Synopsis

Topic – Designing and analysis of Photonic Crystal Fiber for various applications

Photonic crystal fiber (PCF) is a new class of optical fiber based on the properties of photonic crystals. Because of its ability to confine light in hollow cores or with confinement characteristics not possible in conventional optical fiber, PCF is now finding applications in fiber optic communications, fiber lasers, nonlinear devices, high power transmission, highly sensitive gas sensors, and other areas.Photonic crystal fibers are optical fiber with a periodic arrangement of low index material in a background with high refractive index material. The background material in PCF is usually undoped silica and the low index region is typically provided by air holes running along their length. The electromagnetic waves propagate through the PCF due to photonic band gap effect which is analogue to the electronic band gap inside crystal. When light propagates through the PCF dispersion, nonlinearity and birefringence occurs, this has to control by taking suitable geometrical parameters in core and cladding region of PCF. So it requires many numerical techniques to analyze and then to achieve single modeness, high spot size, high numerical aperture, zero dispersion, high nonlinearity, high birefringence, low confinement loss at desired wavelength, which gives tremendous applications in manufacturing various photonic devices.

Research Objectives:

The research objectives are given in the following:

- To analyze two dimensional photonic crystal fiber structure by full vectorial finite element method.

- To create defect on core and cladding region in PCF and to study fundamental properties like V-parameter, effective refractive index, dispersion, birefringence, confinement loss, effective mode area etc. of solid core, hollow core, honey comb and other type of PCF.
- To develop a new kind of PCF that can give zero dispersion, high nonlinearity, high birefringence and low confinement loss at particular wavelength.
- To use designed PCF for various applications like communication, sensing, photonic devices etc.

Thesis overviews and conclusions:

The thesis consists of seven chapters.

Chapter 1

Chapter 1 describes the overview of the thesis. Introduction of the photonic crystal fiber (PCF), light guiding mechanism, types of PCF, fabrication techniques, characteristics and applications of the PCF in different field are presented in brief. A short history and recent work on the photonic crystal fiber has been presented in the chapter 1.

Chapter 2

In this chapter, the governing equations, because of that light is guiding in to fiber, are presented. Structures of the photonic crystal fiber are very complex so we require different numerical techniques, such as Improved Effective Index Method, Plane Wave Expansion Method (PWEM), Multipole Method, Finite Difference Time Domain Method (FDTDM) and Finite Element Method (FEM) and so on, to study these types of the structure and with the help of these numerical methods we study the optical properties of the PCF. Out of all above mention methods, FEM is best suitable numerical method for the computing the structure and properties of the PCF. It takes less computational time, requires less computer memory and provides accurate results. We briefly describe the full vectorial

finite element method (FVFEM) and discuss its advantage over other methods. We also discuss the mode coupling theory and surface plasmon effect in this chapter.

Chapter 3

In this chapter, we design and simulate the highly birefringent, endlessly single mode photonic crystal fiber with very high nonlinearity by using FVFEM. Here we see the effect of the structural parameters such as air hole diameter and pitch (distance between two air holes) on the optical properties of the newly designed photonic crystal fiber. In the proposed design of the photonic crystal fiber, 34 oriented low index circular air holes are arranged in a triangular lattice array within the high index background material silica. Four symmetrical large air holes are introduced by replacing four small air holes in this fiber near the core region. It is then analyzed by FVFEM. The key point is to destroy the symmetry of the structure and make the effective index difference between the two orthogonal polarization states. The background material is silica and holes are empty i.e. air filled, where the refractive indices of silica and air holes are taken as 1.45 and 1 respectively. By optimising the structural parameters we find the appropriate design of the photonic crystal fiber with some unique characteristics.

The simulation results prove that endlessly single-mode, small mode area, nonlinearity and birefringence property mostly depend upon the optimized geometrical fiber parameters such as four symmetrical large air hole along near the core region with diameter (d') = 2.00 μm, pitch (Λ) = 2.30 μm and small air hole presented in cladding region having diameter (d) = 0.80 μm. Endlessly single-mode ($\leq \pi$), small effective mode area of 2.70 μm^2, nonlinear coefficient of 44.39 $W^{-1}km^{-1}$, high phase birefringence of 5.05×10^{-3} and group birefringence of 6.97×10^{-4} with beat length 0.30 mm at wavelength 1.55 μm are achieved. This kind of fiber can be used in optical communication and various polarization sensitive devices.

Chapter 4

Chapter 4 presents an improved design of the photonic crystal fiber with asymmetric cladding, consists of two symmetric air holes near the core region and elliptical hole in the

rest of the portion of the cladding. We study the optical properties of the photonic crystal fiber such as birefringence, confinement loss and dispersion parameter. Here, we replace circular air holes of the cladding region with elliptical air holes. Then by using FVFEM, birefringence, confinement loss and dispersion parameters are studied by introducing two large circular air holes symmetrically located opposite side of the core. The symmetry of the structure is destroyed by introducing two circular air holes near to the core and placed opposite side of the core. We have studied the influence of structural parameters on the optical properties of photonic crystal fiber. Two types of the proposed structure are investigated successfully. The numerical results show that the birefringence of the proposed Type-2 PCF structure is very high compared to the Type-1 PCF structure. The reason of this high birefringence in Type-2 PCF is that the elliptical hole direction is perpendicular which gives rise light to propagate more confined in the core region. The confinement loss of the both polarized modes is very low. The simulation results also show that the zero dispersion wavelengths for both types of the structure come to the near infrared region (around 0.90 μm and 0.95 μm). The proposed PCF structures have very high birefringence to separate the two polarization modes. This kind of PCF structure is very useful for polarizing maintaining devices, dispersion compensating devices, nonlinear applications and sensing applications.

Chapter 5

Chapter 5 is divided into two parts. In first part, we present a dual core photonic crystal fiber based refractive index sensor. Two cores have been created by omitting two air hole placed at the opposite side of the center hole then it becomes two new fiber cores. The central air hole is filled with analyte liquid. Since the two cores have higher refractive index then the cladding region therefore the light is guided in the two cores by index-guiding mechanism. The FVFEM is employed to simulate the guided features of the proposed photonic crystal fiber. The result shows that the refractive index sensor with 1 cm length has the large sensing range and high sensitivity up to -65166.10 $nmRIU^{-1}$ at wavelength 1.25 μm. From the investigation, it is observed that this sensor is very good for sensing the low refractive index liquid up to refractive index equal to 1.30.

In second part of this chapter, we present a novel magnetic field sensor based on magnetic fluid infiltrated dual core PCF. Two air hole situated at the opposite side of the center hole have been filled with magnetic fluid (Fe_3O_4) along length wise that form two independent waveguides. Inside the designed PCF, the mode coupling of two cores under different magnetic field strength is numerically investigated for magnetic field measurement. The performance of the PCF based sensor has been investigated by varying its structural parameters. The external applied magnetic field can be sensed by measuring the shift in peak wavelength of the transmitted optical spectra. The results show that the magnetic field sensor with 1 cm length of PCF has the large sensing range and very high sensitivity of 305.8 $pmOe^{-1}$. It provides an improved result to realize the novel PCF based magnetic field sensor.

Chapter 6

In this chapter, the sensing properties of a D-shaped photonic crystal fiber sensor based on surface plasmon resonance have been investigated by using FVFEM. Photonic crystal fiber sensors are based on the surface plasmon resonance effect between surface plasmon polariton modes and the fiber core modes. It is mainly due to the evanescent fields and its interaction with the analyte. Such type of core-cladding arrangement in a line increases the leakage of the light that propagates through the core and produces more evanescent field. This field interacts with metal layer and excites the free electrons of the metal layer easily and produces surface plasmon. At the particular wavelength, called resonance wavelength, the effective refractive index (n_{eff}) value of the core guided mode is equal to the n_{eff} of the surface plasmon polariton (SPP) mode. Evanescent field easily excites the free electrons of a metal surface at the resonance wavelength which generates the surface plasmon waves (SPWs).

We have used confinement loss spectrum for determining the resonance wavelength, and systematically studied the sensitivity. We have also investigated the effect of the structural parameters and the thickness of the gold film on the sensing properties of the present sensor.The average sensitivity of 7700 $nmRIU^{-1}$ and maximum sensitivity of 9000 $nmRIU^{-1}$ are obtained with a very high resolution of 1.30×10^{-5} RIU from the proposed sensor of

structural parameters small air hole diameter (d_s) = 0.80 µm, large air hole diameter (d_1) = 1.60 µm, pitch (Λ) = 2.30 µm and gold film with thickness (t_g) = 0.04 µm and analytes of RI ranges from 1.43 to 1.46. Driving on the advantages of the latest nano-fabrication technique, the proposed structure can be utilized for a broad scope of applications.

Chapter 7

This chapter carries the summary of the work done so far for my Ph. D. dissertation. The final conclusions and future scopes of the work have been presented at last in this chapter.