td>
</tr>
<tr>
<td>OSA</td>
<td>Optical Spectrum Analyzer</td>
</tr>
<tr>
<td>PBG</td>
<td>Photonic Band Gap</td>
</tr>
<tr>
<td>PCF</td>
<td>Photonic Crystal Fiber</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>PDLC</td>
<td>Polymer Dispersed Liquid Crystal</td>
</tr>
<tr>
<td>PMPCF</td>
<td>Polarization Maintaining Photonic Crystal Fiber</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>SLC</td>
<td>Smectic Liquid Crystal</td>
</tr>
<tr>
<td>SMF</td>
<td>Single Mode Fiber</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>SSFLC</td>
<td>Surface Stabilized Ferroelectric Liquid Crystal</td>
</tr>
<tr>
<td>VOA</td>
<td>Variable Optical Attenuator</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength Division Multiplexing</td>
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Chapter 1

Introduction

Liquid crystal (LC) science and technology now underpins a wide variety of products, from large industrial displays to a wide array of consumer electronics in homes and offices. Non-display applications of LCs in optical communication, nonlinear optics, data/signal/image processing and optical sensing are also receiving increased attention. Due to their unique crystalline phase characterized by the partial order of their constituent molecules along with physical fluidity, LCs can be easily incorporated into desired configurations for a variety of device applications. The large anisotropy of LCs, allows for realisation of external control of the optical properties of LC based devices, which makes LC materials suited for implementing tunable photonic devices for both optical communications and optical sensing systems.

The increasing demand for very high data capacity has meant that all-fiber fast tunable devices are in high demand in optical communications systems. One the most important requirements for an all-fiber tunable device is that it must be easy to integrate with interconnecting fibers. Other requirements, such as a compact design and low power consumption are also crucial.

Of the many technologies based on fiber optics, fiber optic sensing is an area which has also attracted much attention due to its inherent advantages. Optical sensing research has developed several successful fiber sensor types, for example Fibre
Bragg Grating sensors for strain sensing have been widely applied in structural health monitoring. Fiber optic sensing offers many advantages such as dielectric isolation, immunity from electromagnetic interference, chemical passivity, multiplexing capabilities, wide bandwidth, wide operating temperature range, environmental ruggedness and safety in explosive conditions.

Electric field sensing is a common need in the electrical power generation and distribution industries and other areas such as industrial automation. Optical fiber based electric field sensing is attractive, as it can inherit the many advantages of optical fiber sensing, but the natural electromagnetic immunity of optical fibers is a barrier to the development of this type of sensing. As a result, fiber optics based electric field sensing is a research area which has received less attention compared to other sensing areas due to the practical issues involved in creating sensitivity to an electric field, which so far have resulted in solutions with notable disadvantages, for example the difficulty in realising a compact sensor.

The combination of fiber optics and LCs, given the sensitivity of LCs to electric fields, offers an attractive solution. The advantage of LC materials for photonic device applications is two-fold. Firstly, the optical properties of LC based devices can be changed using external fields, which allows for the material to be used as the tuning element within tunable devices. Secondly, since the optical properties of LC based devices are dependent on external parameters such as temperature, electric and magnetic fields, with appropriate device configurations they can also be used as optical sensors for these parameters. In this dissertation both of these possibilities are explored, firstly for tunable photonic device applications for both bulk type and all-fiber device configurations and secondly the use of photonic crystal fiber with LC infiltration as a common platform to implement either tunability for all-fiber
devices for specific applications in optical communication systems or for fiber optics based electric field sensing.

In this introductory chapter Section 1.2 provides a concise description of LC phases while in Section 1.3 a short review of various LC based bulk devices for optical communications and optical sensing systems is provided. Section 1.4 introduces LC infiltrated photonic crystal fibers, with a focus on their use as tunable photonic devices. Finally, Section 1.5 discusses the objectives of the thesis while Section 1.6 presents an overview of the structure of this thesis.

1.1 Liquid Crystals and Tunability

Liquid crystals [1] have attractive anisotropic properties which arise due to the typical elongated shape of their constituent organic molecules which imparts them with a permanent dipole moment. A typical LC molecule consists of two or more benzene ring systems, connected by a linkage group, which gives the molecule an elongated or rod-like shape. The presence of benzene rings is responsible for short range molecular forces and determines the electrical and elastic properties of the LC. At one of the molecule ends there is a long side chain which strongly influences the elastic constants and the phase transition temperature of the LC. At the other end a terminal group is connected which determines the dielectric constants and its anisotropy. Figure 1.1 below shows the typical rod-like shape of an LC molecule. LC molecules display a tendency to orient in a particular direction with their axes aligned in parallel to each other. With appropriate confinement within different geometries they attain uniform alignment throughout the bulk of the material and
thereby show high anisotropy. LC materials due to their large anisotropy combined with relatively low absorption in the infrared wavelengths are considered suitable materials for tunable photonic device applications within the telecommunications wavelength window from 1500 nm to 1600 nm. The refractive indices of LC materials are highly dependent on ambient conditions such as temperature and externally applied electric or magnetic fields. As a result the incorporation of LC materials into a device makes it possible to easily achieve dynamic tunability of the optical properties of the device.

1.1.1 Liquid Crystal Phases

LCs are materials exhibiting properties that are intermediate between solids and liquids [2]. LC molecules have the tendency to align along a common axis, called the director (figure 1.2). LC materials are characterized by their nematic-isotropic phase transition temperature or clearing point below which they exhibit a liquid crystalline phase [3]. Below the isotropic temperature, the LC material can exhibit a number of distinct liquid crystalline phases. The intermediate phases can occur with
temperature changes and such LCs are referred to as thermotropic LCs [4]. The vast majority of thermotropic LCs are composed of rod-like molecules. As per the historical classification [5] based on the molecular arrangement and ordering of LC molecules, thermotropic LCs were classified as nematic, smectic or cholesteric [5]. A nematic liquid crystal (NLC) has a high degree of long range orientational order of the molecules, but no long-range translation order. Thus it differs from isotropic liquids in that the molecules are spontaneously oriented with their long axes approximately parallel to each other. The preferred direction usually varies from point to point in the medium, but a uniformly aligned specimen is optically uniaxial and strongly birefringent. Figure 1.2 below shows the molecular arrangement of LC molecules for the different phases. Smectic liquid crystals have an additional degree of translation order not present in nematics. Along with the orientation order present in nematics, smectic LC molecules tend to arrange themselves in planes or
layers. The commonly occurring smectic phases are smectic A and smectic C (figure 1.2). In smectic A phase the LC director is found to be perpendicular to the layer planes and in smectic C phase the LC director is tilted at an arbitrary angle with respect to the layer planes. This angle referred to as the tilt angle of the smectic C LC; it is a material characteristic and is of significance for tunable device applications.

The cholesteric phase LC which is now simply known as chiral nematic phase is composed of optically active molecules [6,7]. As a result the structure acquires a spontaneous twist about a helical axis normal to the directors. When viewed along the layer direction, the structure appears as a stack of very thin nematic-like layers with the director of each layer twisted with respect to those above and below. The chiral nematic phase can be considered to be composed of quasi-nematic 2-dimensional layers. Figure 1.2 shows the layers with the arrangement and ordering of molecules in a cholesteric phase. In substances that form both nematic and smectic phases the sequence of phase changes with increasing temperature is shown below (figure 1.3),

![Diagram of Phase Sequence](image)

**Figure 1.3:** Phase sequence of LC materials with increasing temperature

(T_M – melting point, T_N – nematic transition temperature and T_C – clearing point).
Although the director indicates the direction of the preferred orientation of LC molecules, the orientation order parameter S is used to represent the degree of orientational order of LCs [8].

The order parameter S of the LC phase is given as:

\[ S = \frac{1}{2} \langle 3 \cos^2 \theta - 1 \rangle \]  

where \( \theta \) is the angle between the long axis of an individual molecule and the director \( n \) (figure 1.4), and the angular brackets denote a statistical average.

![Figure 1.4: Schematic showing the arbitrary orientation of an LC molecule with respect to the average molecular orientation (LC director).](image)

For a perfectly parallel alignment \( S = 1 \), while for totally random orientation \( S = 0 \). In the nematic phase, S has an intermediate value which is strongly temperature dependent. The typical values of the order parameter S are in the range between 0.4 and 0.65 at low temperatures for most LCs [9].

### 1.1.2 Liquid Crystal Anisotropy

LCs show anisotropy of their electrical, magnetic, thermal and optical properties [10, 11]. Variable anisotropy of LCs which can be influenced by external
parameters means that LCs have a controllable tunability of their optical properties which makes them suitable for tunable photonic device applications. The temperature dependence of the dielectric anisotropy is often utilized to achieve tunability with LC based tunable device applications [12]. Due to the relatively slow speed of operation achievable by thermal means, electrical tunability of LCs is often preferred for device applications in optical communications and optical sensing. In this dissertation the electrical tunability of LCs is employed throughout for the experimental demonstrations for various devices for optical communication and optical sensing.

The dielectric anisotropy of LCs is given as:

\[ \Delta \varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp} \]  

where \( \varepsilon_{\parallel} \) and \( \varepsilon_{\perp} \) are the dielectric permittivities in the directions parallel and perpendicular to the director of the LC respectively. The dielectric anisotropy of an LC is determined by two factors which are the anisotropy of polarizability for the elongated molecules of the LC and the dipole orientation effect [13]. The sign of the latter contribution is positive if the net permanent dipole moment of the molecule has only a small angle with its long axis and is negative if the angle is large. Correspondingly, the dielectric anisotropy can be positive or negative. Thus different nematic materials can exhibit widely different dielectric properties.

To achieve electrical tunability with LCs and with LC based devices, it is important to understand the behaviour of the LCs under the influence of an externally applied electric field.

The application of an electric field \( \vec{E} \) to a LC produces a dipole moment per unit volume, often referred as the polarisation \( \vec{P} \). The polarization depends linearly on the electric field at low field intensities, but in general the vectors \( \vec{P} \) & \( \vec{E} \) can have
different directions. $\mathbf{P}$ & $\mathbf{E}$ are related by a tensor, $\chi$, called the electric susceptibility, as follows:

$$\mathbf{P} = \varepsilon_0 \mathbf{\chi} \mathbf{E}$$

or

$$\begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix} = \varepsilon_0 \begin{pmatrix} \chi_{xx} & 0 & 0 \\ 0 & \chi_{yy} & 0 \\ 0 & 0 & \chi_{zz} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix}$$

The induced polarization depends on the orientation of the LC director with respect to the applied field direction. For an arbitrary angle of orientation of the LC director with respect to the applied field, the applied field can be decomposed into components parallel and perpendicular to the LC director (figure 1.5).

The induced polarization is given as:

$$\mathbf{P} = \varepsilon_0 \mathbf{\chi} \mathbf{E} \mathbf{n} + \varepsilon_0 \mathbf{\chi}_\perp \left[ \mathbf{E} - (\mathbf{E} \cdot \mathbf{n}) \mathbf{n} \right] = \varepsilon_0 \mathbf{\chi}_\parallel \mathbf{E} + \Delta \mathbf{\chi} (\mathbf{E} \cdot \mathbf{n}) \mathbf{n}$$

Since the dielectric constants $\varepsilon_\parallel$ and $\varepsilon_\perp$ are related to the susceptibilities as $\varepsilon_\parallel = 1 + \chi_\parallel$ and $\varepsilon_\perp = 1 + \chi_\perp$, therefore $\Delta \mathbf{\chi} = \chi_\parallel - \chi_\perp = \varepsilon_\parallel - \varepsilon_\perp = \Delta \varepsilon$. The electric energy of the LC per unit volume is approximately given by,

$$F_{\text{electric}} = -\frac{1}{2} \mathbf{P} \cdot \mathbf{E} = -\frac{1}{2} \varepsilon_0 \left[ \mathbf{\chi}_\perp \mathbf{E} + \Delta \mathbf{\chi} (\mathbf{E} \cdot \mathbf{n}) \mathbf{n} \right] = -\frac{1}{2} \varepsilon_0 \mathbf{\chi}_\perp \mathbf{E}^2 - \frac{1}{2} \varepsilon_0 \Delta \varepsilon (\mathbf{E} \cdot \mathbf{n})^2$$

If the LC has a positive dielectric anisotropy ($\Delta \varepsilon > 0$), the electrical energy is minimised when the LC director is parallel to the applied field. Conversely, if the dielectric anisotropy is negative ($\Delta \varepsilon < 0$), then the electric energy is low when the LC molecules align perpendicular to the applied electric field.

Rotational viscosity is an important parameter to be taken into account with reorientation of LC molecules on the application of an electric or magnetic field. The dynamic response of LCs to externally applied electric and magnetic fields strongly depends on the rotational viscosity. On the application of an external perturbation as in the case with electric and magnetic fields, the elastic constants of
the LC material determine the restoring torque which arises as the system is perturbed from its equilibrium state. When an electric field is applied to reorient the molecules to control the effective birefringence in an electro optical device, it is the balance between the electric and elastic torque that determines the static deformation of the LC director. Any deformation of the LC director can be divided into a combination of the three possible deformation modes, namely splay, twist and bend [14].

The elastic free energy of a LC given by the Oseen-Frank theory incorporating the three deformation modes is given as [15]:

\[
F = \frac{1}{2} K_{11} (\nabla \cdot \mathbf{n})^2 + \frac{1}{2} K_{22} (\mathbf{n} \cdot \nabla \times \mathbf{n})^2 + \frac{1}{2} K_{33} (\mathbf{n} \times \nabla \times \mathbf{n})^2
\]

Figure 1.5: Parallel and perpendicular components of dielectric constant of the LC, with respect to an applied electric field direction.
where $K_{11}$, $K_{22}$ and $K_{33}$ are the splay, twist and bend elastic constants and $\hat{n}$ is the LC director. The elastic constants are temperature-dependent parameters and they play a larger role in highly confined LC systems. The free energy density is minimised when the director is spatially uniform as often happens in the case with LCs in confined geometries [16].

The response of the LCs to external fields is also dependent in most cases on the interactions between the LC molecules and the forces at the surface boundaries. Reorientation of the LC does not necessarily occur as the applied field rises from zero, rather there can be a threshold phenomenon such that reorientation only occurs above a critical or threshold field. The dielectric anisotropy and the elastic constant are the parameters that determine the threshold electric field for the LC.

For an LC layer of thickness $d$, with the field applied perpendicularly to the plane of the layer, the threshold field for LC reorientation is given as [17, 18]:

$$E_{th} \approx \frac{\pi}{d} \sqrt{\frac{K_{11}}{\varepsilon_0 \Delta \varepsilon}}$$  \hspace{1cm} (1.7)$$

$$E_{th} \approx \frac{\pi}{d} \sqrt{\frac{K_{22}}{\varepsilon_0 \Delta \varepsilon}}$$  \hspace{1cm} (1.8)$$

and bend

$$E_{th} \approx \frac{\pi}{d} \sqrt{\frac{K_{33}}{\varepsilon_0 \Delta \varepsilon}}$$  \hspace{1cm} (1.9)$$

This reorientation of the director under the influence of an electric field is known as the Freedericksz transition and the threshold field required for the reorientation is referred to as threshold field $E_{th}$. The Freedericksz transition threshold for a planar aligning LC is a crucial parameter for LC based devices.
1.2 Tunable Liquid Crystal Photonic Devices.

1.2.1 Liquid Crystals in Optical Communications

The continuously increasing data capacity requirements in telecommunications have led to an increased demand for high speed optical devices for optical communications systems. Highly compact, non-mechanical and high speed optical devices are in a great demand, particularly for the next-generation dynamically reconfigurable networks.

LCs have traditionally been primarily used in LC display (LCD) technologies [19, 20]. In addition to LCD devices, LC materials are considered potentially suitable for tunable photonic device applications. Unlike LC display devices, photonic devices for optical communications applications operate in the infrared range of wavelengths. LCs with their low absorption in the infrared region and large electro-optical response are considered an important material for tunable optical devices in optical communications [21].

With easy tunability achievable by thermal and electrical means extensive research has been undertaken so far to exploit this advantage of LCs for various applications in optical communications. LCs have been employed in bulk optical device applications in optical communications [22]. The use of LC in bulk devices has the advantage of ease of fabrication and allows for precise control of the design characteristics of the device due to the fact that the LC cells can easily made with appropriate thicknesses and suitable shapes. However due to the presence of bulk optical components such devices have high coupling losses and have practical issues with integration with fiber, which reduces their attractiveness in fiber based applications. As an alternative to a bulk approach, LC based devices have been implemented with integrated optics and waveguide based approaches [23]. These
approaches have shown improved performance when compared to bulk devices in terms of low voltage operation and ease of integration with fiber. However miniaturization of the LC based device core to facilitate integration increases the fabrication cost and thereby is problematic for large scale manufacturing.

Despite the issues associated with combining LCs and optical fibers, a variety of LC based devices have been developed and demonstrated, including optical switches, attenuators, filters, and spectrometers [24-29]. LC based tunable filters coupled with fiber optics have been demonstrated for optical communications in various device configuration such as Lyot type filters [30,31] and Fabry-Perot type filters [32, 33]. Some of the other important applications for LC based tunable filters have been in spectral imaging for brain tumor demarcation [34], plasma spectroscopy [35] and for solar imaging [36].

The advantage of employing a solid host matrix combined with the anisotropic properties of a LC was explored with polymer dispersed liquid crystals (PDLC) [37]. PDLC have been used with integrated optics approaches for the demonstration of variable optical attenuators (VOA) [38], an optical dynamic gain equalizer, switchable lens and chopper arrays [39].

In most of these demonstrations of LCs based tunable devices, LCs are employed in bulk configurations, which normally are in the form of a LC cell functioning as a variable phase retarder. For most of the device applications in optical communications, an all-fiber device configuration is often preferred for easy integration with the interconnecting fibers within an optical communication network.
1.2.2 Liquid Crystals for Optical Sensing Applications

LCs with their ability to alter their molecular orientation and material properties under the influence of external parameters are also suited for optical sensing applications. LCs in bulk configurations have been employed for various applications such as chemical sensing, gas sensing [40] and biological sensing [41]. These employ chemically functionalized LC interfaces which change the orientation of the LC as and when the interface comes into contact with the material to be detected. LC materials have also been employed as temperature sensors for food processing applications [42, 43] and a fiber optic integrated temperature sensor was demonstrated using selective reflection in cholesteric LC material [44].

Due to their large electro-optic response, LCs are highly suited for electric field and voltage sensing. For various sensing applications such as electric and magnetic field sensing and also for biological and chemical sensing it is advantageous that the sensor is easy to integrate with fiber optics. Fiber optic sensors [45-47] have the implicit advantages of immunity from electromagnetic interference, safety in potentially hazardous environments and the possibility of large separation between sensor and monitoring station. Additionally, a fiber optic sensor which can be interrogated in the wavelength domain allows for simple multipoint sensing systems facilitated by appropriate wavelength based multiplexing schemes.

Due to the inherent immunity of optical fibers to electromagnetic fields, the primary issues with fiber optics based approaches for the sensing of parameters such as voltage, electric and magnetic fields are the technical difficulties in fabricating an all-fiber device sensitive to these parameters. The incorporation of LCs within an all-fiber sensor head would circumvent this difficulty and allow for easy integration of the sensor head with a fiber optic sensing system.
1.3 Liquid Crystal Infiltrated Photonic Crystal Fibers.

Photonic crystal fibers (PCFs) [48] with their unique periodic transverse microstructure geometry have been instrumental in extending the functionality of optical fibers, both by improving well-established properties and introducing new features. The most recent technology allows manufacturing of a microstructure in air-silica PCF to accuracies of 10 nm on a scale of 1 μm, which allows remarkable control of key optical properties such as dispersion, birefringence, nonlinearity, and the position and width of the photonic bandgaps in the periodic photonic crystal cladding. PCFs guide light either by the modified total internal reflection mechanism (m-TIR) or the photonic bandgap (PBG) mechanism depending on whether the effecting refractive index of the cladding is lower or higher than the core refractive index [49]. For example, commercially available hollow core fiber HC-1550 (NKT Photonics) is an air-guiding fiber which guides light by the photonic bandgap mechanism as the effective cladding index of the PCF (air-silica cladding) is higher than the core refractive index (air). For the solid silica core LMA-10 PCF the guidance mechanism is m-TIR owing to the higher core refractive index of the silica core when compared to the air-silica cladding. Figure 1.6 below

Figure 1.6: Schematic of the PCF cross-section with conditions for the guidance mechanisms.
shows the schematic of a PCF cross-section and the conditions for both of the guidance mechanisms. Infiltration of materials into the holes of the PCF may lead to the switching of the guidance mechanism of the PCF between PBG and m-TIR mechanisms.

1.3.1 Infiltration of Photonic Crystal Fiber with Liquids

The air-hole geometry of a PCF allows for the infiltration of the holes with various materials, which in turn opens numerous possibilities for the fabrication of all-fiber tunable devices. The efficient light-sample interaction within the microstructure of the PCF enables various applications in sensing, spectroscopy and nonlinear optics. Infiltration of fluids or liquids with variable refractive indices allows tuning of the PCF propagation properties. Most of these demonstrations have involved the infiltration of thermo-optic fluids to achieve thermal tuning of the PCF propagation properties. Some of the important early experimental studies with infiltrated PCFs include the demonstration of large waveguide dispersion in a PCF filled with high-index liquid [50]. Polymer filled PCF combining Bragg technology and microstructured fibers for tunable device applications were studied and the possibility of realising active waveguide control by dynamic positioning of a microfluid within a PCF was demonstrated [51]. Infiltration of non-linear fluids also enhances the nonlinearity of the PCF. For example filling the air-holes of the PCF with liquids such as chloroform, nitrobenzene, carbon disulfide and distilled water enhances the nonlinearity of the fiber and leads to supercontinuum generation within PCFs [52, 53].
1.3.2 Liquid Crystal Infiltration

The infiltration of LCs into the holes of the PCF provides the means of achieving active control on the PCF propagation properties [54-57]. With LCs within the holes of the PCF the structures are more commonly referred to as liquid crystal photonic crystal fibers (LCPCFs), and their propagation properties are defined by the refractive indices of the infiltrated LC and the 2-D cross-sectional geometry. The LCPCF structure is unique in that it combines the technology of fiber optics along with the variable anisotropy of the LCs. It provides a platform to equally address the requirements of an all-fiber device configuration and the frequent need for tunability for photonic devices for optical communications and optical sensing applications. With infiltration of LCs in the device there is no need for external coatings or transducers which in turn enhances the compactness and ease of fabrication of the device.

On infiltration with LC the LCPCF propagation properties can be controlled by external parameters such as temperature, electric and magnetic fields and thus LCPCFs can be used for the fabrication of externally controlled all-fiber tunable photonic devices. Equally advantageous is the fact that the propagation properties of the LCPCF will be easily influenced by these parameters and thus can be used for the fabrication of all-fiber based optical sensors for these parameters.

**Photonic Bandgap Transmission in LCPCFs**

Most commercially available PCF are drawn from silica. LCs usually have refractive indices (both ordinary $n_o$ and extraordinary $n_e$) higher than that of silica (~ 1.458). On infiltration of LC materials in solid silica core PCFs the effective refractive index of the cladding becomes higher than that of the silica core.
Under these conditions the propagation properties of the LCPCF are governed by the photonic band gap mechanism. The LCPCF forms a 2-D photonic crystal structure along its cross-section with high index cladding inclusions and the core, acting as the defect in the PBG structure, guides light through the fiber.

The most important difference between an index guiding PCF and PBG based PCF is that in an index guiding PCF there is a continuum of guided modes whereas in PBG fibers there is a discrete set of guided modes separated by photonic bandgaps. As a result, the PBG transmission spectrum is characterized by high (maxima) and low (minima) transmission regimes. The theoretical background for guidance of light through an LCPCF can be analytically explained using the antiresonant reflecting optical waveguide (ARROW) model [58]. The LCPCF structure can be considered as a layered structure consisting of a low index silica core surrounded by an array of high and low index cladding layers. The guiding properties of PBG waveguides are primarily governed by antiresonant reflection from multiple cladding layers. The wavelengths corresponding to the minima of the transmission coefficients are referred to as resonant wavelengths while the wavelengths corresponding to transmission maxima of the spectrum are called antiresonant wavelengths. The transmission maxima originate from the antiresonant nature of the individual cladding layers with respect to the transverse propagation constants. Each layer can be considered a Fabry-Perot (FP) like resonator. The narrowband resonance of this FP resonator corresponds to transmission minima for the light propagating in the core, or as the resonant wavelengths of the low-index core waveguide. The wideband antiresonances of the FP resonator, which are wavelengths experiencing low leakage as a result of destructive interference in the
FP, resonator correspond to a high transmission coefficient for the low index core waveguide.

With the complex PBG fiber structure, each high-index inclusion can be considered as a waveguide that supports normal modes, along with their associated modal cut-off conditions [59]. For a waveguide with a number of modes $m$, a modal cut-off condition corresponds to the wavelength at which the high-indexed inclusion switches from supporting the $m+1^{th}$ mode to the $m^{th}$ mode. The resonant condition is determined by calculating the modal cut-off of the single waveguide. At the modal cut-off the effective index of the cladding is the same as the refractive index of the core (silica) and the entire structure becomes effectively transparent. At this wavelength no guidance takes place and this corresponds to a minimum in the transmission spectrum. The position of these minima in the transmission spectrum of the PBG fiber is given by the cut-off condition as

$$\lambda_m = \frac{2d}{m + 1/2} \sqrt{n_2^2 - n_1^2}; \quad m = 0, 1, 2, 3, \ldots$$

where $\lambda_m$ is the cut-off wavelength of the $m^{th}$ mode, $d$ is the thickness of the high-index layer which is the same as the hole diameter of the PCF, $n_1$ and $n_2$ are the isotropic refractive indices of the material of the fiber (low-index layer) and the material used for infiltrating the PCF hole (high-index inclusion), respectively.

The cut-off positions can be changed by changing the refractive index of the infiltrated material within the holes. As LC materials have variable refractive indices this facilitates tuning of the photonic bandgap and the transmission properties on infiltration within the holes of the PCF. The modes formed within each band are degenerate with isotropic material infiltration. With LC infiltration and due to the anisotropy the degeneracy of the modes is lifted as the polarization
dependent modes will experience different refractive indices. Consequently, additional bandgaps are formed and transmission minima appear that were absent in the isotropic material infiltration case.

Applications of LCPCF

With the advantage of externally controlled tunability, LCPCFs have been employed for various all-fiber tunable photonic device applications. Thermal, electrical or all-optical tuning has been employed for the demonstration of a range of all-fiber devices such as spectral filters, polarizers, polarization controllers. Thermal tuning of LCPCF has been employed for various applications [60-62]. All-fiber devices such as tunable notch filters [63], a Gaussian filter for spectral shaping [64], a tunable bandwidth bandpass filter [65] based on thermal tuning of LCPCFs have all been demonstrated. All-optical modulation in dye-doped NLC infiltrated PCF was demonstrated using a pulsed laser to modulate the spectral position of the bandgaps [66].

Electrical control of the orientation of LC molecules in LCPCFs is useful for many applications, as the refractive index can be adjusted in a much wider range than by using thermal or optical means. The application of an electric field breaks the symmetry of the fiber and induces a polarization dependence of the transmission, which is not present when using thermal and optical means. Among the early demonstrations of electrical tuning of LCPCF, F Du et al [67] demonstrated an electrical tunable fiber-optical switch for applications in optical communications. The use of a dual frequency NLC for infiltration allowed the continuous electrical tuning of LCPCF for applications in an all-fiber polarization controller [68]. Dynamic long period gratings were demonstrated in LCPCF by applying periodic
electric field using a comb electrode for application as a tunable filter [69]. An all-fiber polarimeter was demonstrated using LCPCF, with the device integrated into a silicon v-groove assembly with two orthogonal sets of electrodes to control the polarization axis [70].

The use of a custom-made high refractive index glass based PCF infiltrated with LC was investigated in [71]. The thermal and electrical tunability of the LCPCF was studied and the structure showed low-loss propagation and high birefringence tunability. The work was interesting as the material of the PCF had a refractive index higher than the LC used for infiltration and the LCPCF guided light by an index guiding mechanism. The influence of temperature, electric field and hydrostatic pressure on the propagation properties of LCPCF were studied and their use as optical sensors for these parameters were suggested [72, 73]. Although there have been various studies performed on the thermal and electrical tunability of LCPCFs for tunable device applications, the possibility of using these structures as optical sensors particularly as electric field sensors has not been explored in detail. Due to their all-fiber nature LCPCFs potentially possess the relevant properties and characteristics for them to be used as all-fiber optical sensors for applications in optical sensing of a variety of physical parameters. The large electro-optic response of LCPCFs in particular can be utilized for the fabrication of all-fiber electric field sensors.

1.4 Aim and Objectives of the Research

There is a growing demand for tunable photonic devices in optical communications and optical sensing systems that have a compact and simple design, low power consumption and are based on cost-effective technologies which allow for large
scale production and ease of installation. For various applications in optical communications and optical sensing there is a requirement for technologies that allow for the fabrication of tunable photonic devices with an all-fiber device configuration that is compatible with existing fiber optical networks.

LCs with their high anisotropy combined with photonic crystal fiber provides a suitable common platform to address the requirement of an all-fiber device configuration for tunable photonic devices for applications with optical communication system and optical sensing.

The aim of this research is to: investigate the use of liquid crystal materials in both bulk-type and all-fiber device configurations for tunable photonic device applications in both optical communications and optical sensing systems.

The specific objectives of the thesis are:

- The development of a fast tunable filter employing the microsecond order switching times of ferroelectric LC for the demodulation of multiple sensors in a multiplexed optical sensing system.
- To investigate the electrical tunability of the photonic bandgap transmission of LCPCFs for the development of all-fiber tunable photonic devices for application in optical communication systems.
- The development of a novel technology for all-fiber based electric field sensing using the electrical tunability of LCPCFs and to investigate the dependence of the applied electric field frequency on an LCPCF based electric field sensor.
- To study an LCPCF based electric field sensor in a polarimetric sensing scheme together with control on LC infiltration length to develop a sensor that can be optimized for measurement in a given electric field range.
To investigate the directional electric field sensitivity of a non-circular core PCF infiltrated with LC for applications in all-fiber based 2-dimensional electric field sensing.

1.5 Thesis Overview and Structure.

This dissertation is focussed on the modelling, design and experimental demonstration of LC based tunable photonic devices for applications in optical communication and optical sensing systems with an emphasis on all-fiber device configurations.

In chapter 2 the modeling of a ferroelectric liquid crystal (FLC) based Lyot tunable filter is performed based on the Jones matrices method to evaluate the design parameters of an experimental demonstrator of a channel dropper for the demodulation of multiple Fiber Bragg Gratings. The Lyot filter in each stage uses a passive retarder and an FLC cell is used in a surface stabilized FLC configuration as a variable retarder. The microsecond order switching times of a FLC cell and its potential to be used for the interrogation of multiple FBGs are discussed. The operation of the filter demonstrating a tunable bandpass response for application as a channel dropper is also presented.

In chapter 3, all-fiber tunable devices for optical communication systems based on photonic crystal fibers infiltrated with LC material are dealt with. The following two device applications are presented.

I. All-fiber tunable notch filter

An all-fiber tunable notch filter employing ferroelectric LC infiltrated PCF is demonstrated in the wavelength range from 1500 nm to 1600 nm. The device,
based on the principle of photonic bandgap transmission, has a ~ 22 nm tuning range for the notch.

II. All-fiber variable optical attenuator

The use NLC infiltrated solid core PCF as an all-fiber broadband variable optical attenuator is presented. The electrical controlled device has a flat response for all its attenuation states in the wavelength range from 1500 nm – 1600 nm and provides a ~ 40 dB extinction ratio. The attenuation level is shown to have a linear response relative to the applied voltage.

In chapter 4, a novel technology for the fabrication of all-fiber based electric field sensing based on LCPCF is investigated and presented. Different types of PCFs infiltrated with different LC materials and their transmission responses with an applied electric field are studied and presented. The operation of the sensor based on photonic bandgap mechanism is demonstrated in both transmission mode as an in-line sensor and in reflection mode as an end-point sensor. The sensor is utilised in an intensity based measurement scheme at 1550 nm. The transmitted and reflected powers are shown to change in a linear fashion with electric field intensity. The temperature dependence of the infiltrated PCF is studied to evaluate the effect of temperature variations on the electric field sensitivity of the device.

Chapter 5 is focussed on an experimental study of the dependence of the transmission response of a NLC infiltrated PCF on the frequency of an externally applied electric field. Due to the millisecond response times of nematic LCs the time varying transmission response of the LCPCF is dependent on the frequency of the applied electric field in the range from 50 Hz – 1 kHz. An analysis of the time varying transmission response is performed and an appropriate fitting function is
used to approximate the time response. This fitting procedure is used to simultaneously extract the amplitude and frequency of the applied AC electric field. In chapter 6 the operation of polarimetric electric field sensors based on selectively infiltrated PMPCF is demonstrated. The influence of the length of the infiltrated section of the PCF subjected to an electric field on the polarized transmission of the PCF is studied and presented. NLC materials showing both planar and splay alignment within PCF holes are studied. With control of the length of the infiltrated section subjected to an electric field it is demonstrated experimentally that the phase retardance produced by the PCF can be controlled in order to achieve a monotonically varying polarized transmission response in a particular electric field range. With the use of splay aligning NLC a larger measurable e-field range for the sensor is demonstrated and presented.

In the latter part of chapter 6, the directional electric field sensitivity of selectively infiltrated PMPCF for use as an all-fiber sensor for two dimensional electric field sensing is studied. Based on an initial infiltration length optimization, the orientation of the fiber polarization axis with respect to the applied electric field direction is studied in a polarimetric scheme in order to evaluate the directional sensitivity of the infiltrated PCF. It is shown that for a fixed electric field intensity in the measurable range the sensor allows for the determination of the electric field direction thereby allowing for the estimation of the transverse components of the externally applied electric field.

Chapter 7 concludes the thesis and gives an overview of the future challenges and possible extensions of the work presented in the thesis.
Chapter 2

Liquid Crystal based Channel Dropper for Demodulation of Multiple FBG Sensors

2.1 Introduction

Fiber Bragg Grating (FBG) [74] sensors along and wavelength division multiplexing (WDM) allow for multi-point sensing of various parameters such as stress, strain and temperature. For the viable implementation of such systems FBG interrogation systems are required that are capable of detection, tracking and measurement of small wavelength shifts which is both accurate and fast. Both active and passive detection schemes for demodulation of multiple FBG sensors are employed depending on the requirements. Passive schemes depend on linearly wavelength dependent devices for measurement of the Bragg wavelength and do not employ any electrical, mechanical or active optical devices. On the other hand, active detection schemes involve tracking, scanning, or other demodulation mechanisms to monitor the wavelength change. Fast measurement is a requirement for multipoint monitoring based FBG sensing applications, where dynamic measurements are needed, for example, the measurement of vibrations in structures, which can be in the order of kHz.

Due to the wavelength encoded nature of FBG sensors, FBG sensor arrays can be interrogated either by the use of a broadband light source and a tunable receiver or
by a tunable narrowband light source and a broadband receiver. The basic requirement for an FBG sensor demodulation system based on passive schemes is a high speed multiplexing capability facilitated by a tunable filter to separate the responses from multiple sensors. The use of a high-speed ratiometric wavelength measurement system based on macro-bend fiber based edge filter [75] enhances the measurement speed. To fully exploit the advantage of high measurement speed in the case of demodulation of multiple sensors, the ratiometric wavelength measurement system should utilize a very fast tunable filter often referred to as a channel dropper.

The optical filter types suited for the applications above can be tuned using a variety of techniques which include mechanical methods, electromechanical techniques and temperature tuning of the birefringence of the filter elements. Tuning in the optical domain also has been realized by fiber based Fabry-Perot filters (FPF) [76] and acousto-optic tunable filters (AOTF) [77]. These filters have demonstrated improved performance in terms of speed of operation (multiplexing capability) but a significant disadvantage is their high power consumption.

Nematic liquid crystals have been studied and implemented as tuning materials for filters [78, 79]. Although tunable filters based on nematic liquid crystals exhibit improved optical filter performance by comparison to FPF and AOTF, their applicability to high speed operation is questionable due to the slow response time of the nematic LC material. Ferroelectric liquid crystals (FLC) with surface-stabilized structures [80] possess fast switching speeds (~ microseconds), bistability, excellent electro-optic response, larger switchable birefringence and better phase stability upon repeated electronic switching [81].
This chapter describes the theoretical modelling, design and experimental demonstration of a Surface Stabilized Ferroelectric Liquid Crystal (SSFLC) based tunable filter functioning as a channel dropper for demodulation of multiple FBG sensors. In section 2.2, a brief description of the complete demodulation system based on a ratiometric wavelength measurement system enabled by the SSFLC channel dropper is provided. In this section the theoretical modelling based on Jones matrices method and design of the tunable filter are also described. The tunable filter design is based on a 3-stage Lyot type configuration. In section 2.3 the experimental design and the analysis of the tunable filter transmission response is performed and presented for use as a channel dropper for demodulation of multiple FBG sensors.

2.2 Theoretical Modelling and Design of the Tunable Channel Dropper

The schematic structure of the FBG sensor layout and interrogation system for a WDM based FBG sensors array are shown in figure 2.1. Light from the broadband source is launched into a 3 dB coupler and is passed through a single mode fiber containing an array of FBG sensors. The light reflected back from the grating is passed through the FLC tunable filter which acts as a channel dropper controlled by the voltage applied to it. In this arrangement, the filter opens a relatively narrow transmission passband surrounding the central reflection wavelength of one of the FBGs at a time. Following the FLC based channel dropper, the ratiometric wavelength discriminator accurately determines the exact instantaneous value of the FBG sensor wavelength. As the voltage applied to the FLC channel dropper
changes, the passband is dynamically tuned within the overall spectral range to progressively cover each sensor in the complete sensor array.

2.2.1 Lyot Filter Configuration

The filter configuration employed for the channel dropper is based on the work of Lyot and Ohman [82]. In a Lyot-type interference tunable filter the wavelength dependence of polarization induced by multiple-order waveplates is manipulated to produce a wavelength dependent transmission. The Lyot filter can be considered as a series of individual filter stages each consisting of a fixed/passive retarder and a variable/tunable retarder placed between parallel polarizers. The exit polarizer of the previous stage acts as the input polarizer for the following stage. The thickness, and therefore the retardation of the birefringent elements, increases geometrically in powers of two for each successive stage of the Lyot filter. The fixed retarder, which is a birefringent material, has its optical axis parallel to the interface between the

Figure 2.1: The schematic of the Wavelength Division Multiplexing based FBG sensor array and its interrogation system

29
stages at an angle of 45° with respect to the direction of the input polarization. This ensures maximum suppression of the light with a polarization orthogonal to that of the second polarizer at the output of the unit. Wavelengths which are in phase at the exit polarizer constructively interfere contributing to the total transmission.

Tunable Retarder based on Surface Stabilized Ferroelectric Liquid Crystal (SSFLC)

A surface stabilized smectic C* liquid crystal is employed as the tunable retarder for the Lyot filter. In a smectic C liquid crystalline phase molecules form a layered structure with average orientation of the molecular long axis, denoted by unit vector \( n \), are tilted at an angle \( \psi \) to the layer normal (z axis). When the smectic C phase comprises chiral molecules, the chiral version of the smectic C phase is formed. Figure 2.2 shows the schematic of LC molecular orientation with respect to the layer normal direction for the cases of smectic C and smectic C* LC. One of the effects of chirality of the molecules is to cause the azimuthal angles of the directors to precess slowly from one layer to the next. This creates a macroscopic helical structure with its axis along the layer normal, which tends to have a pitch of around 100-1000 layers. The changes of the azimuthal angle of the directors with respect to the layer normal in the smectic C* phase result in the changes in symmetry of the system and there is a break in the rotational degeneracy of the molecules about their axes. This hinders rotation of the molecules about their long molecular axis and allows a net spontaneous polarization to exist perpendicular to the molecular tilt plane. Hence smectic liquid crystals are ferroelectric [83].

The chirality of the molecules also causes a macroscopic helical structure to exist such that the polarization direction precesses slowly from one layer to the next, thus
on a macroscopic level there is not net polarization. However, in many instances of the use of smectic C* liquid crystals, they are confined to a cell geometry in such a way that the helical structure is suppressed, which is often referred to as surface stabilized state.

If it is assumed that the device is sufficiently thin such that the helical structure is suppressed, then there are two possible stable uniform ground states. In one state the directors are on one side of the smectic cone, and the polarization is pointing upwards, but in the other state the directors are on the other side of the cone and the polarization is directed the opposite way. The system in the surface stabilized state is bistable and external electric field can be used to switch between the two states.

Figure 2.2: LC molecular orientation with respect to the layer normal in the case of smectic C and smectic C*.
The tunable retarder for the current Lyot filter design is based on a ferroelectric liquid crystal material in a surface stabilized configuration, whose optical axis is orthogonal to the direction of the input polarization and can be switched ideally between two stable positions (0° and 45° with respect to the input polarization) by application of an electric voltage above the switching threshold value [83]. The resulting change in the effective refractive index produces the variation in the retardance which will in turn change the peak transmission wavelength of the filter, thereby facilitating tunability.

The design of the three stage Lyot filter is depicted in figure 2.3. The direction of propagation of light is along the z axis, the parallel polarizers are aligned in the x-y plane with their axis along the x-direction. The fixed and tunable retarders are also aligned in the x-y plane so that their optic axes are orthogonal to the propagation direction of light, with rotation of axis in the x-y plane. The fixed retarders have

![Figure 2.3: The three-stage Lyot filter consisting of tunable and fixed retarders. The design includes four linear polarizers (P1 – P4), three fixed retarders (PR1 – PR3) and three electrically controlled tunable retarders (TR1 – TR3).](image-url)
their optical axes oriented at 45° to the input polarization as shown in figure 2.4 and the tunable retarders are aligned such that their axes can flip between states at 45°, in the x-y plane, with the solid line parallel to the x-axis being the orientation in the unswitched state (OFF state) and the dotted line showing the switched state (ON state).

2.2.2 Simulation of the Transmission Spectrum of the Filter

In order to evaluate the filter characteristics and to optimize its design, the transmission spectra of a 2-stage and a 3-stage Lyot filters were simulated using the 2 x 2 Jones matrix methods [84] and analyzed. The Jones matrix method is chosen for the simulations due to its simple 2 x 2 matrix formalism with the ability to take into account the phase correlation between the birefringent elements. The method assumes that the incident beam is totally polarized (degree of polarization = 1) can be represented by its Jones vector after passing through an optical element,
transforms into the emergent beam represented by another Jones matrix and that the
process can be mathematically described using a 2 x 2 matrix representing the
action of each optical element. In the Jones matrix formulation each optical element
that the beam encounters can be represented by a 2 x 2 Jones matrix and the
transmission at the exit of the final optical element can be obtained by a simple
matrix multiplication of Jones matrices in the order of the light propagation through
each element. The method does not take in account the losses incurred within the
different optical elements and assumes an ideal parallel alignment of the optical axis
of the polarizers and birefringent elements. The Jones matrix for a linear polarizer is
given as:

$$\begin{pmatrix}
0 & 0 \\
0 & 1 \\
\end{pmatrix}$$  \hspace{1cm} 2.1

and that of a retarder with its optic axis rotated by 45° is given as:

$$W(\lambda) = \begin{pmatrix}
\cos(\frac{\delta_p(\lambda)}{2}) & -i\sin(\frac{\delta_p(\lambda)}{2}) \\
-i\sin(\frac{\delta_p(\lambda)}{2}) & \cos(\frac{\delta_p(\lambda)}{2}) \\
\end{pmatrix}$$  \hspace{1cm} 2.2

where $\delta_p(\lambda)$ is the retardance at incident wavelength $\lambda$, between the extraordinary
and ordinary rays at the exit of the retarder with a thickness $d$, birefringence
$\Delta n = n_e - n_o$, given as:

$$\delta_p(\lambda) = \frac{2\pi\Delta nd}{\lambda}$$  \hspace{1cm} 2.3

The Jones matrix for the tunable retarder is obtained in the same manner by
substituting the retardance as obtained by equation (2.3) with the corresponding
dispersion relationships for the material of the tunable retarder. For the subsequent
stages, namely the second and third, the retardance is twice and four times
respectively that obtained with the single stage filter.

The 2 x 2 rotation matrix for polarization state rotation by an angle $\theta$ is given as,
To theoretically test the suitability of different birefringent materials for passive/fixed retarders for the current application the following materials were considered. These were considered on the basis of their ease of commercial availability in fixed shapes and sizes as required for the Lyot filter configuration.

The retarders considered for the study were lithium niobate, nematic liquid crystal material (MLC-9300 Merck) and quartz crystals. The following dispersion relations for these birefringent materials for the fixed retarders were considered,

Quartz crystals:

\[
\begin{align*}
n^2_1(\lambda) & = 2.3849 - 0.01259\lambda^2 + 9.36476 \left(\frac{10^8}{\lambda^2}\right) - 1.947 \left(\frac{10^6}{\lambda^2}\right) + 1.6518 \left(\frac{10^4}{\lambda^2}\right) + \frac{0.01079}{\lambda^2} \\
n^2_2(\lambda) & = 2.35728 - 0.0117\lambda^2 + 5.9262 \left(\frac{10^8}{\lambda^2}\right) - 4.4536 \left(\frac{10^6}{\lambda^2}\right) + 1.34143 \left(\frac{10^4}{\lambda^2}\right) + \frac{0.01054}{\lambda^2}
\end{align*}
\]

for lithium niobate at room temperature (at 300 K),

\[
n^2_1(\lambda) = 4.913 + \left(\frac{0.1188}{\lambda^2 - 0.46}\right) - 0.0278 \lambda^2 ; \quad n^2_2(\lambda) = 4.5567 + \left(\frac{0.0234}{\lambda^2 - 0.42}\right) - 0.0224 \lambda^2
\]

and for a nematic LC (MLC-9300):

\[
\begin{align*}
n_0 & = 1.5707 + \frac{1.056 \times 10^4}{\lambda^2} ; \quad n_\alpha = 1.4688 + \frac{0.5822 \times 10^4}{\lambda^2}
\end{align*}
\]

The ferroelectric LC material available for the design of the tunable retarder is FELIX 019/000 (AZ Electronics). The material has a smectic C phase in the temperature range from 2 – 60 °C. The material has a tilt angle of ~ 19°, which implies that in a surface stabilized configuration the tunable retarder cell would switch between 0° and 38° in the OFF and ON states respectively. This is lower than that ideal assumed angle of polarization state rotation of 45° for the tunable retarder cells in the theoretical considerations. The ordinary and the extra-ordinary
refractive indices of the material are 1.487 and 1.651 respectively, measured at 30 °C at 589.3 nm. The material has a helical pitch ~ 40 µm. The wavelength dependent birefringence ($\Delta n$) of this material was deduced in the following manner.

An FLC cell of known thickness (~ 5 µm) was used for the purpose and its polarized transmission was recorded between crossed polarizers in the wavelength range from 400 nm – 650 nm. The light transmitted through the cell between crossed polarizers as a function of wavelength can be expressed as:

$$T = A \sin^2 \left( \frac{\pi \Delta n d}{\lambda} \right) + O$$

where $A$ is the scaling factor depending on the orientation of the optical axis of the retarders with respect to the polarizers, $d$ is the cell thickness and $O$ is an offset to account for the losses incurred due to the different optical elements present in the tunable filter layout. This function was used to perform a fitting on the transmission response of the FLC cell. The extended Cauchy equation [83] for the birefringence $\Delta n$ was used to include the wavelength dependence.

$$\Delta n(\lambda) = k \left( \frac{\lambda^2 \lambda^*}{\lambda^2 - \lambda^*} \right)$$

where $k$ is the proportionality constant and $\lambda^*$ is the mean resonance wavelength.

Figure 2.5 below shows the measured FLC cell transmission response along with the fit based on the above equations. The values of the parameters $k$ and $\lambda^*$ obtained for Felix 019/000 were ~ 3.04 x $10^6$ nm$^{-2}$ and ~ 221.5 nm respectively. These values of the parameters were utilized to generate the wavelength dependent birefringence of the tunable retarder in the wavelength range from 1500 nm – 1600 nm.

Assuming ideal orientation of the passive retarder and tunable retarder axes and zero absorption or losses within the optical elements of the Lyot filter, the optical
axis of the FLC is oriented parallel to the input polarization in the unswitched state, with no effect on the transmission spectrum. This is represented by the simple 2 x 2 rotation (equation 2.4) matrix with the angle \( \theta_{FLC} = 0^\circ \). In the switched state the FLC optical axis is parallel to that of the fixed retarder or at 45° to the x-axis, which is represented by the rotation matrix with the angle \( \theta_{FLC} = 45^\circ \).

![Figure 2.5: The transmission response of an SSFLC cell between crossed polarizers.](image)

In order to demonstrate the ability of the SSFLC channel dropper to demodulate signals from two FBGs, the Lyot filter is designed as follows. It is assumed that there are two FBGs present in the sensor system with Bragg wavelengths centered at 1530 nm and 1550 nm. The optimum design for the Lyot filter in the simulations are set in order to obtain a peak transmission at 1530 nm in the unswitched state and at 1550 nm in the switched state. A transmission bandwidth \( \Delta \lambda_{FWHM} \sim 7 \) nm and a free spectral width (FSR) of \( \sim 40 \) nm are required for channel dropper to demodulate the two FBGs with their Bragg wavelengths centered at 1530 nm and
1550 nm. The theoretical simulation based on Jones matrices is carried out for the Lyot filter to obtain the set design parameters. The transmission spectra obtained from the simulations are shown in figure 2.6, 2.7 and 2.8. The desired peak transmission wavelength of the filter in the off state can be achieved by varying the thickness of the fixed retarder. For a Lyot filter, the peak transmittance is primarily dependent on the passive retarders and their thicknesses. Initially the thickness of the fixed retarder was optimized for the filter to give transmission peak centered at 1530 nm, in the two stage filter with the FLC optical axis aligned along the y axis (unswitched state – $\theta_{FLC} = 0^\circ$). The optimization was performed by careful alteration of the passive retarder thickness during each

![Figure 2.6: The transmission spectra of two-stage and three-stage Lyot filters with lithium niobate as the fixed retarder. With a change in the tunable retarder orientation the peak transmission switches from 1530 nm to 1550 nm.](image-url)
simulation cycle to ensure the transmission peak is centered at the desired wavelength. The thickness of the fixed retarder was also optimized to give a free spectral range of 40 nm in the range from 1530 nm – 1570 nm and to provide a bandwidth of ~ 7 nm ($\Delta\lambda_{\text{FWHM}}$) for the transmission peak as required for the optimum design. The thickness for the fixed retarder has to be carefully chosen as this determines the free spectral width of the filter. The thickness of the tunable retarder element was optimized next to obtain a transmission peak centered at 1550 nm with the optical axis of the tunable retarder (FLC) oriented at 45° ($\theta_{\text{FLC}}$), in the switched state.

As shown in figure 2.5, the peak transmission of the tunable retarder is at 1530 nm in the unswitched state and switches to 1550 nm with the application of a switching
voltage. The optimized thickness for the passive retarder necessary to obtain the desired free spectral width and filter bandpass was estimated to be ~ 405 µm and that of the tunable retarder was found to be ~ 8.4 µm. It can be clearly seen that there is a narrowing of the full width at half maxima (FWHM) of the filter from ~ 16 nm to 7 nm, when the third stage is included. A similar transmission behavior is observed for the two and three-stage filters with the nematic LC material as the fixed retarder (figure 2.7).

Figure 2.8: Transmission spectra of a three-stage Lyot filter with quartz crystals as fixed retarders, generated at different wavelengths by changing the tunable retarders thickness for the switched state.

Though the passive retarder thickness for this case is less than that of the lithium niobate in the previous case, there is a notable increase in the resolution (~ 1 nm) of the filter with the passive retarder, this is due to the higher birefringence of the nematic LC material.
On performing a comparison of the transmission characteristics of the two stage and three stage filters in each case, a narrowing of the filter bandwidth is observed. The free spectral width of the filter remains the same. The third stage is required for the filter to have the desired $\Delta \lambda_{\text{FWHM}}$ of $\sim 7$ nm for the filter bandwidth. The inclusion of a fourth stage will further reduce the filter bandwidth but also increase the losses due to the presence of more optical elements in the experimental set-up of the Lyot filter.

The transmission peaks obtained for a three-stage filter with quartz crystal are shown in figure 2.8, here it can be seen how the peak transmission wavelength of the filter in the switched state can be easily changed by varying the thickness of the tunable retarder. The figure shows five peaks situated at 1530 nm to 1570 nm with a spacing of 10 nm, each obtained by carefully selecting a suitable thickness (using equation 2.3) for the tunable retarder or FLC cell thickness. The optimized thickness for the quartz crystal as the fixed retarder in this case for the first stage was found to be $\sim 4570.0 \mu m$ and the thickness for the tunable retarder varies from $\sim 1.76 \mu m$ to $5.25 \mu m$ in order to obtain a peak transmission for the tunable filter at five equally spaced wavelength positions as shown in the figure 2.8.

It can be seen that any of these three materials can be used for design of the fixed retarder with the tunable SSFLC retarder by utilising them in the filter with an appropriate thicknesses. The use of a nematic LC as a material for the fixed retarder can be advantageous during experimental studies at relatively small thicknesses as it allows fine adjustment of the value of the retardance by applying an electric field. However, nematic LCs at thicknesses greater than 25 $\mu m$ introduce significant insertion losses due to the imperfections of the liquid crystal alignment. High orientational order in thick (> 25 $\mu m$) cells is usually observed only in regions close
to the aligning surface. In practice a nematic LC cell with a thickness of over 100 µm will exhibit weak orientational order and thus high insertion loss and as a result cannot be used as a fixed retarder. Nonlinear crystals like lithium niobate are expensive, as manufacturing of these crystals in the desired shapes and sizes with an appropriate axis orientation involves expensive fabrication techniques. Quartz crystals with appropriate thicknesses and with a moderate optical quality are simpler to fabricate and more economical. They are the most commonly used birefringent materials used for optical retarders.

2.2.3 Optimum Design for the Tunable Filter

The simulation results show that a thickness of ~ 4570 µm is needed for a quartz passive retarder in the first stage of the Lyot filter to obtain the transmission spectrum as shown in figure 2.9. The wavelength of the peak transmission in the switched state was found to be very sensitive to the thickness of the tunable retarder. The optimized thickness obtained from the simulation for all three cases with the three different types of retarders was found to be smaller than ~ 10 µm, which is less than ¼th of the helical pitch of the FLC material, a major requirement for achieving a surface stabilized structure [80]. In practice it is necessary to ensure that the thicknesses of both the fixed and tunable retarders are accurately set in every stage, in order to obtain transmission spectrum characteristics matching the theoretical simulations. The thickness tolerances for the fixed retarders were estimated as ± 50 µm and for the tunable retarders as ± 0.2 µm. The optical axis orientation angle tolerances for both the fixed and passive retarders were estimated as ± 0.5°. With the resolution of ~ 6 nm and free spectral range of ~ 40 nm, the
A filter can separate responses from 8-10 FBGs with equal wavelength spacing within the wavelength range from 1530 nm – 1570 nm as determined by the free spectral range. Also, by increasing the number of stages to increase the resolution and by selectively switching the tunable retarder at the different stages of the filter, multiple states can be created, which would facilitate the inclusion of a larger number of FBGs into the system.

Figure 2.9: Simulated transmission spectrum of the 3-stage Lyot filter in the unswitched state.

The simulated transmission spectrum of the three stage Lyot filter in the unswitched state is as shown in figure 2.9. The optimum design parameters were obtained and the thicknesses of the passive as well as the tunable retarder were estimated. A free spectral width (separation between peak wavelengths) of ~ 50 nm and a filter
bandpass of ~ 6 nm are obtained for the 3-stage filter in the current design. In the wavelength range of interest, 1520 nm -1580 nm, the filter is designed to have a peak transmission at 1550 nm in the unswitched state.

2.3 Experimental Demonstration of the FLC Tunable Channel Dropper

2.3.1 Fabrication of Passive and Tunable Retarders for the Lyot Filter

The optimum filter design parameters appropriate for an application of the filter as a channel dropper for the demodulation of FBG sensors were estimated using theoretical simulations based on Jones matrices as mentioned in the previous section. Custom-made quartz crystals (AR coated) with specifications based on the theoretical simulations performed were used as passive retarders in each stage. The thicknesses of the quartz crystals used in the first, second and third stages are ~ 5.01 ± 0.01 mm, 10.02 ± 0.01 mm and 20.04 ± 0.01 mm respectively. A broadband source (Superlum Diodes Ltd., 1490-1640 nm) and an optical spectrum analyzer were used to study the transmission characteristic of each filter stage by arranging the filter components on a fiber U-bench (Thorlabs). The transmission spectrum of the 3-stage filter is calculated from the experimentally recorded transmission response of the individual stages.

The tunable retarder cells for each stage were fabricated using the standard liquid crystal cell fabrication technique. The FLC cells were fabricated using Indium tin oxide (ITO) coated glass microslides (~ 1 x 1 cm). The glass surfaces were coated with a polymer by spin coating and then were unidirectionally rubbed in order to create planar alignment of the FLC molecules. The required thicknesses for the FLC
cells were obtained by placing Teflon spacers with suitable thicknesses. The thicknesses of the FLC cells were estimated by recording the empty cell transmission. The wavelength-dependent transmitted intensity of the empty cell shows an interference pattern which directly relates to the thickness of the gap between the cell walls. By properly assigning the interference order (k-values) to the transmittance maxima obtained at different wavelengths (λ), the thickness of the cell d, can be estimated using the following relationship, k = (2.d)/λ [86]. The estimated thickness for the FLC tunable retarder in first stage was ~ 6.0 ± 0.05 µm. For the second stage two FLC cells of ~ 6.0 ± 0.05 µm thickness were used and for the third stage four FLC cells of ~ 6.0 ± 0.05 µm thickness were used.

2.3.2 Experimental study of the Filter Transmission Spectrum

The measured transmission spectrum of the Lyot filter in the unswitched state in the wavelength range of 1520 nm – 1580 nm is as shown in figure 2.10. The transmission peak of the spectrum is found to be centered on 1550 nm and a filter bandpass of ~ 6 nm is obtained experimentally. Figure 2.11 shows the measured transmission spectrum of the filter in the switched state, on the application of voltage of 10 V DC.

On the application of the electric field, the peak transmission of the filter is found to switch to 1573 nm. The peak transmission of the switched state is determined by the tunable retarder thicknesses and the birefringence of the tuning element (FLC cell). The transmission peak in the switched state can be manipulated by varying the thicknesses of the tunable retarders. The experimental results shown in figure 3 are plotted along with the numerical solutions of the theoretical curves (solid lines) generated used the Jones matrix method. There is a good match between the
experimental results and the theoretical data in the case of the unswitched state, since the effect of the FLC cells is absent in this case.

In the switched state, a slight mismatch occurs due to the fact that the FLC material used in our experiments has a tilt angle of ~ 38°, whereas theoretically we have considered that the FLC cell molecules undergo a director reorientation of 45° on the application of the switching voltage. The losses incurred when light passes through the FLC cell glass plates and the absorption in the FLC material also contributed to the mismatch. Furthermore, inaccuracies in the measurement of the FLC cell thicknesses have led to the mismatch in the peak wavelength for the experimental and theoretical curves. The peak wavelength of the filter shifts from 1550 nm (unswitched state) to 1573 nm (switched state) with a shift ~ 23 nm. The filter's passband can be further narrowed by including more stages in the filter, but it should be noted that inclusion of more stages will add to the total insertion loss of the filter.

Figure 2.10: Theoretical and experimental transmission spectra for the 3-stage Lyot filter in the unswitched state.
The filter design as demonstrated here can be used effectively as a channel dropper for a ratiometric wavelength measurement system. The switching of the SSFLC cells is obtained with a modest applied voltage of 10 V DC. The free spectral width (peak separation) of ~ 50 nm and a filter passband of ~ 6 nm obtained experimentally is sufficiently wide to extract the reflection spectrum of a single FBG along with the shift in wavelength when there is a change in the parameter being sensed. As an example, if the parameter being sensed is strain, an FBG with strain sensitivity of ~ 1.2 pm µε⁻¹ centered at 1550 nm will shift of its peak transmission wavelength to a wavelength within the range of about 2 nm around 1550 nm, if it experiences strains of the order 2000 – 3000 µε. This is well within the filter passband of ~ 6 nm of the filter design demonstrated here. With the microsecond order switching speeds of the SSFLC material, a filter design as demonstrated here could also be used for applications with FBG dynamic strain.

Figure 2.11: Theoretical and experimental transmission spectrums for the 3-stage Lyot filter in the switched state on the application 10 V DC to SSFLC cells in each stage.
sensing where the FBGs are subjected to dynamic strains with frequencies of the order of kHz. The power fluctuations in the incident light and the variations in the transmission power of different wavelengths as they pass through the filter will not affect the measurements at the receiving end as the ratiometric wavelength measurement system is independent of any input power fluctuations. Taken together the tunable filter and the ratiometric system form a complete and high speed system for the demodulation of multiple FBG sensors.

2.4 Summary

In this chapter, the discrete wavelength tunability of two and three-stage Lyot polarization interference filters with different materials for fixed retardance and a surface-stabilized FLC material as a tuning element has been analyzed theoretically using the Jones matrix method. The discrete wavelength tunability of a three-stage Lyot polarization interference filter with quartz crystals as passive retarders and surface stabilized ferroelectric liquid crystal cells as tunable retarders was designed and experimentally verified. The choice of the appropriate material for each optical element within the filter was studied, with regard to the birefringence and retardance. The analysis suggested that quartz crystals as materials for the fixed retarders with appropriate choice of thicknesses in each stage can result in transmission peaks centered at any predetermined wavelength values but that this also pre-determines the free spectral width of the filter. The thickness and birefringence characteristic of the filter design depicted in this chapter are optimized to switch between any two wavelengths in the range of 1530 – 1570 nm, with a free spectral width of ~ 40 nm and a bandpass of ~ 6.0 nm. It is shown theoretically that the tunable Lyot polarization filter with a quartz crystal as a fixed
retarder and surface-stabilized FLC material as a tunable retarder with the appropriate design parameters can be efficiently used with the ratiometric wavelength measurement system to construct a highly efficient demodulation system for multiple FBG sensors.

A free spectral width of ~ 50 nm and a filter bandpass of ~ 6 nm were obtained experimentally for the filter design. The electrical tunability of the filter is obtained with very low applied voltages. A tunable filter of this type can be used as a front-end to a ratiometric wavelength measurement system, to function as a channel dropper. Such systems have potential applications in WDM-based demodulation of FBG sensors, commonly found in the case of distributed strain sensing, for example for structural monitoring, industrial sensing, FBG sensors based haptic-telerobotic surgical systems.

The use of a ferroelectric liquid crystal tunable device functioning as a channel dropper is suitable for the particular application of demodulation of multiple FBG sensors. The current tunable filter configuration uses a fiber U-bench with fiber to free space collimators to interface the bulk optical elements of the Lyot filter. Given bulk optical configuration, it is easier to fabricate retarders with the required shapes and sizes as per the specifications of the filter. This allows for accurate control of the tunable filter transmission response. However, it should be mentioned that tunable filters based on bulk/free space device configurations have implementation issues with an existing fiber optic networks arising due to the difficulties with coupling and integration. For most practical applications with optical communications and optical sensing all-fiber device configurations are most suitable and a common requirement.
Chapter 3

LCPCF based All-fiber Tunable Devices

3.1 Introduction

For various practical device applications in optical communications an all-fiber device configuration is a major requirement. This enhances the device compatibility with existing fiber-optic technology, facilitating ease of integration and coupling. With all-fiber devices the shortcomings of the bulk-type devices such as losses due to presence of a large number of optical components and complexity of coupling are eliminated. While in chapter 2 the operation of a ferroelectric liquid crystal based bulk type tunable filter for a specific application aimed at the demodulation of multiple FBG sensors was described, in this chapter the use of LC devices in all-fiber device configurations with a variety of applications in optical communications is explored. It has always been a challenge to incorporate active tunability with an all-fiber device configuration. For this purpose most technologies use external coatings/buffers or miniaturized active tunable devices based on, for example, integrating of an electro-optic crystal with a fiber. An all-fiber device configuration with an inherent tuning mechanism has not been truly feasible until the development of PCF [48]. With its typical air-hole micro-structure, PCF allows for the possibility of infiltrating the holes with various materials to achieve tunability in
the fiber propagation properties and thereby making it feasible to implement all-fiber tunable devices.

PCFs infiltrated with liquids and polymers have been demonstrated for tunable device applications [50, 51]. Among the materials selected for infiltration, LCs have proven to provide the largest tunable range owing to their high dielectric and thermal anisotropy. With LC infiltration and tunability possible by thermal and electrical means, various temperature and voltage controlled tunable all-fiber devices have been demonstrated [57].

In this chapter the operation of LCPCF based devices based on PBG and tuning mechanisms are experimentally studied for applications in optical communications. In section 3.2 a brief description of the PBG mechanism and the electrical tuning of photonic bandgap transmission are provided. Section 3.3 gives the details of the experimental demonstration of an all-fiber variable optical attenuator based on a NLC infiltrated PCF. The working principle and demonstration of an all-fiber tunable notch filter using ferroelectric liquid crystal (FLC) infiltrated PCFs are explained in section 3.4.

3.2 Photonic Bandgap Guidance and Tuning in LCPCFs

LC materials usually have refractive indices (both ordinary and extraordinary) higher than silica. Most commercially available photonic crystal fibers use silica as the fabrication material which has refractive index of ~1.45. Infiltration of LC materials into PCF can lead to a change in the guidance mechanism. The PCFs used for the experiments for this chapter were solid silica core PCFs. Solid silica core PCF such as large mode area PCFs (LMA PCF series from NKT photonics) and polarization maintaining PCF (PM-1550-01; NKT photonics) transmit light through
the modified total internal reflection mechanism [48]. Infiltration of an LC in the holey cladding region of these types of PCFs leads to a change in the guidance mechanism to PBG. On LC infiltration the holey cladding region takes on the refractive index of the LC which is higher than the core refractive index (silica), and thereby the transmission through such LCPCFs is governed by the photonic bandgaps formed in the periodic high index cladding region [87].

An Antiresonant Reflecting Optical Waveguide model [58] for microstructured optical fibers with low refractive index core surrounded by high index cylindrical inclusions was suggested by N. M. Litchnister et al [88]. In this model it was suggested that the confinement loss of such fibers is strongly dependent on wavelength. Also, the position of loss maxima are largely determined by the individual properties and the thickness of the high index layers rather than their positions and numbers (periodicity). The spectra of these fibers can be tuned by changing the refractive index of the high index inclusions with potential applications for designing tunable photonic devices.

Understanding of the behaviour of LC molecules within the holes of PCF on the application of electric field is very important for determining the tunable spectral characteristics of the LCPCF. A long range orientation order for the LC molecules within the PCF holes is a requirement for photonic bandgap transmission through the LCPCF. Depending on the type of LC mixtures and their initial alignment within the PCF holes, the reorientation effect of LC on the application of voltage can cause a disturbance in the PBG condition. NLC mixtures which have a planar alignment within the PCF holes show threshold effects for LC molecular reorientation. The reorientation of the LC molecules begins above a threshold electric field referred to as the Freedericksz transition threshold [10, 89]. The
application of an external voltage above the threshold voltage reorients the NLC molecules in the direction of the electric field. Also, as the molecules begin to reorient, the formation of reverse tilted domains takes place which acts as an orientational defect [90]. These defect domains within the PBG structure act as scattering loss centres. The reorientation of the molecules combined with the formation of defect domains within the holes of the PCF causes decay in the long-range orientation order of the LC and leads to a disturbance in the PBG condition. As a result the light propagating through the core of the PCF escapes increasingly to the cladding region as the electric field strength is increased.

In such cases the effect of the externally applied voltage is to cause attenuation of the light propagation through the LCPCF. With an increase in the voltage and the continued reorientation of the LC molecules, the light propagating through the core increasingly escapes into the cladding and results in a gradual attenuation of light through the core of the LCPCF. In section 3.2 below, this behaviour of a nematic LC infiltrated PCF is used for the demonstration an all-fiber electrically tunable VOA.

The photonic bandgap transmission properties of the solid core LCPCF can also be externally tuned by applying an external electric field. In this case, the effect of the externally applied electric field is to change the effective refractive index of the filled cladding region (high index layer) and continuously change the photonic bandgap position of the LCPCF structure. FLC with its additional degree of translational order is likely to have better alignment characteristics within confined cylindrical geometries such as that of a PCF hole. FLCs have been shown to possess microsecond order response times due to the first order coupling between their macroscopic polarization and an applied electric field. Infiltration of FLC into PCF
can allow for electronic tuning of photonic bandgap transmission with potential applications in fast tunable devices for optical communications. In an FLC infiltrated PCF, as the applied voltage increases, the resulting torque produced by the spontaneous polarization and the applied electric field reorients the molecules within the holes of the PCF. Due to the combined effect of the reorientation of the FLC molecules within the holes of the infiltrated PCF on the application of the voltage, the effective refractive index of the cladding region changes. This causes the photonic bandgaps to shift with the application of an external electric field. The operation of FLC infiltrated PCF device employing active electronic tuning of the photonic bandgaps is explained and demonstrated in section 3.3.

3.3 Experimental Demonstration of an All-fiber VOA.

3.3.1 Fiber based VOAs

VOAs are widely used in optical communications and are a key element in optical networks for dynamic control of optical power levels in network channels. For example VOAs are used for power equalization in optical add/drop modules and optical cross-connects. They can also be used to switch on/off channels and protect receivers, for example to ensure that the input power level to a receiver is always lower than the overload threshold for the receiver, regardless of the optical path loss. In WDM networks VOAs are needed for gain adjustment to equalize power levels in multi-channels as amplifiers have wavelength-dependent gains. In addition, VOAs are used in dense wavelength division multiplexing (DWDM) systems to control wavelength and output powers of the distributed feedback laser diodes. There have been various approaches used for fabricating VOAs such as opto-mechanical systems, micro electromechanical systems, planar lightguide circuits
and thermo-optic methods [91-93]. However these approaches have the disadvantages of slow response time due to mechanical or thermal control, the difficulty of integration with other optical devices and high manufacturing costs. VOAs based on LC materials [94] particularly PDLC [95, 96] have been studied in detail, but these employ complex system configurations utilising free-space optics which increases cost and induces high insertion losses. Robustness, compact size and low cost are necessary requirements for VOAs in optical networks. An all-fiber configuration for a VOA solves the interface problem between a VOA and a single mode fiber (SMF), ensuring low insertion loss and negligible back reflections.

3.3.2 Design of an LCPCF based VOA

The fiber used for the demonstration of the LCPCF based VOA is the commercially available LMA-10 (Crystal Fibre A/S, Denmark) solid core PCF (Figure 3.1). The high-index solid core PCF has a diameter of ~ 10 µm, which is surrounded by seven rings of air holes arranged in a triangular lattice. The hole diameter is ~ 3.0 µm and the inter-hole spacing is ~ 7.0 µm while the cladding diameter is ~ 125 µm. The NLC mixture used to infiltrate the fiber is 5CB (Merck Ltd), which has a nematic phase at 22.5 °C – 35.5 °C and becomes isotropic at temperatures higher than 35 °C. The ordinary and extraordinary refractive indices of the NLC are ~ 1.52 and ~ 1.71 evaluated at 1550 nm using the Cauchy’s relations [97]. The specifications and properties of the LC materials and PCFs used for the experiments in this chapter are given in table 3.1 and 3.2.

A section of the LMA-10 fiber is used and one end is initially spliced to an SMF28 pigtail using a standard fusion splicer. The splice loss is minimised by optimising
the splicing conditions to achieve minimal PCF air-hole collapse at the splice joint. This was done by setting an appropriate fusion time and fusion current [98].

Table 3.1: Properties of the LC materials used for the study.

<table>
<thead>
<tr>
<th>LC</th>
<th>Δn</th>
<th>Δε</th>
<th>T_C (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5CB</td>
<td>0.19 (1550 nm; 20 °C)</td>
<td>10 (20 °C; 1 kHz)</td>
<td>35</td>
</tr>
<tr>
<td>FELIX 019/000</td>
<td>0.164 (589.3 nm; 20 °C)</td>
<td></td>
<td>82</td>
</tr>
</tbody>
</table>

Table 3.2: Specifications of the PCFs used for the study.

<table>
<thead>
<tr>
<th>PCF</th>
<th>d (hole diameter)</th>
<th>Δ (pitch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMA-10</td>
<td>3.3 μm</td>
<td>7 μm</td>
</tr>
<tr>
<td>PM-1550-01</td>
<td>Large hole – 4.5 μm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Small hole – 2.2 μm</td>
<td>4.4 μm</td>
</tr>
</tbody>
</table>

Figure 3.1: SEM image of the LMA-10 PCF cross-section.
The open end of the PCF was infiltrated with the NLC by immersing the cleaved end of the fiber into a drop of 5CB at room temperature so that the NLC gets drawn into the PCF air-holes due to capillary action. A typical infiltration length of ~ 2.4 cm was achieved. The infiltrated end was observed under a polarising microscope to ascertain the quality of infiltration, before subjecting it to the electric field to study its attenuation properties.

A small section less than 1 mm in length of the 5CB infiltrated LMA-10 PCF was observed under a polarising microscope to examine the effect of the applied voltage on the reorientation of the LC molecules. The infiltrated fiber was sandwiched between electrodes to allow the application of the voltage. Figure 3.2 shows the

![Figure 3.2: Photographs of the LMA-10 PCF section infiltrated with 5CB as observed under a polarizing microscope at voltages 0 Vpp, 200 Vpp and 370 Vpp at 1 kHz.](image)

photographs of the 5CB infiltrated section of the LMA-10 PCF as observed under the polarizing microscope in crossed polarizers mode at three different voltages.
The study was performed with visible light transmitted perpendicular to the PCF axis. In the crossed polarizers mode with the axis of the fiber aligned along the polarizer, the infiltrated holey region of the fiber transmits minimum light. This suggests that the LC molecules are mostly aligned along the axis of the fiber within the PCF holes. As the voltage applied to the infiltrated fiber is increased to 170 Vpp, the LC infiltrated region becomes brighter and a change in colour of the transmitted light is observed. The colour of the transmitted light changed as the voltage was increased further and infiltrated region was the brightest at the maximum voltage of 380 Vpp. The birefringence of the NLC infiltrated holey region of the PCF continuously changes with the applied field above the threshold voltage, this causes the change in colour when observed through the polarizing microscope. This observation confirms that LC molecules within the holes begin to reorient under the action of the electric field at a voltage of ~ 170 Vpp and undergo progressively larger reorientation as the voltage is increased further.

The experimental set-up to study the electronic tunability and attenuation properties of the infiltrated PCF is as shown in Figure 3.3. The infiltrated end was placed between two electrodes to allow the application of an electric field in a direction perpendicular to the fiber axis. The electric field was provided by a square wave voltage applied to the PCF using a waveform generator and a voltage amplifier. The light was launched into the PCF from the spliced end and was collected from the infiltrated end by butt-coupling it to another SMF pigtail using an XYZ nano-positioner stage. A broadband source was used together with an OSA to record the spectrum and a tunable laser source together with a high-speed power meter for the attenuation and time response studies.
3.3.3 Attenuation response and time response of an LCPCF based VOA.

In order to study the spectral properties and attenuation characteristics of the nematic LC infiltrated PCF, a square wave voltage of frequency 1 kHz is applied to the LCPCF device. Light from the broadband source is transmitted through the infiltrated section of the PCF and the spectrum at different voltages is recorded by the OSA. Figure 3.4 shows the spectral characteristics of the device in the wavelength range from 1500 nm – 1600 nm with a change in the applied voltage. The spectrum shows a flat response for the entire wavelength range as can be seen from figure 3.4. For applied voltages from 0 Vpp to 170 Vpp the spectral response of the fiber is that of the source and no change in the photonic bandgap transmission was observed in the wavelength range. Attenuation of the transmitted intensity is observed from a voltage of ~ 170 Vpp and attains its maximum value at a voltage of ~ 300 Vpp. The NLC molecules undergo continuous reorientation due to the application of the voltage and the optical power transmitted through the core of the
PCF reduces and is coupled increasingly into the infiltrated cladding region with an increase in voltage above 170 Vpp. This implies that the NLC molecules align themselves along the electric field direction as voltage increases, in this case perpendicular to the fiber axis. The reorientation of the LC molecules within the holes of the PCF results in propagation loss as the long range orientation order decays along the length of the fiber. This is due to the formation of orientation defects with the increasing electric field which act as scattering loss centres in the PBG structure. In such cases the PBG condition is disturbed and the light propagating is no longer confined in the core of the PBG structure and escapes into the LC filled cladding region due to scattering.

Figure 3.4: 3-D plot showing the spectral response of the 5CB infiltrated LMA-10 PCF in the wavelength range 1500 nm – 1600 nm as the applied voltage is varied from 0 to 380 Vpp at 1 kHz.
The attenuation in the voltage range from 170 Vpp to 310 Vpp varies linearly with the increase in voltage. In order to demonstrate this the broadband source was replaced with a tunable laser and the transmitted intensity through the device was measured at voltages from 140 Vpp to 310 Vpp in steps of 4 Vpp. Figure 3.5 shows the transmitted intensity through the fiber at wavelengths 1525 nm, 1550 nm and 1575 nm. As can be seen the attenuation shows a linear response with an increase in voltage in the range from ~ 170-310 Vpp. An extinction ratio of ~ 40 dB is obtained between the high and low transmission states of the device. As expected from figure 3.4, the spectral response at different voltages showed that the linear response is maintained for the entire wavelength range from 1500 nm – 1600 nm. A linear fit performed on the data at 1550 nm shows that a ~ 3.5 Vpp increment is required to produce an attenuation of 1 dB for the attenuator as shown in figure 3.6.
The response time of the device was estimated by applying a low frequency (5 Hz) square wave voltage at 300 Vpp to the infiltrated PCF and measuring the output power in time steps of ~ 0.05 msec using a high-speed optical power meter at 1550 nm. The switch ON and switch OFF time responses of the device are shown in figure 3.7(a) & (b).

The measured values for the ON and OFF times $t_{on}$ and $t_{off}$ are ~ 4 ms and ~ 20 ms respectively, estimated from the time plots as the time taken for the transmittance to change from 90% to 10% and 10% to 90% respectively.

The response time of the LCPCF based VOA as demonstrated here is of the order of milliseconds, which in general is significantly faster than VOAs demonstrated by thermal tuning. The LCPCF structure as demonstrated here can be used as the core of a highly efficient in-line electronically controlled variable fibre optic attenuator.

Figure 3.6: Linear response of the attenuation in the voltage range from 170 Vpp to 310 Vpp at 1550 nm, shown with the linear fit for the data.
3.4 Ferroelectric LC Infiltrated PCF based All-fiber Tunable Notch Filter.

3.4.1 Tunable Notch Filters and Gain-equalization Filters in Optical Communication Systems

Wavelength division multiplexing combined with erbium doped fiber amplifiers (EDFA) have a demonstrated ability to enhance the capacity of lightwave communication systems [99, 100]. In particular, there is interest in using DWDM systems to enhance the capacity of both existing long-haul optical networks and future local area networks. One of the problems in implementing optical amplifier based WDM systems, even in the absence of nonlinear effects in fiber, is that the maximum transmission distance is limited by a non-uniform gain of the EDFA and the amplified spontaneous emission (ASE) noise added by every EDFA in the network chain [101]. Systems comprising of concatenated chains of optical
amplifiers should have an adequate signal-to-noise ratio (SNR) over the range of wavelengths that WDM will cover. Although EDFAs can simultaneously amplify many signals, the gain is dependent on wavelength and therefore each signal will experience different optical gain. In long haul systems, the lack of uniform gain leads to severe SNR differences among channels, that can result in a high bit error rate (BER) for some channels. ASE noise also contributes to saturation in subsequent amplifiers in the cascade, thereby reducing the gain available for the wanted signals.

Gain-equalizing optical filters such as notch filters are often used in long-haul WDM systems to flatten the EDFA gain bandwidth, and thus increase the maximum transmission distance. Tunable gain equalization/gain flattening filters have been implemented with various approaches involving the use of Fabry-Perot and Mach-Zehnder type optical filters [102]. Acousto-optic tunable filters [103] and both long period gratings (LPG) and FBGs have been used for gain flattening with multi-wavelength systems [104, 105]. Integrated optics based approaches has been implemented with two or more fiber amplifiers of different doped glass compositions combined within an amplifier chain to obtain a wide-band hybrid amplifier [106] with a very broad gain spectrum.

This section describes the operation of a simple all-fiber tunable notch filter using an FLC infiltrated PCF with potential applications for gain-equalization in WDM systems. The electronic tunability of the LCPCF filter was achieved by applying an electric field to the infiltrated photonic crystal fibre which facilitates the photonic bandgap tuning of the ferroelectric LC infiltrated PCF. The tunability is obtained in the wavelength range of 1500 nm -1600 nm, with a free spectral range of ~ 20 nm.
3.4.2 Design of the ferroelectric LC Infiltrated PCF device

The FLC material used for the experiments was Felix 019/000 (AZ Electronics), which has a ferroelectric C phase in the temperature range from 2 - 60 °C, with a tilt angle of ~ 38°. The isotropic temperature of this ferroelectric LC mixture is at 82 °C. The ordinary \(n_o\) and extraordinary \(n_e\) refractive indices of the material are 1.487 and 1.651 respectively, measured at 30°C at 589.3 nm. The measurements for the tunable filter device were performed at room temperature. The fiber used for this demonstration was the polarization maintaining photonic crystal fibre (PMPCF), PM-1550-01 (Crystal Fibre A/S) with a solid silica core. The PCF has two large holes of diameter 4.5 µm and small holes of diameter 2.2 µm with a pitch (inter-hole spacing) of 4.4 µm (figure 3.8 (a)). The infiltration was performed by dipping the cleaved end of the fibre into a drop of the ferroelectric LC material at a temperature between 80 – 90 °C. This allows for an easy infiltration of FLC.

![Figure 3.8: (a) SEM micrograph of PM-1550-01 PCF, (b) Unfilled PM-1550-01 and ferroelectric LC filled PM-1550-01 observed under crossed polarizers.](image-url)
mixtures into the PCF holes and also allows for the FLC molecules to attain a uniform alignment after the sample cools down to room temperature. The FLC molecules get drawn into the PCF due to capillary forces. The PCF section used for this study had a length of 5 cm, which was placed between a pair of electrodes to allow the application of an electric field perpendicular to the fibre axis. The FLC infiltrated PCF sample was observed under a polarising microscope to estimate the infiltration length and ascertain the alignment within the PCF holes. A total infiltration length of ~ 1.3 cm was estimated for the FLC infiltrated PCF sample and the alignment was observed to be largely along the axis of the PCF. Figure 3.8 (b) shows the photographs of the empty and infiltrated PM-1550-01 with the FLC, observed under crossed polarizers with visible light illumination. The alignment of the FLC molecules along the PCF axis suggests that the smectic layers within each hole are formed perpendicular to the fiber/hole axis. FLCs when confined within micrometer dimension cylindrical structures without any alignment layer orient themselves with the smectic layers forming perpendicular to the cylindrical axis. In such cases the LC molecules are aligned approximately parallel to the axis, which is in accordance with the observation by J. Y. Liu et al [107].

The experimental setup used for the demonstration of the all-fiber tunable notch filter was as shown in figure 3.9. Light from the broadband source (Superlum Diodes Ltd.; 1490-1640 nm) was coupled into a fibre linear polarizer and then coupled into the infiltrated end of the PLCF. The PLCF output coupled through a free-space analyzer is inputted to an OSA. The coupling of light at the input and collection at the output from the PLCF was done using the 3-stage XYZ-nano-positioner waveguide stage. The coupling loss was circa 1.5 – 2.0 dB with fibre
butt-coupling using the nano-positioner. The polarized transmission spectrum was recorded for a voltage range from 0 - 150 V DC.

3.4.3 Electrical Tuning of Photonic Bandgaps with FLC Infiltrated PCF

The polarized transmission spectrum with both the input and output polarizers arranged parallel to each other as measured for different voltages showed the presence of transmission minima (notch) at around 1550 nm. The presence of transmission minima is a characteristic of PBG guidance in PCFs. As the externally applied voltage is incremented from 0 V – 60 V DC, there is no change in the position of the notch, suggesting that in this voltage range 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. The lower electric field range threshold at 60 V DC for the reorientation of FLC molecules within the holes of the fiber could be due to the presence of a depolarization field forming within the silica layers of the PCF on the application of the voltage [108]. For voltages from
60 V to 110 V DC, a shift of the transmission minima towards the lower wavelengths is observed with an increase in voltage, as shown in figure 3.10. An overall shift of ~ 22 nm for the spectral notch from 1554 nm (60 V) to 1532 nm (110 V) was observed. The shift of the transmission notch for the voltage range from 60 V – 110 V shows a linear response, as shown in figure 3.11. 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. The electrically induced reorientation of the FLC molecules mainly within the two large holes of the PCF creates anisotropy in the LCPCF cross section. This also leads to a change in the effective refractive index of the cladding region and thus contributes to the shift in PBG positions. Further increases in the voltage to 150 V DC resulted in no shift in the spectrum, with the transmission minimum remaining centered at 1532 nm. This could be attributed to the fact that the FLC molecules may have attained the maximum reorientation state within the PCF holes.

Figure 3.10: Polarized transmission spectrum of the FELIX 019/000 infiltrated PMPCF at different voltages from 70 V – 110 V DC.
An all-in-fibre tunable notch filter of this type, in this particular wavelength range is useful for spectral shaping of the cavity of a mode-locked fibre laser, in tunable dispersion control within and outside the cavity and also for Amplified Spontaneous Emission filtering and gain flattening of erbium doped fibre amplifiers.

**3.5 Summary**

The use of LCPCFs is a useful and viable technology for the fabrication of all-fiber tunable devices for many applications in optical communications. The applicability of a NLC infiltrated PCF for use as an electronically controlled in-line all-fiber VOA in the wavelength range from 1500 nm – 1600 nm was experimentally demonstrated. The device operates on the principle of PBG mechanism and has a low insertion loss and exhibits ~ 40 dB attenuation between its high and low

![Figure 3.11: Linear shift of the spectral minimum (notch) with changing voltage.](image-url)
transmission states as a square wave voltage was applied to the NLC infiltrated part of the PCF. The attenuation of the LCPCF structure was linear in the voltage range from 170 Vpp to 310 Vpp and the spectral response of the device for the entire wavelength range was flat for all attenuation states. The attenuator was also shown to have response time in the order of milliseconds. With its simple all-fiber in-line configuration it has the advantages of ease of optical coupling and interfacing, low insertion loss, as well as low fabrication cost. The nematic LCPCF structure could be efficiently used as an all-fiber VOA for applications in optical networks for optical power level equalization, control and maintenance.

The infiltration of a FLC in PCF and the electronic tunability of the photonic bandgaps are demonstrated in the wavelength range of 1500 nm- 1600 nm. The transmission profile of the LCPCF shows a tunable notch-filter like behaviour in the wavelength range from 1532 nm – 1554 nm. The transmission minimum (notch) in the spectral profile of the LCPCF can be tuned by the application of an external voltage and the shift in the transmission minima position with a change in the applied voltage is found to be linear. A tunable range of ~ 20 nm is achieved and a linear response of the spectral shift with a change in voltage was observed for voltages from 60 V – 110 V DC. A device based on such an LCPCF structure with ferroelectric LC infiltration has potential applications in the fabrication of an all-in-fibre tunable notch filters for the spectral shaping of the cavity for fibre lasers and for ASE filtering and gain flattening in fibre amplifiers.
Chapter 4

All-fiber Electric Field Sensing using LCPCFs

4.1 Introduction

Infiltration of LCs into the holes of PCFs allows for external control of the propagation properties of the LCPCF. In chapter 3 this property of the LCPCFs was utilised for the demonstration of all-fiber electrically tunable devices for applications in optical communication systems. Infiltration of LC materials makes a PCF susceptible to external field variations, a property which can be utilized to fabricate all-fiber sensors for parameters such as temperature and also magnetic and electric fields.

In this chapter a novel technology for the fabrication of all-fiber electric field sensors is described and experimentally demonstrated. Conventional electric field sensors use antennas, conductive electrodes or metal connections and because of their metallic content are often likely to perturb the unknown field. Furthermore, many conventional sensors involve a conductive path from the sensor to the interrogation system which can be problematic in high field strength or high voltage environments due to the risk of electrical breakdown. Fiber optic sensors for voltage and electric field measurement are widely used in both electromagnetic compatibility measurements and in the electric power industry [109]. Unlike their conventional counterparts, fiber optic based electric field sensing techniques
minimally disturb the electric field and apart from the sensor head, the connecting fibers are inherently immune to electromagnetic interference [110]. They have several economic and performance advantages over conventional electrode based sensors, most importantly they can provide true dielectric isolation between the sensor and the interrogation system in the presence of very high electric fields or voltages. A wide variety of fiber optic based electric field sensing schemes have been proposed and reported to date. These are mostly based on electro-optical crystals employed either in bulk optics or free-space type configurations or in an integrated waveguide type configuration [111-115]. However such schemes have a number of disadvantages such as high losses due to the presence of bulk optics, high coupling losses, costly integration with interconnecting optical fiber, limited mechanical reliability and are difficult to produce in quantity. Small size, simple design and an all-fiber configuration with high measurement accuracy are major requirements for fiber based electric field sensors.

This chapter describes the design and operation of an LCPCF based all-fiber electric field sensing device. The active region of the sensor probe consists of an NLC infiltrated section less than 1 cm long of a commercially available solid core PCF. The sensor can be operated in transmission mode as an in-line sensor but also in reflection mode, allowing for the implementation of an end point type sensor. Since the birefringence of the infiltrated fiber is susceptible to variations in an external electric field, the sensing mechanism is intrinsic to this type of structure. The diameter of the sensor is ~ 125 microns which is determined by the cladding diameter of the PCF, and therefore the sensing device is inherently very compact, lightweight and can also be easily integrated with fiber optics. The sensor operates in the telecommunications window at an operating wavelength of 1550 nm. The
transmission and reflection response with electric field intensity is studied at 1550 nm and is presented here. In section 4.2, the theoretical background and the working principle of the LCPCF based e-field sensor are described. A performance evaluation and feasibility study of NLC infiltrated PCFs are presented in section 4.3 for use as all-fiber electric field sensors. Section 4.4 describes the experimental demonstration of the LCPCF based all-fiber electric field sensor with the capability to be used in an end-point type and in-line type configurations. Due to the temperature dependence of the infiltrated nematic LC mixture, the performance of the device is influenced by temperature variations, therefore the temperature dependence of the sensor is also studied for a temperature range from 10°C to 90°C and is presented in this section.

4.2 Performance Evaluation and Feasibility of LCPCFs for Electric Field Sensing

4.2.1 Theoretical Background for the LCPCF based Electric Field Sensor

The underlying principle of LCPCF for electric field sensing is the electric field dependent PBG transmission of cladding infiltrated solid silica core PCFs. When the NLC infiltrated cladding region of the PCF is subjected to an electric field, the NLC molecules undergo reorientation which changes the effective refractive index of the cladding and under certain conditions allows for tuning of PBG transmission. For LC mixtures which create planar alignment within the holes of the PCF, the propagation through the PCF core is governed by the ordinary refractive index of the infiltrated NLC, in the absence of external field.
On the application of an electric field above the threshold, referred to as the Freedericksz transition threshold [10], the LC molecules undergo reorientation within the micro holes. In the case of an LC layer of thickness $d$, the threshold electric field $E_{th}$ for LC reorientation is given as:

$$E_{th} = \left( \frac{\pi}{d} \right) \sqrt{\frac{K_{11}}{\varepsilon_0 (\varepsilon_{||} - \varepsilon_{\perp})}}$$  \hspace{1cm} (4.1)

where $K_{11}$ is the splay elastic constant for the nematic LC and $\varepsilon_{||}, \varepsilon_{\perp}$ are the dielectric permittivities. As a simple approximation and assuming planar anchoring conditions, the hole diameter of the PCF can be treated as the effective thickness of the LC layer with a planar geometry.

Below the threshold field the propagation properties of the structure are governed by the ordinary refractive index of the LC given the long range orientation order of the LC molecules, aligned along the axis of the fiber (Figure 4.1).

Above the threshold the LC molecules reorient themselves along the direction of the applied field and the propagation is governed by the effective refractive index,
which is partially set by the extraordinary refractive index of the NLC. As the LC molecules begin to reorient under the action of the electric field, there is a loss in the uniformity of the long range LC molecular alignment. With an increase in the applied electric field intensity, the formation of reverse tilted domains takes place which causes a loss in the LC long range orientation order. As a result the PBG condition for transmission in the operating wavelength range is disturbed as light is coupled into the cladding region. In effect as a result there is a gradual decrease in the optical power transmitted through the core of the LC infiltrated PCF with an increase in the electric field intensity.

4.2.2 Sensor Preparation and Experimental Setup

The PCFs used for the experiments for this study were LMA-10, LMA-8 and PMPCF (PM-1550-01, Crystal Fibers). LMA-10 and LMA-8 are endlessly single mode fibers [116] with a circular core and the PM-1550-01 is a high birefringence fiber. The LMA-8 fiber has seven rings of air-holes of diameter 2.7 µm around a core of diameter 8.5 µm. The LMA-10 and PM-1550-01 fiber have been used for the experimental demonstrations in chapter 3 for all-fiber tunable photonic devices. In this chapter the detailed study as to their applicability as an electric field sensor is presented.

The nematic LC materials used for infiltration were 5CB and MDA-05-2782 (Merck Ltd). The MDA-05-2782 has a clearing temperature at 106°C and its ordinary and extraordinary refractive indices are ~ 1.49 and ~ 1.61 measured at 589.3 nm (Merck Datasheet). The properties and specifications of the LC materials and the PCFs used for the studies in this chapter are given in table 4.1 and 4.2.
A section of each of the three fibers was spliced to an SMF28 fiber pigtail using a standard fusion splicer. Splicing of the PCF to an SMF fiber was used to ensure low loss core-to-core light coupling into the PCF, which involved optimisation of the fusion current and fusion time [98]. The splicing was undertaken in such a way as to ensure minimal air-hole collapse at the splice joint to reduce coupling losses. The splicing loss estimated for the LMA-10 case was ~ < 1 dB, for LMA-8 ~ < 2 dB and for PM-1550-01 the loss estimated was ~ <4 dB. After splicing, the transmission spectrum (1500 nm – 1600 nm) of the spliced PCFs was observed to ensure the

Table 4.1: Properties of the LC materials used for the study.

<table>
<thead>
<tr>
<th>LC</th>
<th>Δn</th>
<th>Δε</th>
<th>Tc (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5CB</td>
<td>0.19 (1550 nm; 20 °C)</td>
<td>10 (1 kHz; 20 °C)</td>
<td>35</td>
</tr>
<tr>
<td>MDA-05-2782</td>
<td>0.164 (589.3 nm; 20 °C)</td>
<td>7.2 (1 kHz; 20 °C)</td>
<td>102</td>
</tr>
</tbody>
</table>

Table 4.2: Specifications of the PCFs used for the study.

<table>
<thead>
<tr>
<th>PCF</th>
<th>d (hole diameter)</th>
<th>Λ (pitch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMA-10</td>
<td>3.3 μm</td>
<td>7 μm</td>
</tr>
<tr>
<td>PM-1550-01</td>
<td>Large hole – 4.5 μm</td>
<td>4.4 μm</td>
</tr>
<tr>
<td></td>
<td>Small hole – 2.2 μm</td>
<td></td>
</tr>
<tr>
<td>LMA - 8</td>
<td>2.7 μm</td>
<td>5.6 μm</td>
</tr>
</tbody>
</table>
absence of interference pattern formations, which would be indicative of unwanted air hole collapse during splicing.

Infiltration of the nematic LC material was done by dipping the cleaved end of the PCFs into the LC material at room temperature and the length of infiltration obtained for each PCF was \( \sim 1 \) cm. The LC material is drawn into the PCF air-holes by capillary action. For the PM-1550-01 PCF selective infiltration of the two large holes was performed by deliberately collapsing the surrounding smaller holes using a standard fusion splicer [98]. The infiltrated ends of all three PCFs were observed under a polarising microscope to examine and ascertain the quality of infiltration and also changes in alignment with the applied electric field.

The electric field was applied to the infiltrated PCF by means of two electrodes positioned at the opposite sides of the cladding at the infiltrated end of the PCF. In order to avoid any movement or shaking of the fiber on the application of electric field due to electrostriction effect, the infiltrated fiber end within the electrodes was firmly glued to the electrode surfaces. The distance between the electrodes was equal to the cladding diameter of the PCF which was 125 \( \mu m \). In this geometry the electric field was applied perpendicularly to the fiber axis. A square wave voltage is applied to the infiltrated PCF using a high voltage power supply (up to 1000 V) by modulating its output using a low voltage square wave signal from a function generator.

Each of the three fibers was infiltrated with the two nematic LC mixtures and the output transmittance at 1550 nm was measured in each case. The transmitted output power was low for MDA-05-2782 infiltrated LMA-10 and PM-1550-01 and also for 5CB infiltrated LMA-8. This is due to the fact that for these LC and PCF combination the position of transmission minimum was in the wavelength range
from 1500 nm - 1600 nm. For this comparative study 5CB infiltrated LMA-10 and PM-1550-01 and also MDA-05-2782 infiltrated LMA-8 were used. The experimental set-up used to study the electrical tunability of the nematic LC infiltrated PCFs to determine their applicability as electric field sensors is as shown in Figure 4.2. Linearly polarized light from a tunable laser source operating at 1550 nm was coupled into the SMF fiber and passed through the infiltrated PCF ends. A polarization controller employed as a linear polarizer at the input was used to minimize polarization induced instabilities in the output transmittance. In the absence of an applied electric field, LCPCFs exhibit small birefringence as a result of imperfections in the planar (along the fiber axis) alignment of the LC molecules. At voltages above the threshold of reorientation, the LCPCFs become highly birefringent. The output from the infiltrated end of the LCPCF is coupled to another SMF fiber using a butt-coupling technique involving an XYZ nano-positioner stage, with the SMF output coupled to a high speed optical detector.

Figure 4.2: Schematic of the experimental setup to study the transmission response and temperature dependence of the NLC infiltrated PCF.
Both the nematic LC mixtures used for infiltration were observed to have a planar alignment within the holes of the PCFs used. Consequently, all the LCPCFs displayed the threshold effect for NLC molecule reorientation on the application of the field. Each sample of the LCPCF was observed under a polarizing microscope in transmission mode by viewing the color change in the transmitted light with the application of electric field. On the application of the square-wave voltage, the color of the transmitted light from the infiltrated region changed and the brightness increased with increasing voltage. In order to determine an approximate value for the threshold voltages, the voltages at which the color of the infiltrated PCF begins to change were recorded. The estimated threshold value for 5CB infiltrated LMA-10 is ~ 170 V, for 5CB infiltrated PM-1550-01 it is ~ 100 V and for MDA-05-2782 infiltrated LMA-8 it is ~ 330 V. Since LMA-8 has the smallest hole diameter its threshold voltage as expected is higher, in accordance with equation 4.1. LMA-10 has a hole diameter larger than LMA-8 and for the case with PM-1550-01 since only the large holes of diameter 4.5 microns were infiltrated the threshold voltage was observed to be the lowest.

4.2.3 A comparative study of different LCPCFs for Electric Field Sensing

Using the experimental setup described in the previous section, the transmission responses of the various LC and PCF combinations were measured. Figure 4.3 (a) shows the transmission response at 1550 nm of the 5CB infiltrated LMA-10 with increasing voltage in a voltage range from 0 to 1000 V. Below the threshold voltage the transmitted power remained almost constant from 0 V to 170 V. Above the threshold the transmitted power gradually decreases until a value of 440 V is
reached and remains in a low transmission state till 660 V, while above 660 V the
transmission increases again. A more accurate estimate of the threshold voltage
from the transmission profile for the 5CB infiltrated LMA-10 is 170 V. In the
voltage range from 170 V to 440 V the transmitted power decreases almost linearly
as shown in figure 4.3 (b). A linear fit performed for the data from 170 V to 440 V
yields a slope of $\sim 0.15$ dB/V.
A similar transmission behavior is observed in the case of PM-1550-01 selectively infiltrated with 5CB at 1550 nm, as shown in figure 4.4 (a). The estimated threshold voltage is ~ 90 V. For PM-1550-01 the transmitted power shows a linear response in the voltage range from 90 V to 400 V. Figure 4.4 (b) shows the linear part of the response of the fiber in the voltage range from 90 V to 400 V with the linear fit. The slope of the linear fit is estimated to be ~ 0.034 dB/V.

Figure 4.4: (a) Output transmission profile for PM-1550-01 selectively infiltrated with 5CB, at 1550 nm in the voltage range from 0 V – 1000 V. (b) Linear transmission response in the voltage range from 90 V to 400 V.

As can be observed from the transmission profile in Figure 4.4 (a), the transmitted power over the linear response region shows slight fluctuations with an increase of
the applied voltage. This is due to the fact that even after the collapse of the smaller holes of the PMPCF to achieve selective infiltration, some of the smaller holes may still remain open and are partially infiltrated. The presence of LC in these partially filled smaller holes and its reorientation on the application of electric field causes changes in the birefringence of the fiber and thus contributes to the disturbance in the propagation characteristics of the infiltrated PMPCF.

Figure 4.5 (a) shows the transmission response of MDA-05-2782 infiltrated LMA-8 at 1550 nm with increasing voltage. The threshold voltage for LMA-8 is comparatively high at ~ 330 V. The infiltrated fiber shows a linear response in a voltage region of 330 V to 860 V (Figure 4.5 (b)). A linear fit performed for the data from 380 V to 860 V gives a slope of ~ 0.06 dB/V. As can be seen, MDA-05-2782 infiltrated LMA-8 shows a linear response for a comparatively larger voltage range.

LCs have temperature dependent refractive indices, due to this the electric sensor is affected by temperature variations. The temperature dependence of the LCPCF electric field is studied and presented later in this chapter. LC materials lose their anisotropic properties above the clearing temperature. The MDA-05-2782 has a clearing point at ~ 106 °C which renders the LC and PCF combination suitable for electric field sensing applications in high power and high voltage environments where there is a possibility of the sensor being subjected to higher temperatures up to 90 °C. Therefore the MDA-05-2782 and LMA-8 combination is selected for the demonstration of a working LCPCF electric field sensing probe, described in the next section.
4.3 Demonstration of an LCPCF Electric Field Sensing Probe and Temperature Dependence studies

4.3.1 All-fiber Electric Field Sensor Probe based on LCPCF

The sensor probe fabricated for the demonstration of all-fiber electric field sensing was a < 1 cm long MDA-05-2782 infiltrated section of LMA-8 PCF, as shown in the figure 4.6. To ensure effective core-to-core light coupling from the SMF input fiber to the PCF, a section of the PCF is spliced with a SMF-28 fiber using a

Figure 4.5: (a) Output transmission profile for MDA-05-2782 infiltrated LMA-8 at 1550 nm in the voltage range from 0 V – 1000 V. (b) Linear transmission response in the voltage range from 330 V to 860 V.

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standard fusion splicer. The splicing conditions are optimized in order to ensure minimal air-hole collapse at the splice joint as previously described and also to provide sufficient mechanical strength for manual fiber handling. This is achieved by optimising the fusion current, fusion time and the number of re-arcs applied during the splicing. The coupling loss estimated after splicing was less than 2 dB for LMA-8 with SMF-28 fiber. The spectral response of the PCF in the wavelength range from 1500 to 1600 nm showed no interference pattern formation after splicing, which suggests that the splicing had not altered the endlessly single mode operation of LMA-8.

The open end of the PCF was infiltrated with MDA-05-2782 at room temperature by dipping the cleaved end into the LC material. An infiltration length of ~ 0.5 cm was obtained. The broadband transmission spectrum of the infiltrated PCF sample was recorded using a tungsten halogen source and an OSA. Figure 4.7 shows the

Figure 4.6: Nematic LC infiltrated PCF probe for electric field sensing with electrodes
recorded transmission spectrum of the infiltrated PCF in the wavelength range from 600 nm to 1700 nm. The low transmission region was observed to be in the wavelength range from 875 nm – 1150 nm. The structure has a PBG transmission region in the telecommunications wavelength window and an insertion loss of < 3 dB is estimated for the NLC infiltrated PCF at 1550 nm. The spectrum reflected from the cleaved end of the PCF recorded in the wavelength range from 1500 to 1600 nm was found to be flat and the formation of interference patterns was not observed.
4.3.2 Electric Field Measurement Principle and Experimental Arrangement

The electric field was applied to the infiltrated PCF using a combination of a high voltage power supply modulated by a standard waveform generator. This provides a positive polarity voltage waveform that varies in time in a sinusoidal fashion from zero volts up to a peak value, $V_{\text{peak}}$, with an average value of $V_{\text{peak}}/2$. A sinusoidal waveform was selected since the most common artificial electric fields are sinusoidal. The maximum value of $V_{\text{peak}}$ used in the experiment was 1200 V. The frequencies used were 1 kHz and 50 Hz, chosen to reflect a commonly used frequency for LC characterisation and the typical frequency of mains power respectively. A common practice in defining electric field intensity is to define it as volts-RMS per mm. Given the nature of the waveform the relationship between the $V_{\text{peak}}$ value and the RMS value is given by $V_{\text{rms}} = (3/8)^{1/2} V_{\text{peak}}$. Therefore given the maximum value of $V_{\text{peak}}$ utilised, in effect the sensing device was subjected to electric field intensities in the range from 0 to 6.0 kVrms/mm given that the distance between the electrodes was ~ 125 microns. The experimental set-up to study the influence of electric field on the transmission properties and temperature dependence of the MDA-05-2782 infiltrated LMA-8 was the same as that shown in figure 4.2.

The output from the infiltrated end of the PCF is coupled to another SMF fiber by butt-coupling using an XYZ nano-positioner stage and is connected to a high speed optical power meter to record the transmittance as the applied electric field is varied. To study the infiltrated PCF sample in reflection mode the experimental setup as shown in figure 4.8 was employed. The light from the tunable laser source is passed
through a fiber circulator and is coupled to the infiltrated PCF. In this case the infiltrated end of the PCF is left open and the reflected light from the air-PCF interface is coupled using the circulator to a high speed optical powermeter for detection and measurement.

4.3.3 Electric Field Intensity Measurements using the LCPCF Probe

A. Transmission Response with an Electric Field

In the experiments a polarization controller employed as a linear polarizer was utilised to maximise the extinction ratio of the transmitted power at a high electric field intensities when the infiltrated PCF becomes highly birefringent. The measurement of the transmission response was performed with the state of input polarization set in order to maximise the transmission extinction ratio and to
improve the sensitivity of the device to an electric field. The transmission response of the device with increasing electric field intensity is shown in figure 4.9.

![Graph showing transmission response](image)

**Figure 4.9:** Transmission response of MDA-05-2782 infiltrated LMA-8 with a changing electric field intensity (1 kHz) at 1550 nm measured at room temperature.

Between the field intensity of zero and that of circa 2.35 kVrms/mm, the transmission response remains unchanged. Above this threshold field intensity, the NLC molecules begin to re-orientate which results in a gradual decrease in transmission through the infiltrated PCF with the increasing electric field until an electric field intensity of ~ 4.89 kVrms/mm is reached. The transmission response in the range of electric field intensities from 2.35 kVrms/mm to 4.89 kVrms/mm is close to linear. The linear part of the transmission response for the infiltrated PCF in this electric field range is shown in figure 4.10.
A linear fit performed for this electric field range shows that the slope of the response is \( \sim 10.1 \text{ dB-kVrms/mm} \), confirming that MDA-05-2782 infiltrated LMA-8 can be used for electric field intensity measurements in this electric field range. Assuming an accuracy of 0.01 dB for the optical power measurement system, the estimated resolution of the device over the usable e-field intensity measurement range is \( \sim 1.0 \text{ Vrms/mm} \).

Given that one of the most likely applications of the sensor could be in a 50 Hz/60 Hz AC high voltage transmission environment, the device was also tested in the transmission mode for its sensitivity to a sinusoidally varying electric field at 50 Hz. The transmission response is as shown in figure 4.11. At 50 Hz a higher threshold electric field was observed (\( \sim 2.93 \text{ kVrms/mm} \)). Due to the limitations posed by the high voltage power supply in delivering peak voltages above 1200 V,
it was not possible to extract the full linear range of the device with an applied 50 Hz AC voltage. However the transmission response in figure 6 confirms that the sensor can be used for 50 Hz/60 Hz AC voltage and electric field sensing.

![Transmission vs Electric Field Intensity](image)

**Figure 4.11:** The transmission response of MDA-05-2782 infiltrated LMA-8 with electric field intensity (50 Hz) at 1550 nm measured at room temperature.

The performance and sensitivity of the device can be further enhanced by employing the sensor in a ratiometric power measurement scheme. The threshold effect of the infiltrated LC puts a limit on the lower measurable electric field intensity. Since the threshold field is inversely proportional to the hole diameter of the PCF, the use of a solid core PCF with larger hole diameter could reduce the threshold field for the device.

**B. Reflection Response with an Electric Field**

The reflected power response at 1550 nm with an increasing electric field (1 kHz) is as shown in figure 4.12. The reflected power from the infiltrated PCF is relatively
low (~ 20 dB), due to the low reflectance from the air-silica interface (~ 4%). The response with a varying electric field is found to be similar to the transmission

response for the infiltrated PCF. Due to the expected low measured optical power, arising from the loss upon reflection from the silica-air interface of the cleaved PCF end, there was greater uncertainty in the measured values due to the system noise. It should be noted that the use of the polarization controller in the reflection mode resulted in no change in the reflected power due the fact that the degree of maintaining of the initial polarisation state in the reflection mode configuration is significantly lower than that in the transmission mode. Above the threshold field the reflected power decreased with an increasing electric field and the response was again found to be linear with a changing electric field. The linear sensing range is from ~ 2.35 kWrms/mm to ~5.14 kWrms/mm. The linearity of the reflected power

Figure 4.12: Reflected power response of MDA-05-2782 infiltrated LMA-8 with a changing electric field intensity (1 kHz) at 1550 nm measured at room temperature.
with an increasing electric field is depicted in figure 4.13, shown with the linear fit. The linear fit for the plot provides an estimate of the sensitivity of the device in

![Figure 4.13: Linear part of the reflected power response of MDA-05-2782 infiltrated LMA-8 with electric field intensity (1 kHz) at 1550 nm shown with a linear fit.](image)

reflection mode as ~ 4.55 dB-mm/kVrms. Assuming an accuracy of 0.01 dB for the optical detector in the measurement system, the estimated resolution of the device operated in the reflection mode is ~ 2.2 Vrms/mm. The reduced sensitivity of the device in reflection mode is due to the fact that unpolarized light was used and that the state of polarization changes after reflection from the open ended PCF. The increased level of system noise in the reflection mode has also contributed to the reduced sensitivity of the device. In the reflective configuration the infiltrated PCF can be used as an end point e-field sensor, which is an added advantage for the fabrication of sensors for e-field measurement probes in confined spaces.
Table 4.3 below summarises the e-field sensing parameters estimated for MDA-05-2782 infiltrated LMA 8 PCF in both transmitted and reflection modes. It is possible to increase reflected power using a reflective coating at the open end of the PCF, improving the sensitivity of the device in reflection mode.

Table 4.3: Comparison of e-field sensing parameters of MDA-05-2782 infiltrated LMA-8 in transmitted and reflected modes.

<table>
<thead>
<tr>
<th>Sensor configuration</th>
<th>Sensitivity (dB per kVrms/mm)</th>
<th>Measurable e-field intensity range (kVrms/mm)</th>
<th>Estimated resolution (Vrms/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitted mode</td>
<td>~ 10.1</td>
<td>2.35 – 4.95</td>
<td>~ 1</td>
</tr>
<tr>
<td>Reflected mode</td>
<td>~ 4.55</td>
<td>2.35 – 5.14</td>
<td>~ 2.2</td>
</tr>
</tbody>
</table>

4.3.4 Temperature Dependence of the LCPCF Probe

It is well known that temperature dependence of the transmission properties of PCF is minimal. However, the LC material used for infiltration has a temperature dependent refractive index [115]. The temperature dependence of the infiltrated PCF was studied at an operating wavelength of 1550 nm in order to evaluate the effect of temperature on the device performance and sensitivity. The infiltrated section of the fiber was subjected to different temperatures using a Peltier module in the range from 10°C to 90°C, while the electric field was varied. The transmission plots at different temperatures as obtained with a change in electric field intensity in the range from 0 – 6 kVrms/mm are shown in figure 4.14.
Figure 4.14 shows the plot obtained for reflection mode. As can be observed from the plots the sensor maintains its linear response in the electric field range from 2.35 kVrms/mm to 5.14 kVrms/mm. To evaluate the change in the sensitivity of the sensor with changes in temperature, a linear fit was performed on the individual plots at each temperature for both the transmission and reflection modes in the linear electric field range from 2.35 kVrms/mm to 5.14 kVrms/mm. Figure 4.16 shows the sensitivity variation for the sensor in both reflection and transmission modes at different temperatures in the range from 10°C to 90°C.

The refractive indices (both $n_e$ & $n_o$) of the LC decrease with an increase in temperature up to the NLC isotropic temperature (clearing point), resulting in a decrease of the effective refractive index of the cladding. In the temperature range from 10°C to 40°C it was observed that the change in the sensitivity was minimal.
(<5 %), suggesting that the operation of the sensor is not influenced by temperature fluctuations within the range of typical room temperatures up to 40°C.

At temperatures above 40°C the slope of the transmission versus electric field intensity plots, decreases and therefore the sensor sensitivity decreases for both operating modes. This is due to the fact that the effective refractive index of the cladding decreases at a lower rate with temperature for a temperature range from 10°C to 40°C, while above 40°C the rate of this decrease is higher as the temperature approaches the clearing point (106°C) of the NLC material used.

For the temperature range from 40°C and up to 90°C there was a significant change in the sensitivity of the sensor in both the transmitted mode and reflected mode but the response (transmitted & reflected) of the sensor maintained it’s linearity in the

Figure 4.15: Reflection responses of the sensor versus electric field intensity at different temperatures from 10°C to 90°C.
measurable electric field range. To maintain accuracy across a broader range of operating temperatures, the sensor requires an associated means of active temperature monitoring and correction.

4.4 Summary

The application of nematic LC infiltrated solid core PCF as an all-fiber based electric field intensity measurement device was studied and experimentally demonstrated in this chapter. A performance evaluation and feasibility study of NLC infiltrated PCFs for use as fiber optic electric field sensors was performed in the telecommunication window at 1550 nm. Three different commonly available PCFs and two different NLCLC materials were used. The infiltrated PCFs, guiding light through the PBG mechanism, were found to respond to high voltages applied to them by means of electrodes. The transmitted power through the infiltrated PCFs

![Figure 4.16: E-field sensitivity variation with temperature change for transmission and reflection modes.](image-url)
is found to vary linearly with voltage in different voltage ranges for all the three PCFs studied. The MDA-05-2782 infiltrated LMA-8 fiber showed a linearly decreasing transmitted power response with increasing voltage in the voltage range from 330 V to 860 V. The slope of the linear response shows that compared to the other two PCFs, LMA-8 fiber can provide better resolution in a wider high voltage/high electric field range.

The electric field sensing mechanism of a nematic LC infiltrated PCF is intrinsic to the LCPCF structure which results in a simple sensor structure. The sensor, based on the electrical tunability of the infiltrated PCF is shown to have a linear transmission and reflection responses with changing electric field intensity. The sensor probe consists of less than 1 cm long infiltrated section of a solid core PCF and has a diameter of ~ 125 microns. A simple all-fiber design for the sensor makes it compact and allows for easy integration and coupling with interconnecting fiber optics. A light intensity based measurement scheme is employed with the sensor operating in the telecommunications window at 1550 nm. The device is capable of operating as an in-line sensor in the transmitted mode and also as an end point sensor in the reflected mode. The temperature dependence of the sensor probe at an operating wavelength of 1550 nm has been studied and the sensor has a moderate temperature sensitivity in a room temperature environment. For a high temperature environment as in the case of the measurement of electric fields at high power electrical facilities and high voltage transmission lines, the device can be operated with calibration correction for temperature, which requires the addition of a temperature monitor. As an inherent electric field sensing devices LCPCFs can also be used for high voltage sensing with the voltage being applied using a fixed electrode configuration.
Chapter 5

Frequency Dependence of Liquid Crystal Infiltrated Photonic Crystal Fiber devices

5.1 Introduction

The electrical tunability of propagation properties of LCPCF facilitated by an externally applied electric field leads to various important applications with the advantage of an all-fiber device configuration. In chapters 3 and 4 of this dissertation the application of the electrical tunability of LCPCF in all-fiber tunable devices and an electric field sensor was studied.

Liquid crystal materials are characterized by electric permittivity [118], which is frequency dependent in the range from THz to frequencies below 1 kHz [119-121]. As a result infiltration of liquid crystals into a PCF leads to the propagation properties of the LCPCF being highly dependent on the frequency of the applied electric field. In chapter 4 the use of a nematic LC infiltrated PCF for sensing of an electric field was demonstrated. However given the wide range of frequencies that can arise with electric fields, it is important to understand how the frequency of the electric field influences such a sensor.

For most of the experimental studies and demonstrations of electrical tunability of LCs, the applied electric field used is usually an AC field (voltage) with a frequency in the range of ~ 1 kHz [10]. The use of AC fields (voltages) in experimental
studies of LCs is a precautionary measure which avoids degradation of the LC material caused by DC induced space charge defects in the LC. For the same reason LCPCF electrical tunability studies usually are performed by applying AC fields (or voltages) in the region of ~ 1 kHz.

L. Scolari et al have demonstrated the frequency tunability of a nanoparticle doped liquid crystal filled PCF for application as a gain equalization filter [122]. The response and relaxation times of nematic LC mixtures to an electric field are typically in the order of milliseconds [123] and hence the propagation properties of nematic LC infiltrated PCF depend on the frequency of the applied electric field at frequencies close to 1 kHz. In this chapter an experimental study of the dependence of the transmission properties of a nematic LC infiltrated PCF on the frequency of an applied electric field in the range from 50 Hz – 1 kHz is performed and the results are presented. The time varying transmission response of the LCPCF on the application of a sinusoidal AC field is observed to be of a periodic nature in the frequency range from 50 Hz – 1 kHz. As a result and with the use of an appropriate $\sin^2$ fitting function the main parameters of the applied AC field can be extracted. Consequently, in this chapter the potential application of LCPCF as an all-fiber sensor for a fiber based electric field frequency monitor is demonstrated in the range of frequencies from 50 Hz to 1 kHz. The additional advantage of a LCPCF sensor to simultaneously detect and measure the frequency and amplitude of the electric field signal in a larger electric field range at 50 Hz voltages/electric field is also demonstrated.

In section 5.2 the theoretical background is given and the analysis of the time varying transmission response of the LCPCF is performed and presented. The $\sin^2$ fitting function and its importance in terms of extracting the applied electric
field parameters are also explained in this section. In section 5.3 a study performed on the transmission response of the LCPCF with electric fields at different frequencies is presented. The results with the use of a $\sin^2$ fitting function on the time varying transmission response to extract the frequency and amplitude of the applied electric field are also presented.

5.2 Time Varying Transmission Properties of LCPCFs

5.2.1 Background for Frequency Dependence of LCPCF

On the application of an external electric field, the NLC molecules undergo reorientation which changes the effective refractive index of the holey cladding region and allows for the tuning of photonic bandgap transmission. Since the response times of NLC mixtures (switch ON and switch OFF) are usually limited to the order of ~ msec, the time response of the transmission through the LCPCF will strongly depend on the frequency of the applied electric field. The application of an AC electric field with a frequency in the order of 1 kHz will produce an amplitude modulated time varying transmission response strongly dependent on the applied electric field frequency.

The extinction ratio of the amplitude modulated transmission response depends on the amount of tilt attained by the NLC molecules as they re-orientate under the action of the field. For a given electric field strength the maximum tilt of the NLC molecule is defined as the angle between the orientation of the NLC molecule (NLC director) in the absence of the field and in the presence of the field. For LC mixtures which create planar alignment within the holes of the PCF, a simple planar approximation can be assumed to describe the behaviour of LC molecules under the effect of an applied electric field. The hole diameter of the PCF can be taken as the
thickness of the LC layer, provided the field is applied perpendicular to the length of the fiber. Under these conditions it can be assumed that the maximum tilt of the NLC molecule is obtained in the case of planar aligning LCs. This is in comparison with splay aligning liquid crystals, which in the absence of electric field have a certain amount of pre-tilt with respect to the fiber axis. When compared to the LC molecules in a planar alignment to that of an LC in a splay alignment, with the electric field acting perpendicular to the length of the fiber in both cases, there is a larger number of LC molecules with an inclination to the electric field direction, that is orthogonal to the length of the fiber (Figure 5.1).

This implies that on the application of the electric field and with the LC molecular reorientation, the LC director in the planar aligning case tilts towards the electric field direction at an angle larger than that for the splay aligning case. In the case of a planar aligning LC a higher change in the field induced birefringence is obtained which implies that the maximum extinction ratio for the time varying transmission

Figure 5.1: Schematic showing the orientation of LC molecules within PCF holes for both planar and splay alignments.
response for a given electric field strength is obtained in the case with planar aligning liquid crystals.

The NLC molecules within the PCF micro-holes reorient under the influence of the electric field above the Freedericksz transition threshold. Above the threshold field the molecules tend to reorient increasingly towards the direction of the applied field which results in a change in the effective refractive index of the cladding. The maximum field induced change in the effective refractive index of the cladding in this case results when the field is acting perpendicular to the fiber axis.

On the application of the AC field above the threshold electric field strength and as the amplitude of the electric field signal undergoes a sudden change, the NLC molecules re-orientate. The reaction time within which the NLC molecules reorientate when the electric field is turned on is given as [10]:

\[
\tau_{ON} = \frac{\gamma_1}{\left(\varepsilon_{||} - \varepsilon_{\perp}\right)(E^2 - E_{th}^2)}
\]

where, \(\gamma_1\) is rotation viscosity of the NLC, \(\varepsilon_{||}\) and \(\varepsilon_{\perp}\) are dielectric permittivities of the NLC which are dependent on the applied electric frequency and \(E_{th}\) is the threshold electric field.

The relaxation time within which the NLC director decays under the influence of the LC molecular forces, when the field is switched off, is given as [10]:

\[
\tau_{OFF} = \frac{\gamma_1 d^2}{K_{11} \pi^2}
\]

where \(K_{11}\) is the splay elastic constant of the NLC. The NLC molecules re-orientate dynamically under the influence of the alternating field and produce a time varying transmission response for the LCPCF which is dependent on the reaction and relaxation times of the infiltrated LC mixture.
5.2.2 Experimental Setup for studying the LCPCF Frequency Dependent Transmission Response

For these experiments the commonly available solid core PCF, LMA-10 was used. The LC used for infiltration of the PCF was the low molecular weight NLC 5CB (Merck). The specifications and properties of the LC and PCF used for the study are provided in tables 3.1 & 3.2 in chapter 3. For the fabrication of the LCPCF, the sample preparation methods described already in chapter 4 were used.

Prior to LC infiltration a section of LMA-10 PCF was spliced to an SMF fiber using a conventional fusion splicer for coupling of light into the PCF with minimized losses. The spectrum of the spliced PCF was observed in the wavelength range from 1500 nm to 1600 nm to make sure that there was no interference pattern formation due to splicing and that the transmission response was flat. This ensured that the true spectral response of the LCPCF is obtained after infiltration. The infiltration of the PCF was carried out at a temperature above the isotropic temperature (~ 40 °C) of the NLC. This allows for the NLC molecules to attain a uniform planar alignment as the sample cools down to room temperature. The LC infiltration length obtained within the PCF was ~ 0.5 cm.

The experimental set-up to study the frequency dependent transmission response of the infiltrated PCF is as shown in figure 5.2. The electric field was applied to the infiltrated PCF sensor head with the use of two electrodes in such a way that the field acts perpendicular to the length of the PCF. In this arrangement the sensor has the highest sensitivity to the applied electric field, for the reasons explained in the previous section. Light from a tunable laser source at 1550 nm is coupled into the infiltrated PCF. The light transmitted through the infiltrated end is collected by butt-coupling using an SMF fiber and is coupled into a high-speed optical powermeter.
for detection and measurement. In order to avoid any movement of the PCF section under the electrodes on the application of the electric field, the infiltrated end of the PCF was firmly glued between the electrodes.

The time response of the transmittance through the infiltrated PCF was recorded using the high-speed powermeter for frequencies of the applied electric field in the range from 50 Hz – 1 kHz. The powermeter employed had an unaveraged measurement speed of $10^6$ measurements per second, which is more than adequate for optical power measurements where variations occur in the low kHz region. The electric field was applied in the form of a sinusoidally varying positive polarity waveform using a combination of a high voltage power supply (1000 V) modulated by a standard waveform generator.

On splicing the PCF with a standard SMF 28 fiber a splicing loss of ~ 1 dB is obtained. The insertion loss at 1550 nm on infiltration of 5CB into the PCF is

![Diagram](image)

**Figure 5.2:** Schematic of the experimental set-up used to study the frequency response of LCPCF.
estimated as ~1 dB. The spectrum of 5CB infiltrated LMA-10 showed a flat response in the wavelength range from 1500 nm – 1600 nm. The broadband spectrum of the 5CB infiltrated LMA-10 sample (figure 5.3) in the wavelength range from 600 nm – 1700 nm shows the presence of photonic bandgaps. As can be observed from the figure 5.3, the wavelength region from 1300 nm to 1600 nm is a region of photonic bandgap transmission for the liquid crystal/PCF combination. This wavelength region is useful for various broadband applications such as for all-fiber based variable optical attenuators as described in chapter 3 and also for single wavelength applications such as for all-fiber based electric field sensing studied in chapter 4.

Figure 5.3: Broadband transmission spectrum of LCPCF at room temperature in the absence of an external electric field.
5.2.3 Analysis of the Time Varying Transmission Response of the LCPCF

In order to study the time varying transmission response of the infiltrated PCF at 1550 nm, a square wave electric field signal with an intensity ~ 1.8 kVrms/mm was applied and the time response was recorded with the high-speed powermeter. Figure 5.4 shows the input squarewave signal (@ 5 Hz) along with the infiltrated PCF transmittance.

Figure 5.4: LCPCF transmission response to a 5 Hz squarewave signal at 1.8 kVrms/mm, shown with the input waveform.

As can be seen, the transmittance response is similar for both the low and high half-periods of the applied squarewave signal. The NLC molecules undergo a reorientation when there is a change in the electric field strength, this happens twice during each cycle of the input signal. With the reference to figure 5.4, at the beginning of each half cycle and as the electric field amplitude undergoes a change,
the NLC molecules re-orientate with a time constant as given by equation 5.1. Initially the LC molecules reorientation causes degradation of the periodic structure quality in the holey region of PCF and the decrease in the transmission response takes place. Once the LC molecules assume the new orientation (in this case along the direction of the electric field) the periodic structure quality improves and the transmission returns to its high value. This switch ON response is comparatively fast and depends on the applied electric field strength. The switch ON time in this case is estimated as $\tau_{\text{ON}} \sim 4$ msec. At high electric field intensities above the threshold electric field the switch ON time of the NLC reduces to values in the order of 1 msec in accordance with equation 5.1. Given the millisecond order switch ON time of the infiltrated NLC, the LC molecules in the holes of the PCF will re-orientate dynamically in phase with applied electric field at frequencies below 1 kHz.

As a result, an LC infiltrated PCF can be used for detection and measurement of the frequency and amplitude of an applied electric field in the frequency range from 50 Hz – 1 kHz. On the application of a sinusoidally varying electric field, the transmission response of the infiltrated PCF is observed to be periodical with a frequency that is twice that of the frequency of the input signal. This is in accordance with the explanation given above. Figure 5.5 shows the transmission response of the LCPCF at 1550 nm when a sinusoidally varying electric field with the amplitude of $\sim 2.5 \text{ kVrms/mm}$ is applied at a frequency of 500 Hz. As can be observed the transmission response is periodically varying with a frequency of 1 kHz.
Figure 5.5: LCPCF transmission time response to a sinusoidal electric field waveform with amplitude of ~ 2.5 kVrms/mm and a frequency of 500 Hz.

5.3 Applications of LCPCF for the Estimation of Multiple Parameters for a Variable Electric Field

5.3.1 Combined Influence of Frequency and Electric Field Strength on the LCPCF Transmission Power Response.

The transmission response of the LCPCF at different frequencies of the applied electric field from 50 Hz – 1 kHz with the electric field intensity varying from 0 – 5.0 kVrms/mm is shown in figure 5.6. It should be mentioned that all the measurements for this section using the high-speed powermeter are averaged over time, with a sampling rate of ~ 1000 measurements per reading. For all frequencies the LCPCF transmittance varies with increasing electric field intensity above the
threshold electric field. The threshold electric field for molecular orientation decreases as the frequency of the input signal is increased from 50 Hz to 1 kHz. This behaviour for the LCPCF is found to be similar to that obtained by L. Scolari et al [121]. The transmittance response above the threshold field is observed to be close to linear with an increasing electric field but the region of linearity is found to increase as the frequency is lowered. A notable feature in the transmittance response with increasing electric field is the appearance of transmission peaks in the electric field range from 2.5 kVrms/mm to 3.5 kVrms/mm at higher frequencies. This is because on the application of an electric field above the threshold and with the reorientation of the LC, anisotropy is introduced. As a result the infiltrated section of the PCF under the action of the electric field behaves as a variable retarder introducing a phase delay between both orthogonal components of the modes propagating through the photonic liquid crystal fibre.

Figure 5.6: Frequency dependence of the transmission response of LCPCF with varying electric field intensity at 1550 nm.
This phase retardation is expressed as [124]:

\[ \delta = \frac{2 \pi l \Delta n}{\lambda} \]  

where \( \Delta n \) is the effective birefringence of the liquid crystal and \( l \) is the length of the infiltrated section of the PCF.

The effective birefringence of the infiltrated section of the PCF is set by the average orientational state attained by the NLC molecules at each electric field intensity. In this case, the transmission of the linearly polarized input light from the tunable laser source by the LCPCF with an increasing electric field shows oscillatory behaviour as the transmittance is related to \( \delta \) as [125]:

\[ T = \sin^2 \left( \frac{\delta}{2} \right) \]  

At 50 Hz the transmission response is observed to be linear for the entire electric field range above the threshold electric field from 1.5 kVrms/mm to 4.5 kVrms/mm. At frequencies above 100 Hz due to lower thresholds for molecular reorientation, transmission responses show several minima and maxima at electric field intensities above 2.5 kVrms/mm. At very high field intensities (for example, as in the case of fields of the order of 3.5 kVrms/mm) the transmission increases as a consequence of the improved periodicity of the holey region infiltrated with the LC. As the LC molecules regain their long range orientation order in the direction of the applied field, the larger LC-silica refractive index contrast provides better mode confinement and the guided light throughput increases.
5.3.2 Application of LCPCF for Frequency Monitoring of an External Electric Field

The dynamic properties of LCPCF in responding to a periodically varying electric field offer the possibility to measure an unknown repetition frequency for an applied electric field. In order to demonstrate this, the transmission response of the LCPCF was recorded at an electric field intensity of ~ 2.5 kVrms/mm for frequencies from 50 Hz – 1 kHz at increments of 50 Hz. The time responses of the infiltrated PCF transmission for an applied electric field with frequencies of 250 Hz, 500 Hz, 750 Hz and 1 kHz are shown in figure 5.7. In order to estimate the frequency \( f \) and other parameters such as the amplitude \( A \) of the applied electric field from the captured time response of the LCPCF, it is necessary to use a fitted function. A good candidate function is a \( \sin^2 \) function as follows:

\[
T(t) = A\left\{\sin^2 (2\pi f t)\right\} \tag{5.5}
\]

with \( A \) being the amplitude and \( f \) the frequency of the applied waveform.

For each case in figure 5.7 a sinusoidal fitting based on equation 5.5 is also shown. To demonstrate the ability to measure an unknown frequency, the repetition frequency was estimated using this sinusoidal fitting. The estimated frequency in each case, obtained as a result of fitting, when compared to the known applied frequency was found to be within a ~ ± 0.5% error margin. Figure 5.8 shows the plot of applied frequency with the percentage error in the measurement of frequency using the LCPCF device in the frequency range from 50 Hz – 1 kHz. This suggests that equation 5.5 is a good approximation for the time response of the LCPCF transmission in this frequency range and can be used to extract the frequency of an externally applied sinusoidally varying electric field with fixed amplitude. It should
Figure 5.7: LCPCF transmission time response at frequencies, (a) 250 Hz, (b) 500 Hz, (c) 750 Hz, and (d) 1 kHz, shown along with a sin² fitting.
be mentioned that slight changes in the frequency (~ 10 Hz) of the external electric field can lead to a change in the shape of the transmission response waveform, but the use of the fitting function can compensate for this and will still allow the frequency to be estimated correctly.

5.3.3 Combined Frequency and Amplitude Estimation for an Electric Field at 50 Hz

The comparatively larger linear range of the transmittance response with electric field intensity at 50 Hz also offers further potential applications. The LCPCF sensor allows one to estimate the frequency and amplitude simultaneously for a much larger electric field range at 50 Hz. To demonstrate this, the time response of the

![Percentage error vs Frequency of Applied e-field, Hz](image)

Figure 5.8: Applied electric field frequency plotted along with percentage error in the measurement of frequency.
Figure 5.9: LCPCF transmission time response for 50 Hz at electric field intensities of (a) 1.5 kVrms/mm, (b) 2.0 kVrms/mm, (c) 2.5 kVrms/mm, and (d) 3.0 kVrms/mm, shown along with a sin² fitting.
transmittance at different electric field intensities above the threshold electric field is recorded for a frequency of 50 Hz. As in the previous case a $\sin^2$ fit based on equation 5.5 is performed on the time response for the transmittance of the LCPCF in an electric field range from 1.5 kVrms/mm – 3.0 kVrms/mm. Figure 5.9 above shows the transmission response recorded at different electric field intensities along with the $\sin^2$ fit based on equation 5.5. The fitting parameters such as the amplitude $A$ and the frequency $f$ with increasing electric field intensity as obtained for each parameter are shown in figure 5.10.

It is observed that the frequency of the periodic variations in the transmission response is maintained at 50 Hz as the electric field intensity increases. Also, the amplitude of the periodic transmission response is found to increase linearly with increasing electric field intensity in this range.

It is worth noting that given the dynamic response of the structure to AC fields and the demonstrated ability to measure both amplitude and frequency, the development of a fiber based electrical signal waveform monitor using an LCPCF based sensor may be feasible. This may be possible if the time varying nature of an unknown electric can be reproduced in the transmission response of an LCPCF with enough fidelity, so that it is possible to envisage estimating not just the amplitude and frequency of the electric field but also the actual waveform shape itself. The simple all-fiber design of the sensing scheme proposed here provides the advantage of immunity from unwanted electromagnetic interference and the safety provided by dielectric isolation in high electric field environments.
In this chapter the dependence of the transmission response of a nematic liquid crystal infiltrated photonic crystal fiber on the frequency of an externally applied electric field was experimentally studied and presented in the frequency range from 50 Hz – 1 kHz. It was demonstrated that due to the millisecond order response time of the NLC to an applied electric field, the time varying transmission response of

5.4 Summary

In this chapter the dependence of the transmission response of a nematic liquid crystal infiltrated photonic crystal fiber on the frequency of an externally applied electric field was experimentally studied and presented in the frequency range from 50 Hz – 1 kHz. It was demonstrated that due to the millisecond order response time of the NLC to an applied electric field, the time varying transmission response of
the LCPCF is highly dependent on the frequency of the input signal waveform in the frequency range from 50 Hz – 1 kHz. The LCPCF transmission response on the application of a sinusoidally varying electric field is found to vary periodically and it has been demonstrated that the transmission response can be approximated using a $\sin^2$ function. Subsequently, the fitted function can be used to retrieve the input waveform parameters such as frequency and amplitude. The input frequency could be measured using the LCPCF device with an accuracy of 99.5 % in the frequency range from 50 Hz – 1 kHz. For the case of electric field signals with a frequency of 50 Hz the measured amplitude is found to vary linearly and the measured frequency is maintained at 50 Hz for an electric field range from 1.5 kVrms/mm – 3.0 kVrms/mm.

The results obtained with the studies as presented in this chapter show that the assumed sinusoidal function used for the theoretical fitting is a good approximation to the time varying transmission response of the LCPCF. The fitting function can be used to extract the parameters such as frequency and amplitude of the AC signal. The ability to detect the frequency of the applied AC field is an added advantage for the LCPCF based electric field sensor. These results demonstrate the application of a liquid crystal infiltrated photonic crystal fiber based sensor for fiber based electrical signal frequency monitoring in the frequency range from 50 Hz – 1 kHz and potentially an all-fiber based waveform monitor for electrical signals at a frequency of 50 Hz.
Chapter 6

Polarimetric Electric Field Sensors based on LCPCFs

6.1 Introduction

Polarimetric optical fiber sensors based on highly birefringent fibers have been extensively investigated for sensing of hydrostatic pressure, strain, vibration, temperature, acoustic waves etc [126, 127]. Most of these sensors are based on interferometric schemes employing high birefringent (HB) fibers. In an HB fiber strong asymmetries are introduced in order to remove the quasi-degeneracy of two orthogonally polarized modes and to allow for a single polarization mode to propagate. In polarimetric sensors a phase delay in the orthogonally propagating polarization modes induced by external parameters is used for the detection and measurement of the unknown parameters. A polarization maintaining photonic crystal fiber (PMPCF) with its elliptical core is an HB fiber and has been employed for various sensing applications for pressure, stress and vibrations [128-130].

In this chapter a liquid crystal infiltrated PMPCF is used in a polarimetric measurement scheme for electric field sensing. In chapter 4, planar aligning nematic liquid crystal infiltrated PCF was introduced as a novel technology for fabrication of all-fiber electric field sensors for the measurement of electric field intensity. The use of a liquid crystal infiltrated circular core PCF allows for the measurement of
electric field intensity in a range of fields as determined by the threshold electric field and electric field induced photonic bandgap of the LCPCF structure. A selectively infiltrated PMPCF was employed for the study. The polarization effects in a selectively infiltrated PMPCF were studied [131, 132]. In this chapter nematic LC infiltrated elliptical core PMPCF with an optimized infiltration length is used in a polarimetric sensing scheme. The optimization of the length of the infiltrated region of the LCPCF subjected to an electric field makes it possible to obtain a linear transmission response for a given electric field range. A lower threshold electric field and improvement in overall measurable electric field range is obtained with the use of splay aligning nematic liquid crystals. With the use of an elliptical core PCF the sensor head is also shown to have a useful directional sensitivity to the applied electric field. This property of the LC filled PMPCF is made use for the demonstration of an all-fiber based directional electric field sensor.

In section 6.2 the working principle and experimental setup for an LC infiltrated PMPCF based polarimetric electric field sensor is described. Section 6.3 describes experimental studies and results obtained with infiltration length optimization. The results obtained with two LCPCF samples with both planar aligning and splay aligning nematic LCs are presented. In section 6.4 the directional electric field sensitivity of an LC filled PMPCF sensor head is studied and presented.

6.2 Polarimetric Electric Field Sensing Scheme with LCPCFs

6.2.1 Background for the Polarimetric Sensing Scheme for Electric Field

In a polarimetric measurement scheme an optical sensing device, under the influence of the parameter to be sensed, is located between an optical polarizer and
a polarization analyser. The sensing device splits the incident light wave into two orthogonal linearly polarized waves. These two waves propagate with different phase velocities in the polarizing device and their phases are shifted by a quantity $\varphi$. The magnitude of this phase will depend on the parameter being sensed and thus by measuring the phase shift it is possible to quantify the unknown physical parameter, assuming a suitable calibration has taken place.

A cross-sectional view of the PMPCF used for the experiments is shown in figure 6.1. The birefringent axis of the PMPCF is along a direction orthogonal to the axis passing through the centre of the two large holes as shown in figure 6.1. On infiltration of the two large holes of the PMPCF with an NLC mixture the birefringent axis undergoes a 90° rotation [133]. The refractive index of the two holes is now set by the effective refractive index of the infiltrated NLC mixture. On the application of the electric field the LC molecules undergo reorientation and align themselves along the field direction. The reorientation of the NLC molecules changes the effective refractive index within the large holes which changes the phase birefringence of the fiber. The overlap of the propagating 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 an external electric field. Under these conditions the infiltrated PCF behaves as a variable phase retarder, with the retardance increasing with an increase in the length of the infiltrated section subjected to the applied electric field.

In a fashion similar to a Polarization Maintaining (PM) fiber, the PMPCF with its elliptical core supports two eigenmodes, with dominant electric field components in $x$ and $y$ directions (Figure 6.1). The eigenmodes are characterized by their effective
refractive indices \( n_x \) and \( n_y \). On infiltration and on the application of the electric field, the fiber birefringence changes to:

\[
\Delta N = (n_{y0} - n_{x0}) - (n_{yE} - n_{xE})
\]  

where \( n_{y0} \) and \( n_{x0} \) are the effective refractive indices in the absence of an electric field and \( n_{yE} \) and \( n_{xE} \) are the effective indices with the applied electric field. The phase retardance for the light propagating through the infiltrated PCF is given as:

\[
\phi = \phi_0 + \phi_E \quad \text{where} \quad \phi_E = \kappa_0 \Delta NL
\]

\( \phi_0 \) is the inherent retardance of the infiltrated PCF and \( \phi_E \) is the phase retardance induced by the electric field, \( \kappa_0 = \frac{2\pi}{\lambda} \) is the wavenumber, \( \lambda \) is the free space wavelength and \( L \) is the length of the infiltrated section under the influence of the applied electric field.

Figure 6.1: Selectively infiltrated PMPCF probe showing the axes orientation and applied field direction. The hole geometry of the PMPCF used for infiltration is shown in the bottom left.
Direct measurement of the effective indices of the modes of the infiltrated PMPCF is difficult and thus in order to characterize the retardance induced by the applied electric field it is convenient to express the field-induced phase retardance using the characterisation term $E_\pi$ as follows:

$$\phi_E = \pi \frac{\Delta E}{E_\pi}$$

where $\Delta E$ is the change in electric field intensity. The sensor characterization term $E_\pi$ can be measured by converting the phase shift into a change in the light intensity transmitted by the fibre using a linear polarizer. If the input and output polarizers are parallel and are at 45° with respect to the infiltrated PCF optical axis ($n_y$), the output intensity is given as,

$$I = \frac{I_0}{2} \left[ 1 + \sin \left( \phi_0 + \pi \frac{\Delta E}{E_\pi} \right) \right]$$

The transmitted intensity varies sinusoidally with the electric field intensity with a period set by the electric field induced phase retardance term which depends on the length of the infiltrated section under the influence of the external electric field. The sensitivity of such a PMPCF fibre sensor to an electric field increases with a decrease in the value of $E_\pi$. Since $E_\pi$ is inversely proportional to the length of infiltration, the sensitivity of the device will increase as the length of the infiltrated section subjected to the applied electric field increases. The optimization of the length of the infiltrated region of the LCPCF subjected to an electric field makes it possible to obtain a linear transmission response for a given electric field range.
6.2.2 Experimental Setup for Polarimetric Electric Field Sensing

The polarization maintaining PCF used for the experiments is the commercially available PM-1550-01 (Figure 6.1). The presence of two large holes around the core of the PCF introduces a nonaxisymmetric distribution of effective refractive index around the core. A non-circular core combined with a large air-glass refractive index step in the PCF creates a strong form birefringence [134]. It has five rings of air-holes around its solid core. The small holes are of diameter ~ 2.2 µm and the two large holes defining the birefringent axis of the fibre have a diameter of 4.5 µm. The fiber has non-circular core, with a major axis 5.4 µm long and a minor axis 4.3 µm long. The intrinsic birefringence of the PMPCF is ~ 4.0 x 10^{-4} [135].

For the experiments the two large holes of the PMPCF were infiltrated with NLC mixtures. The nematic LC mixtures used for infiltration were MDA-05-2782 and MLC-7012 (Merck). The ordinary and extraordinary refractive indices of MDA-05-2782 are ~ 1.49 and ~ 1.61 respectively measured at 589.3 nm and the isotropic temperature of material is ~ 106 °C (Merck datasheet). The MLC-7012 material has an ordinary refractive index of ~ 1.464 and an extraordinary refractive index of ~ 1.53 measured at 589.3 nm (Merck datasheet). It has an isotropic temperature of 91 °C. The specifications and properties of the LC materials and PCF used for the studies in this chapter are given in table 6.1 and 6.2 below.

In order to examine and ascertain the alignment of the nematic LC mixtures in the holes of PM-1550-01 PCF, the NLC mixtures where infiltrated into a silica capillary with ~ 5 µm inner diameter, which is of the order of the diameter of the large holes of PM-1550-01. The NLC infiltrated capillaries were then observed under a polarizing microscope. The alignment of MDA-05-2782 was found to be planar, whereas MLC-7012 was found to have a splayed alignment.
A section (~ 30 mm) of the PMPCF is initially spliced to a Polarization Maintaining (PM) fiber pigtail using a standard fusion splicer. The fusion current, fusion time and number of arc discharges are optimized to achieve minimal air-hole collapse of the PMPCF at the splice joint and also to ensure minimal degradation of the PM fiber structure at the splice joint [98]. The splice loss for the PMPCF to PM fiber joint is estimated to be ~ 6 dB.

Table 6.1: Properties of the LC materials used for the study.

<table>
<thead>
<tr>
<th>LC</th>
<th>( \Delta n )</th>
<th>( \Delta \varepsilon )</th>
<th>( T_c ) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDA-05-2782</td>
<td>0.164 (589.3 nm; 20 °C)</td>
<td>7.2 (1 kHz; 20 °C)</td>
<td>102</td>
</tr>
<tr>
<td>MLC - 7012</td>
<td>0.066 (589.3 nm; 20 °C)</td>
<td></td>
<td>91</td>
</tr>
</tbody>
</table>

Table 6.2: Specifications of the PCFs used for the study.

<table>
<thead>
<tr>
<th>PCF</th>
<th>( d ) (hole diameter)</th>
<th>( \Lambda ) (pitch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM-1550-01</td>
<td>Large hole – 4.5 μm</td>
<td>4.4 μm</td>
</tr>
<tr>
<td></td>
<td>Small hole – 2.2 μm</td>
<td></td>
</tr>
</tbody>
</table>

The sensor head is a < 1 mm NLC infiltrated section of the PMPCF (Figure 6.1). Selective infiltration of the two large holes was performed by collapsing the smaller holes around the core using a standard fusion splicer. In order to achieve this, the cleaved end of the PMPCF is kept between the electrodes of the fusion splicer and
controlled arc discharges are applied. The offset distance from the centre of the electrode axis, fusion current, fusion time are optimized in order to collapse all the smaller holes around the core leaving only the two large holes open [136]. A microscope image of the arc-treated end of the PMPCF is shown in figure 6.2.

![Figure 6.2: Microscope image of the cleaved end of the PMPCF after arc treatment with the fusion splicer.](image)

Subsequently, the PCF was infiltrated with a nematic LC mixture by dipping the cleaved end of the PCF into a drop of the NLC mixture at room temperature. The infiltrated PCF is observed under a polarising microscope to ascertain the quality of infiltration and care is taken to ensure that both the holes of the PMPCF are evenly infiltrated. Uneven infiltration results in high insertion loss and sinusoidal spectral interference patterns. After infiltration the collapsed end is cleaved off resulting in the total length of infiltration within the PCF after cleaving in the order of ~ 1 mm. This is done to minimise the insertion loss of the sensor, which increases with an increase in the length of infiltration. For MDA-05-2782 filled PMPCF an infiltration length of ~ 0.8 mm was observed using the polarizing microscope by cleaving after infiltration and for the MLC-7012 filled sample the infiltration length
achieved using the same method was ~ 1.6 mm. The disparity between the lengths achieved and the 1 mm desired length is a result of the limited accuracy with which the cleave length can be set. Furthermore due to the limitations of the translation stage of the polarizing microscope the measurement accuracy for the total infiltration length is ± 0.1 mm. The infiltration of the LC mixture into the PCF introduces an additional insertion loss of ~ 6 dB at 1550 nm for both the NLC samples.

To test the feasibility of utilizing the selectively infiltrated PMPCF sensor head for polarimetric electric field sensing the experimental set-up shown in figure 6.3 was employed. Light at 1550 nm from a tunable laser source was linearly polarised using a polarization controller (DPC5500; Thorlabs) and coupled into the input PM fiber with the selectively infiltrated PMPCF spliced to its other end. The PMPCF is clamped on to a precision bare fiber rotator and the rotator is mounted on an XYZ

---

Figure 6.3: Schematic of the experimental set-up for polarimetric e-field sensing.
nano-positioner stage (1.0 µm translation accuracy). The infiltrated end of the PCF is positioned between two electrodes with a spacing of ~ 150 µm between them. The fiber axis \( (n_y) \) of the PCF is arranged to be parallel with the electric field direction as in figure 6.1. This was done by using the fiber rotator and by viewing the end facet of the PMPCF under a high resolution digital microscope. The transmission of the infiltrated PCF in the presence of an external electric field is found to be dependent on the orientation of the fiber optical axis with respect to the direction of the electric field. With the axis of the fiber aligned along the electric field direction, the electric field induced birefringence change is maximised. The directional sensitivity of the sensor head is explained in detail in section 6.3 below.

The light transmitted by the PMPCF after passing through the infiltrated section was butt-coupled to an output PM fiber pigtail and then coupled to an in-line polarimeter (IPM5300 Thorlabs). The butt coupling at the infiltrated end was done using another XYZ nano-positioner stage. The output from the polarimeter is passed through a free-space analyser and coupled to the optical detector to record the value of transmittance.

The electric field was applied to the infiltrated PCF using a combination of a high voltage power supply modulated by a standard waveform generator operating at 1 kHz. This provides a positive polarity voltage waveform that varies in time sinusoidally from zero Volts up to a peak value, \( V_{\text{peak}} \), with an average value of \( V_{\text{peak}}/2 \). The maximum value of \( V_{\text{peak}} \) used in the experiment is 1000 V. The relationship between the \( V_{\text{peak}} \) value and the RMS value is given by:

\[
V_{\text{rms}} = (3/8)^{1/2} V_{\text{peak}}.
\]

Since the distance between the electrodes in the experimental arrangement was ~ 150 µm, in effect the sensing device is subjected to electric field intensity in the range from 0 to 4.1 kVrms/mm.
In order to study the influence of the length of the infiltrated section within the electric field on the output transmittance, the infiltrated section was translated between the electrodes, using the input nano-positioner stage, in fixed length steps. The polarized transmittance was recorded in the range from 0 to 4.1 kVrms/mm. It should be mentioned that although a sinusoidally varying AC field was applied to the sensor head the polarized transmission data provided by the high-speed optical power meter is averaged over time. It is also possible to alter the infiltration length by altering the quantity of LC material introduced into the PMPF, but achieving the equivalent fine increments in the infiltrated length for the purpose of this study would involve micro litre control of the infiltrated LC quantity which is difficult to realise experimentally. It is for this reason that translation of the infiltrated section with respect to the electrodes is used as a more practical alternative.

6.2.3 Experimental Results and Discussion

A. MDA-05-2782 Infiltrated PM-1550-01

The length of infiltration could not be estimated with accuracy better than 0.1 mm due to the limitation of the experimental setup. For this reason, the initial adjustment for a length of the infiltrated section within the electrodes area was done by translating the PMPCF into the space between the electrodes up to the point when a noticeable change (~ 1 dB) in the output transmittance was observed between the zero and maximum values of the applied electric field. This length of the infiltrated section within the electrodes was taken as the reference point. The infiltration length within the electrodes was incremented in 20 µm steps from the reference point and the electric field was varied from 0 to 4.1 kVrms/mm in each case. The polarized transmission at 1550 nm for MDA-05-2782 infiltrated PM-
1550-01 for different lengths of the infiltrated section subjected to varying electric field is shown in figure 6.4. For the sample infiltrated with MDA-05-2782 the electric field threshold for LC molecular reorientation was estimated to be 2.0 kVrms/mm. As discussed in the previous chapter, the relatively large threshold is due to the planar alignment of this material within the holes of the PCF. As longer lengths of the infiltrated section of the PCF are subjected to an electric field, the field induced phase retardance of the PMPCF increases. The polarised transmitted power decreases monotonically until the length of the infiltrated section subjected to electric field produces a phase change of $\pi/2$. Beyond this and as the length of the infiltrated section subjected to electric field is increased further, the $\pi/2$ phase retardance is attained at lower electric field strengths, above which the transmitted power increases again. From figure 6.4 it can be observed that for the case of 80 $\mu$m...
and 100 µm infiltration lengths the phase retardance of \( \pi/2 \) is attained at electric field intensities of \( \sim 3.4 \text{kVrms/mm} \) and \( \sim 2.9 \text{kVrms/mm} \) respectively. As can be observed from figure 6.4, the transmitted intensity above the threshold shows that the 60 µm infiltration length case provides the largest change in transmittance while also providing a monotonically decreasing response. Figure 6.5 shows the normalized transmittance response for the 60 µm sample along with a

![Figure 6.5: Transmission response (dots) with 60 micron length of infiltrated section within the electrodes and its sine fit (solid red line).](image)

sinusoidal fit based on equation 6.4 for an electric field range from 2.0 kVrms/mm to 4.1 kVrms/mm. The value of the sensor characterization term \( E_x \) estimated from the fit was \( \sim 2.35 \text{kVrms/mm} \). The built-in retardation term \( \phi_0 \) in equation 6.4 is a measure of the inherent phase retardance of the PMPCF and the phase retardance due to the infiltrated section outside the electrodes. It depends on various parameters such as temperature and mechanical stress the PCF is subjected, and thus varies between measurements. In order to provide an estimate of the sensitivity
of the device a linear response for an electric field can be assumed in the range from 3.4 - 4.1 kVrms/mm for the 60 µm sample. A linear fit for the data in this range provides an estimate of the sensitivity of the device as ~ 20 dB per kVrms/mm. Assuming a resolution of 0.01 dB for the optical power measurement system, the estimated resolution of the device over this e-field intensity range was ~ 5 x 10^{-5} kVrms/mm (50 Vrms/m).

The PMPCF samples infiltrated with nematic LCs, have a planar alignment within the holes of the PCF and thus demonstrate a threshold behaviour for the reorientation of the LC molecules. Therefore the field induced birefringence change can only be obtained above a threshold electric field. The LCPCF sensor’s lower electric field measurement range in this case is limited by the threshold electric field.

B. MLC-7012 Infiltrated PM-1550-01

Nematic LC mixtures with a splayed alignment do not show threshold effects [137]. Figure 6.6 shows the polarized transmittance at 1550 nm for MLC-7012 infiltrated PMPCF recorded for different lengths of the infiltrated section within the electrodes. The initial adjustment for the length of the infiltrated section was carried out as explained in the section above. The infiltration length was incremented in steps of 50 µm from the reference point for this sample. Unlike the MDA-05-2782, the reorientation of the LC molecules within the holes of the PCF takes place at very low values of the electric field. Since the birefringence of MLC-7012 is lower than that of MDA-05-2782, longer lengths of infiltrated section had to be subjected to the electric field to attain a phase retardance of the same order of magnitude. A near linear response was obtained in the case with 150 µm length of the infiltrated section within the electrodes for the entire applied electric field range. Figure 6.7
Figure 6.6: Transmission response of MLC-7012 filled PM-1550-01 at 1550 nm with varying electric field intensity obtained for different lengths of infiltrated section between the electrodes.

shows the normalized transmission response obtained at this length of the infiltrated section within the electrodes. A fit based on equation 6.4 for an electric field range from 0 to 4.0 kVrms/mm is also shown. The value of $E_\pi$ for the MLC-7012 filled sample estimated from the fit was $\sim 6.56$ kVrms/mm. The MLC-7012 infiltrated PMPCF has a useful electric field measurement range from 0 to 4.0 kVrms/mm and by careful adjustment of the length of the infiltrated section within the electrodes the sensor can be fabricated so it has a linear electric field response using a measurement scheme based on transmission intensity. In this case a linear electric field range can be assumed for the 150 µm sample from 1.0 kVrms/mm to 4.1 kVrms/mm. On performing a linear fit the sensitivity in this case is estimated as $\sim 2.0$ dB per kVrms/mm. Assuming a resolution of 0.01 dB for the optical power measurement system, the estimated resolution of the device over this e-field intensity range is $\sim 5 \times 10^{-3}$ kVrms/mm ($\sim 5 \times 10^3$ Vrms/m).
The MDA-05-2782 infiltrated PMPCF sensor has a lower $E_\pi$ value when compared to an MLC-7012 infiltrated PMPCF sensor, and therefore displays a significantly higher sensitivity to electric field intensity and thus a higher measurement resolution than the MLC-7012 infiltrated PMPCF sensor. However the advantage of the MLC-7012 infiltrated PMPCF sensor is that it can operate from e-field intensities close to zero, whereas the MDA-05-2782 infiltrated PMPCF sensor only operates above a threshold electric field value.

With an appropriate choice of an LC mixture for infiltration and by controlling the length of infiltration these structures can be customized for the measurement of electric field intensity in a specified electric field range. Given the high birefringence of the NLC mixtures available and the hole size of the PMPCF used, it is estimated that control on the infiltration length with an accuracy of ~ 1 $\mu$m is desirable, in order to achieve precise control of the electric field induced phase

Figure 6.7: Transmission response (dots) with 150 micron length of infiltrated section within the electrodes and its sine fit (solid red line).
retardance. It should be mentioned that precise control on the length of infiltration (~ µm accuracy) is difficult to achieve with the standard procedure used by various authors for infiltrating PCFs (also used in our experiments). Acceptable control on the infiltration length within the PCF can be achieved by injecting a known quantity of LC mixture into the PCF using a controlled syringe pump arrangement with ~ 1µL volume delivery and/or by fiber cleavers with high precision control of the cleave length to obtain a required infiltration length by cleaving.

6.3 Directional Electric Field Sensor Probe using LC Infiltrated PMPCF

Most of the demonstrations of fiber based electric field sensors 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 [138] 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 [139, 140], 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 produce on a large scale.

In the previous section the capability of an LC filled PMPCF probe to measure the electric field intensity was demonstrated. Due to the elliptical core of the PMPCF
combined with an electric field induced phase birefringence on LC infiltration the LCPCF probe is sensitive to the direction of the applied electric field.

### 6.3.1 Directional Sensitivity of an LC Infiltrated PMPCF Probe

The electric field directional sensitive sensor probe consists of a less than 1 mm long selectively infiltrated section of a PMPCF. Figure 6.8 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 \(\theta\). Figure 6.9 shows the schematic of the large diameter holes of the PCF along 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

\[
  n_E = n_e \sin \phi
\]

Figure 6.8: Infiltrated PCF polarization axis orientation and electric field direction

PCF orientation with respect to the electric field direction. The angle between the electric field direction and the fiber polarisation axis (\(n_y\)) is \(0\). Figure 6.9 shows the schematic of the large diameter holes of the PCF along 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 6.10, where $\varphi$ is the angle between the fiber propagation direction ($z$) and the NLC director and $n_e$ is the extraordinary refractive index of the NLC.

![Figure 6.9: Large holes of PMPCF with NLC molecular alignment on application of electric field.](image)

As the NLC molecules re-orient along the electric field direction (increase in $\varphi$) the component $n_E$ increases in magnitude. Linearly polarized light with a polarisation direction at $45^\circ$ 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 $\theta$), the component of $n_E$ along $n_y$ given by,

$$n_y = n_E \cos \theta$$

6.6 decreases as $\theta$ increases from $0^\circ$ to $90^\circ$, so in this case the phase retardance experienced by the light decreases. Using the same explanation as above, an
Increase in \( \theta \) from 90\(^\circ\) to 180\(^\circ\) will produce the same retardance as \( \theta \) going from 90\(^\circ\) to 0\(^\circ\). As a result, the polarized transmission response of the infiltrated PMPCF with the polarization axis of the PMPCF rotated from 90\(^\circ\) to 180\(^\circ\), with respect to the electric field direction, will be the same as when rotation is from 90\(^\circ\) to 0\(^\circ\).

The PMPCF probe selectively infiltrated with MLC-7012 was chosen for this study. This sample was chosen as the MLC-7012 showed a splayed alignment. As mentioned and demonstrated in the previous section, splay aligned LC mixtures within PCF holes have a low electric field threshold for LC molecular reorientation and provide a larger useful electric field measurable range.

The experimental set-up used for the study is the same as shown in figure 6.3. The electric field was applied in the form of a sinusoidally varying positive polarity waveform at 1 kHz frequency, using a combination of a high voltage (1000 V)
power supply modulated by a standard waveform generator. By careful adjustment with the XYZ translation stage and by observing the polarised transmission the infiltration length under the electrodes can be optimized for a particular phase change. 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. This ensured that a monotonically decreasing transmittance response was obtained for an increasing electric field strength in the range from 0 to 4.0 kVrms/mm.

The sensitivity of the infiltrated PMPCF to the direction of an electric field is studied in a polarimetric scheme, with the length optimized infiltrated section of the PMPCF being the sensing element. In order to change the orientation of the fiber with respect to the electric field direction, the infiltrated fiber section was mounted on a precision fiber rotator and was rotated within the fixed electrodes to study the effect of change in fiber orientation with respect to applied electric field direction.

6.3.2 Evaluation of the Directional Electric Field Sensitivity of the LC Infiltrated PMPCF Probe

Figure 6.11 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 each orientation angle. For each case of the orientation of the PCF polarization axis, the $n_c \cos \phi$ component increases with electric field intensity, resulting in higher phase retardance of the propagating light so that a decrease in the polarized transmission occurs. From figure 6.10 it can also be
observed that as the electric field intensity increased, there is an increase in the difference between the transmitted power at $\theta = 0^\circ$ and at $\theta = 90^\circ$. It was also

![Figure 6.11: 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.](image)

observed that the slope of the transmission response with electric field intensity reduced with an increase in $\theta$ from $0^\circ$ to $90^\circ$ as the fiber was rotated, in the electric field range from 1.0 to 4.0 kVrms/mm. A sinusoidal fitting based on equation 6.4 on the polarized transmission response at $\theta = 0^\circ$ and at $\theta = 90^\circ$ yielded an estimate of the $E_\pi$ values as $\sim 7.02$ kVrms/mm and $\sim 4.82$ kVrms/mm respectively. The sensor has a higher sensitivity to electric fields oriented parallel to the PCF polarization axis. The sensitivity decreases as the angle $\theta$ is increased and is found to be lowest when the polarization axis is orientated orthogonally to the electric field direction. Figure 6.12 shows the angular dependence of the transmitted power versus
orientation of the PCF polarization 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 $\sim -0.07$ dB/degree at a fixed electric field intensity of 3.67 kVrms/mm. It should be noted that while the data in Figure 6.12 is plotted with a linear intensity scale, the relationship is non-linear as expected from equation 6.4. A dB intensity scale was used in order to provide an estimate of the angular sensitivity of the device. As explained in section 6.3.1, at a fixed value of the electric field intensity the $n_r \cos \theta$ component decreases in magnitude as $\theta$ is increased from 0° to 90° by rotation of the 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. As discussed in section 6.3.1, the

Figure 6.12: 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.
response of the sensor is similar for \( \theta \) going from 0° to 90° and from 180° to 90°, this gives rise to a directional ambiguity which can be resolved with the use of two such similar sensors, placed orthogonally to each other in the electric field.

6.4 Summary

In this chapter the performance of a nematic liquid crystal infiltrated polarization maintaining photonic crystal fiber as an all-fiber electric field sensor has been evaluated. The sensor probe is a < 1mm infiltrated section of the PMPCF and such a simple all-fiber design makes it very compact and allows for easy integration and coupling with fiber optics. A polarimetric scheme has been employed wherein the phase retardance of the selectively infiltrated PMPCF is controlled by carefully adjusting the length of the infiltrated section subjected to the electric field. By appropriate adjustment of the infiltration length within the electrodes the sensor can be optimized to provide a linear transmittance response to an external electric field. Nematic liquid crystal mixtures exhibiting both planar and splayed alignment within the holes of the PCF have been investigated. A sensor based on a splay aligned nematic LC mixture was shown to have a larger measurable electric field range, and consequently can be used for measurements of low electric field intensities. A planar aligned NLC mixture has improved sensitivity at high values of electric field. The nematic LC infiltrated PMPCF studied in this chapter is capable of operating as an in-line sensor for electric field intensity measurements using a source operating in the telecommunication window at 1550 nm. As an inherent electric field sensor the device can also be used as a voltage sensor with voltage being applied using a fixed electrode configuration. An appropriate choice of LC material for infiltration and the optimization of the infiltration length of selectively infiltrated PMPCFs
would allow for the design and fabrication of compact, low loss, all-fiber electric field sensors for low and high electric field environments.

The directional sensitivity of a splay aligning nematic liquid crystal infiltrated polarization maintaining PCF in an electric field for sensing of electric field components was also investigated and demonstrated in this chapter. A probe, which consists of a section of a selectively infiltrated PMPCF, was optimized so that it had a monotonically varying transmission response for a particular electric field range. This was 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 demonstrated 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.
Chapter 7

Conclusions and Future Research

In this chapter the overall conclusions of the thesis are presented. The conclusions are divided into six sections based on the different research strands investigated and reported in this thesis. In this thesis, liquid crystal materials have been investigated for a variety of device applications in both bulk-type and all-fiber type configurations for tunable photonic devices in optical communications and optical sensing systems. Based on the infiltration of liquid crystal into photonic crystal fibers, a common platform has been developed to address the need for an all-fiber configuration for tunable photonic devices for specific applications in optical communications and for electric field sensing. The investigations performed in this thesis have led to the design and development of tunable photonic devices such as a liquid crystal based channel dropper for the multiple sensor systems, an all-fiber tunable filter and a variable optical attenuator for optical communication systems and a novel technology for all-fiber based electric field sensors.

Finally, in this chapter some possible future research directions are considered as an extension of this research. LC infiltration of PCFs is an area that holds numerous possibilities for the development of all-fiber tunable photonic devices.
1. A ferroelectric liquid crystal based tunable filter for demodulation of multiple FBG sensors

In this thesis the employment of surface stabilized ferroelectric LC cells as tunable retarders in a Lyot polarization interference filter was studied theoretically and experimentally. Theoretical studies on two-stage and three-stage Lyot filters were performed, and the design parameters of the Lyot filter were determined for an experimental demonstrator of the tunable filter. With the microsecond order switching times of a ferroelectric LC, the demonstrated filter is found to be suitable for the demodulation of multiple FBG sensors.

The key conclusions from this study are:

- An SSFLC cell can function as a tuning element within a Lyot filter and, with an appropriate thickness, can provide fine tuning of the key spectral parameters of the bandpass response of the tunable filter.
- With an FSR of ~ 40 nm and a filter bandpass of ~ 6 nm obtained experimentally, FLC based tunable Lyot filter can be used as a front end to a ratiometric wavelength measurement system, to function as a channel dropper for the demodulation of multiple FBG sensors employed in a WDM based sensing system.
- While bulk type filters allow for accurate control of the tunable filter transmission response, they incur insertion losses due to the presence of bulk optics and for fabrication, difficulties arise with coupling to external interconnecting fibers.
- An alternative device configuration which is simpler to interface to fiber is desirable, to overcome the limitations of the bulk device described above.
2. Liquid crystal infiltrated photonic crystal fiber for applications in optical communication systems.

Electrical tuning of the photonic bandgap transmission properties of a liquid crystal infiltrated PCF is experimentally studied in this thesis for applications in optical communications systems. The infiltration of LCs into PCFs allows for the electrical tunability of the photonic bandgaps of the fiber in a wavelength range from 1500 nm – 1600 nm, which allows for the implementation of a variable optical attenuator and an all-fiber tunable notch filter, suited for various applications in optical communication systems and potentially in optical sensing.

From these studies the following conclusions were drawn:

- Liquid crystal infiltrated photonic crystal fiber is found to be a suitable technology for the implementation of a variety of all-fiber tunable photonic devices for optical communications, with the important advantage of simple fiber interfacing.
- A nematic LC infiltrated PCF operating on the principle of photonic bandgap guidance was demonstrated as an all-fiber electrically controlled broadband variable optical attenuator. The LCPCF device exhibits ~ 40 dB attenuation between it’s high and low states and has a linear attenuation response with applied voltage.
- The electrical tuning of photonic bandgaps of a smectic LC infiltrated PCF was demonstrated in the wavelength range of 1500 nm – 1600 nm for application as an all-fiber tunable notch filter. A linear response for the spectral shift of the notch (transmission minima) with a change in voltage was demonstrated and a tunable range of ~ 20 nm was obtained.
3. A liquid crystal infiltrated photonic crystal fiber electric field sensing probe.

In this thesis the use of nematic LC infiltrated solid core photonic crystal fiber as an all-fiber based electric field intensity measurement device was studied and experimentally demonstrated. Different combinations of commonly available PCF and LC mixtures were investigated to study the transmission response with an applied electric field of a varying intensity. The sensor based on the electrical tunability of the LC infiltrated PCF is shown to have a linear transmission and reflection responses with a varying electric field intensity. The temperature dependence of the electric field sensor was also studied.

The key conclusions from these studies are:

- The external electric field dependent transmission properties of a nematic liquid crystal infiltrated PCF can be used as a basis for an electric field sensor. The LCPCF based sensor can provide a resolution of ~ 1 Vrms/mm and with the simple all-fiber design of the sensor ensures a compact form factor and allows for easy integration and coupling with fiber optics.

- The sensing device is capable of operating as an in-line sensor in the transmitted mode and also as an end point sensor in the reflected mode.

- As an inherent electric field sensing device the sensor can also be used for high voltage sensing in the range from 500V - 15 kVolts, with the voltage being applied using a fixed electrode configuration.

- There was a significant change in the sensitivity of the sensor with change in temperature in the range from 0 °C – 90 °C but the transmission and reflection response of the sensor maintains its linearity in the measurable electric field range.
• To maintain accuracy across a broader range of operating temperatures, the sensor requires an associated means of active temperature monitoring and calibration correction.

• A disadvantage of the use of planar aligning LCs is the presence of a threshold which limits the measurable electric field range.

4. Evaluation of the response of an LCPCF electric field sensor to the frequency of the applied electric field.

The dependence of the transmission response of a nematic liquid crystal infiltrated photonic crystal fiber on the frequency of an externally applied electric field was experimentally studied in the frequency range from 50 Hz – 1 kHz. Due to the frequency dependent dielectric permittivity of the LC, the transmission response of the LCPCF is found to be dependent on the applied electric field frequency.

The key conclusions of this study are:

• Due to the millisecond order response time of the NLC, the time varying transmission response of the LCPCF is highly dependent on the frequency of the input signal waveform in the frequency range from 50 Hz – 1 kHz.

• The LCPCF transmission response in time on the application of a sinusoidally varying electric field is found to vary periodically. The time varying transmission response can be approximated using an appropriate scaled sin² function. The fitted function can be used to retrieve the input electric field waveform parameters such as frequency and amplitude.

• The input frequency could be measured using the LCPCF device with an accuracy of 99.5 % in the frequency range from 50 Hz – 1 kHz. For the case of electric field signals with a frequency of 50 Hz the measured amplitude is
found to vary linearly and the measured frequency retains its accuracy for an electric field range from 1.5 kVrms/mm – 3.0 kVrms/mm.

- The ability to detect the frequency and amplitude of the applied AC field is an added advantage for the LCPCF based electric field sensor, which could find potential application as an all-fiber based signal waveform monitor.

5. All-fiber electric field sensor based on a polarimetric sensing scheme using LCPCFs.

In this thesis selective infiltration and infiltration length optimization for the LC filled polarization maintaining PCF is studied for all-fiber electric field sensing applications. A polarimetric scheme was employed wherein the phase retardance of the selectively infiltrated PMPCF was controlled by carefully adjusting the length of the infiltrated section subjected to the electric field. Both planar aligning and splay aligning LC were studied for their suitability in LC infiltrated PCFs for electric field sensing.

From these investigations it was concluded that,

- By appropriate adjustment of the infiltration length within the electrodes the sensor can be optimized to provide a linear transmittance response to an external electric field in a polarimetric electric field sensing scheme.

- A planar aligned NLC mixture resulted in a significantly improved resolution of 0.05 Vrms/mm at high values of electric field but has a comparatively higher low end measurable electric field range due to threshold effects. A sensor based on a splay aligned nematic LC mixture was shown to achieve a larger measurable electric field range, and can be
used for measurements of low electric field intensities in the order of 0.5 kVrms/mm.

- An appropriate choice of LC material for infiltration and the optimization of the infiltration length of selectively infiltrated PMPCFs would allow for the design and fabrication of compact, low loss, all-fiber electric field sensors for low and high electric field environments.

- The advantage of using the LCPCF sensor in polarimetric sensing scheme is that the measurable electric field range can be easily optimized for specific applications.

6. **Directional electric field sensitivity of the LCPCF electric field sensing probe.**

The directional sensitivity of a splay aligning nematic liquid crystal infiltrated polarization maintaining PCF in an electric field for sensing of electric field components was also demonstrated in this thesis. A probe which consists of a section of a selectively infiltrated PMPCF was optimized to achieve a monotonically varying transmission response for a particular electric field range by adjusting the length of the infiltrated section subjected to an electric field.

The key conclusions from this study are:

- The LCPCF based sensor is capable of simultaneous detection and measurement of the direction and magnitude of the applied electric field making it a true all-fiber directional electric field sensor.

- The sensor probe was a less than 1 mm length infiltrated section of the PMPCF and has a simple all-fiber design which makes it very compact and allows for easy integration and coupling with fiber optics.
• The sensor probe has higher sensitivity to electric field component aligned along the PMPCF polarization axis. The sensitivity was lowest when the polarization axis is oriented orthogonal to the electric field direction.

• A linear relationship was established between the angle of orientation of the polarization axis with respect to the electric field direction and the transmitted power at fixed electric field intensity.

• 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.

• The LC infiltrated 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.

**Overall conclusions of the Thesis.**

The overall conclusions from this research and thesis are:

• The incorporation of liquid crystal materials provides a means to achieve easy tunability which is very suited to the implementation of tunable photonic devices in both optical communication and optical sensing systems.

• The infiltration of LC into PCFs provides a suitable common platform to design and fabricate simple and compact all-fiber tunable photonic devices which can be easily integrated with optical fiber networks and sensing systems.

• A novel technology for all-fiber based electric field sensing is developed using liquid crystal infiltrated PCF. A simple and compact all-fiber sensor head based on LCPCF allows for the accurate measurement of electric field
intensity, along with detection and measurement of electric field signal parameters such as frequency, amplitude and also the direction of the electric field.

**Future Research Challenges:**

**All-fiber magnetic field sensing using LCPCF**

Liquid crystals normally have a very low sensitivity to magnetic fields. The doping of ferromagnetic particles enhances the magnetic field sensitivity of liquid crystals. These new type of liquid crystals are referred to as ferronematic liquid crystals [141]. Infiltration of ferromagnetic particle doped nematic LC into PCF will lead to a significant increase in the sensitivity of the PCF propagation properties to magnetic fields. With appropriate device configurations such structures can be used for the fabrication of all-fiber based magnetic field sensors.

Fiber optics based magnetic field sensors demonstrated so far employ intrinsic and extrinsic mechanisms, but these suffer from complex fabrication processes and/or low sensitivity. The use of a ferronematic LC mixture for infiltration could lead to the development of a true all-fiber magnetic field sensor with a high intrinsic sensitivity.

**All-fiber based current sensor using LCPCF**

Infiltration of a ferronematic LC in PCF with an appropriate device configuration could also be used in an all-fiber current metering device. For this work appropriate ferronematic liquid crystals need to be custom synthesized to possess a high sensitivity to magnetic fields when infiltrated within the holes of the PCF. With an appropriate choice of a nematic LC host and the optimization of doping
concentration of the ferromagnetic particle, the sensitivity of ferronematic LC to a magnetic field can be enhanced so that sensing of the magnetic fields created by current carrying conductors in electric power applications is possible.

The infiltration of these custom synthesised LCs can be used for the fabrication of all-fiber current sensors. With appropriate device configuration or with a magnetic flux concentrated the LCPCF sensor probe can detect and measure the magnetic field intensity and can give a measure of the current. These sensors can also be employed in electric power grids for fault monitoring.
References


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*IEEE International Conference on Photonics (ICP)*, 2010.


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Ferroelectric Liquid Crystal Mixture

FELIX®-019/000

for chevron mode with oblique SiO alignment layer

Material Properties

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<th>Property</th>
<th>Value 1</th>
<th>Temperature 1</th>
<th>Value 2</th>
<th>Temperature 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clearing Point</td>
<td>106 °C</td>
<td>+20 °C</td>
<td>116 m Pa s</td>
<td></td>
</tr>
<tr>
<td>Rotational Viscosity</td>
<td>γ₁</td>
<td>+20 °C</td>
<td>116 m Pa s</td>
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<tr>
<td>Optical Anisotropy</td>
<td>Δn</td>
<td>589.3 nm</td>
<td>0.1240</td>
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</tr>
<tr>
<td></td>
<td>nₑ</td>
<td>589.3 nm</td>
<td>1.6152</td>
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<tr>
<td></td>
<td>nₒ</td>
<td>589.3 nm</td>
<td>1.4912</td>
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<tr>
<td>Dielectric Anisotropy</td>
<td>Δₑ</td>
<td>1.0 kHz</td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ε₁</td>
<td>1.0 kHz</td>
<td>11.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ε⊥</td>
<td>1.0 kHz</td>
<td>4.1</td>
<td></td>
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<tr>
<td>Elastic Constants</td>
<td>K₁</td>
<td>+20 °C</td>
<td>pN</td>
<td></td>
</tr>
<tr>
<td></td>
<td>K₂</td>
<td>+20 °C</td>
<td>pN</td>
<td></td>
</tr>
<tr>
<td></td>
<td>K₂/K₁</td>
<td>+20 °C</td>
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</tr>
<tr>
<td>Low Temp. Storage (Cells)</td>
<td></td>
<td>-20 °C</td>
<td>Passed</td>
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<td>Low Temp. Storage (Cells)</td>
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<td>-30 °C</td>
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<td>Low Temp. Storage (Cells)</td>
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<td>-40 °C</td>
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<tr>
<td>HTP Dopant: S-811</td>
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<td>+20 °C</td>
<td>-10.3 μm⁻¹</td>
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</tbody>
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Electro-Optical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value 1</th>
<th>Temperature 1</th>
<th>Value 2</th>
<th>Temperature 2</th>
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</thead>
<tbody>
<tr>
<td>Twist Angle</td>
<td>240 °</td>
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<tr>
<td>d*Δn</td>
<td>0.85 μm</td>
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<tr>
<td>d/p</td>
<td>0.53</td>
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<tr>
<td>Polyimide Type</td>
<td>Type IV</td>
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<tr>
<td>Threshold Voltage</td>
<td>V₁₀, φ=0°</td>
<td>+20 °C</td>
<td>2.37 V</td>
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<tr>
<td>Saturation Voltage</td>
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<td>Steepness</td>
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<td>+20 °C</td>
<td>4.2 %</td>
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### Physical Properties

<table>
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<th>Property</th>
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<tbody>
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<tr>
<td>Twist Angle</td>
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</tr>
<tr>
<td>clearing point</td>
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</tr>
<tr>
<td>optical anisotropy</td>
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<td>Cleaning Point</td>
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<td>Physical</td>
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### Electro-Optical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Low Temp. Storage (Bulk)</td>
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</tr>
<tr>
<td>Low Temp. Storage (Cells)</td>
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</tr>
<tr>
<td>n0</td>
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<tr>
<td>n1</td>
<td>1.5304</td>
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<tr>
<td>n2</td>
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### Chemical Properties

<table>
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<th>Property</th>
<th>Value</th>
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<tr>
<td>MLC-7012</td>
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