Chapter-3

Propagation Characteristics of Photonic Crystal Fiber and Study of their Modal Features based on a Few Designing Techniques

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This particular chapter, highlights a new class of fiber that allows propagation of electromagnetic wave in a different fashion rather than the one followed by conventional optical fibers. Additionally, this chapter deals with the description of some of the techniques that can be helpful in designing and study of the modal properties of photonic crystal fibers.

1. INTRODUCTION

Photonic crystal fiber (PCF) has been under great research interest for the past few years owing to their unique structures [1]. It is composed of a number of air holes in regular lattices because of which unique they are also

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known as holey fiber. Based on their lattice structure as well as geometrical parameter, it is possible to bring variation in modal properties and design. Additionally, alteration in the lattice structures can be formed by varying the air hole diameter (*d*) and the spacing between them which is considered as pitch '*Λ*' [1-2]. By convenient change in the structural parameters (or geometrical parameters), the modal behavior of a PCF can also be altered. PCF offers innumerable advantages based on their unique properties that are not feasible through the use of conventional optical fiber.

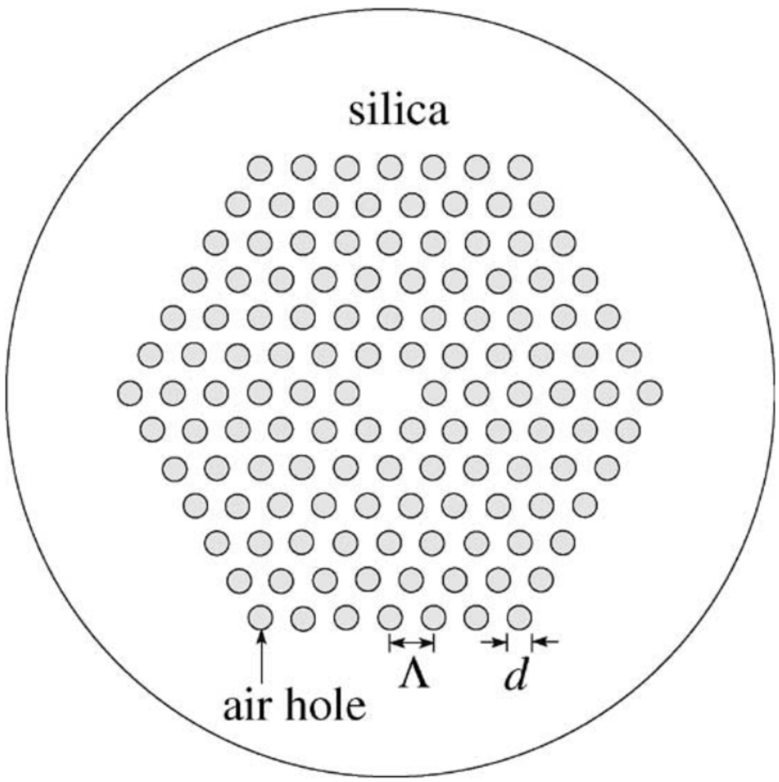

Fig. 1 Schematic of the solid core Photonic crystal fiber [1]

With subsequent discovery of conventional optical fiber that propagate light through total internal reflection (TIR) *P. Russell* came up with a unique structured fiber and named it as holey fiber [3-12]. Thereafter, a few researchers established the fact that rather than conventional technique, PCF can propagate light through photonic band gap effect. Based on the propagation characteristics PCF falls into two categories: (a) index guiding i.e., modified total internal reflection and (b) air-guiding i.e., photonic band gap effect. The former one is considered to follow the conventional total internal reflection phenomenon. The later one follows photonic band gap effect in which coherent backscattering of light leads to the guiding of light into core [1-3, 11-13].

1.1 The guiding mechanism of photonic crystal fiber:

(a) Air guiding mechanism:

It follows the conventional total internal reflection phenomenon in which light can propagate from core to cladding with distinction of refractive indices between the core and the cladding. The core has to be of higher refractive index than that of the cladding which is composed of air holes in periodic arrangements inside it. Owing to the periodic arrangement of air holes the total internal reflection is considered to be as modified total internal reflection [4-10]. Solid core PCF follows modified total internal reflection phenomenon, which is illustrated schematically in figure 1.

(b) Photonic band gap effect:

The distinction in refractive indices between the core and the cladding is not necessary to confine light through the core of PCF. The periodic arrangement of air holes in a hollow core PCF leads to coherent backscattering of light into the core. This leads to the confinement of light through the core and is called photonic band-gap effect [4-10]. Basically, hollow core PCF follows photonic bandgap effect to propagate light. Figure 2 shows the schematic illustration of hollow core PCF.

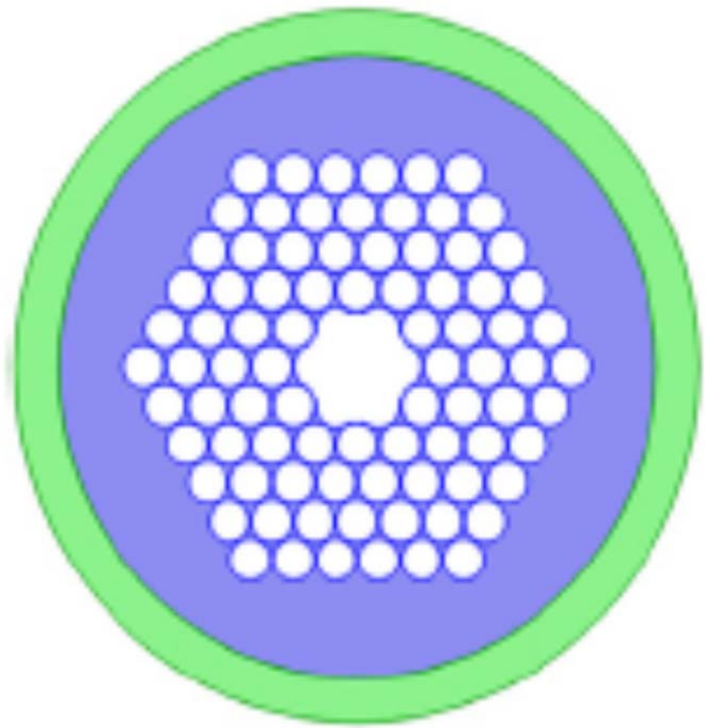

Fig. 2: Schematic of the Hollow core photonic crystal fiber [14]

Furthermore, PCF includes certain explicit characteristics such as *photonic-band gap fiber* (PCFs that can confine light by band gap effects), *holey fiber* (PCFs using air holes in their cross-sections), *hole-assisted* fiber and *Bragg fiber*. PCFs can also be considered as a subgroup of a more general class of

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microstructured optical fibers, in which light is guided not only by refractive index differences but also by structural modifications [15-16]. Because of its ability to confine light in hollow cores that is not possible in conventional optical fiber [17], it has several applications. Some of the common areas of applications of PCFs include fiber-optic communications, fiber lasers, nonlinear devices, high-power transmission, sensors and in other areas and other types of sensing based applications. PCFs have been proposed to acquire certain properties like single mode operation over a wide wavelength range, allowing nonlinear effects for small mode area, large mode area for creating high-power optical beams, an enormous control over dispersion for variable air-hole diameter (d) and pitch (Λ) [18]. Several numerical techniques have been established to study the guiding properties of PCF such as finite difference time domain method (FDTD) [19-20], finite element method (FEM) [20-21], effective index method (EIM) [22], multipole method (MM) [23-25], beam propagation (BPM) [26-28] finite difference method (FDM) [29], boundary element method (BEM) [30, 31] and plane wave expansion (PWE) [32-35] etc.. As PCF is influenced by some dimensionless quantities like d/Λ and λ/Λ, it can be used for designing purpose and also to establish certain modal property [36].

2. DESCRIPTION OF THE DESIGNING TECHNIQUES USED TO MODEL PHOTONIC CRYSTAL FIBER:

2.1 Effective index method (EIM):

To design this exceptional fiber, several numerical as well as analytical technique has been established until now [2]. The well-known techniques can provide strong analogies to draw the modal behavior of PCF with that of conventional optical fiber [1-2]. Using effective index method (EIM) analysis, designing of PCF was reported in 2007 by Hongbo Li and Mafi et al They studied and reformulated effective refractive index of PCF. There are several methods that can be used to design PCF, but out of all the mentioned methods EIM methods are more adaptable to determine the measurable quantities and take lesser time compared to other methods. Most importantly, this technique is also suitable for deviation in refractive index of 0.01 and thus a small change in refractive index can change the measurable parameters [37]. During investigation of modal properties of PCF, they considered one or seven missing air hole of the core using finite element method and compared with step-index fibers. The EIM method which they put forwarded consider as effective measures for the experimentalists [2]. Later on fully vectorial EIM was used to analyze and simulate propagation characteristics of PCF. There, they explained about the dependence of structural parameters such as normalized air hole spacing, pitch and radius of the unit cell on dispersion, guided mode and fundamental space filling mode. They found high negative dispersion and wavelength of zero dispersion using EIM technique [38-39, 19].

2.2.1 Theoretical consideration:

Effective index methods (EIM) has been carried out to establish losses with respect to the material based PCF, thus to evaluate several parameters we need to have effective refractive index of cladding material which can be calculated as follows [20, 40-42]:

$$n_{eff} = \overline{n} + (n_s - \overline{n})cosh^{-2}(\frac{\lambda}{\wedge}) \tag{1}$$

Where, $\overline{n} = fn_{air} + (1-f)n_m$

$f = \frac{\pi}{2\sqrt{3}}(d/\wedge)^2$, is the filling fraction and n_m is the refractive index of the material.

The modal properties of fiber can be characterized by certain parameters like V_{eff}, W_{eff} and U_{eff} [2, 5, 40-42], these are defined as follows:

$$V_{eff} = \frac{2\pi}{\lambda} a_{eff} \sqrt{n_{co}^2 - n_{cl,eff}^2} \tag{2}$$

$$U_{\mathrm{eff}} = \frac{2\pi}{\lambda} a_{eff} \sqrt{n_{co}^2 - n_{eff}^2} \tag{3}$$

$$W_{eff} = \frac{2\pi}{\lambda} a_{eff} \sqrt{n_{eff}^2 - n_{cl,eff}^2} \tag{4}$$

Where n_{co} and n_{cl} are refractive indexes of the core and cladding respectively and R is radius of core for PCF fiber [2-11, 40-42].

2.3 Finite element method (FEM):

Finite element technique is considered to be a numerical approach to build the modal characteristics of PCF. In this particular approach, the cross section of the fiber is divided into few segments to analyze the modal properties of PCF. Rather than solving wave equation, variational method is used during this approach. Before analyzing the modal characteristics of PCF, an equivalent discretized model of each divided segment is assembled

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together to get the contribution of each segment, which results in matrix eigenvalue problem and that provide the valuable information towards the change [43-45].

2.3.1 Formulations:

Fundamental equations that is used in finite element technique is the Maxwell's equations by assuming an isotropic source free medium in which the field oscillates as $e^{i\omega t}$ is given as follows [46]:

$$\Delta \times E = -i\omega\mu H \tag{5}$$

$$\Delta \times H = i\omega\varepsilon E \tag{6}$$

Here, ω is the angular frequency, ε and μ are the permittivity and permeability of the medium respectively.

Additionally, as the cladding is composed of periodical air holes, the electromagnetic fields can be decoupled into transverse electric (TE) and transverse magnetic (TM) modes in which the propagation is proportional to $e^{i\beta z}$. By solving equation for TM and TE modes the governing equation can be evaluated is given by [46]:

$$p\Delta_t^2\varphi + qk_0^2\varphi_z = 0 \tag{7}$$

In which p=ε_r^{-1}, q=1 can be considered for TE mode (φ_z=H_z), p=1, q= in case of TM mode (φ_z=E_z). Besides, the transverse part of Δ operator is given by:

$$\Delta_t = \hat{x}\, {}^{d}\!/_{dx} + \hat{y}\, {}^{d}\!/_{dy} \tag{8}$$

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In finite element method, the structural domain of PCF is sub divided into some triangular elements with three vertices at each node of the triangle and is illustrated in figure 3 [46].

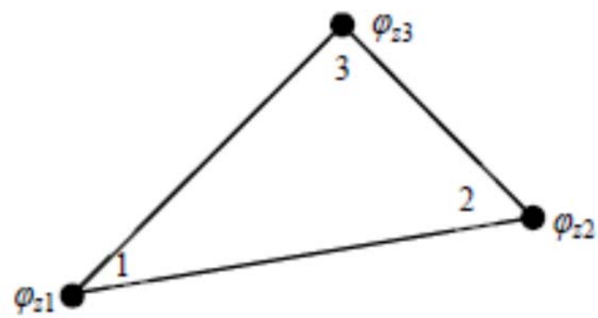

Fig. 3: Triangular element of the structure [46].

This is suitable for discretization scalar electromagnetic fields in finite element method which is given by:

$$\varphi_z^e(x,y) = \sum_{i=1}^{3} \varphi_{z_i}^e \psi_i^e \tag{9}$$

Where, the number of nodes in each segment is i and the value of φ_z at the vertex point (x_i, y_i) can considered to be φ_{zi}^e. The linear interpolation function of each triangular element can be expressed as follows:

$$\psi_i^e = \frac{1}{2A_e}(\alpha_i + \beta_i x + \gamma_i y) \tag{10}$$

$$\left.\begin{aligned} \text{Where, } \alpha_i &= x_j y_k - x_k y_j \\ \beta_i &= y_j - y_k \\ \gamma_i &= x_k - x_j \end{aligned}\right\} \tag{10.1}$$

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Here, i, j and k are indices that permute in clockwise order for $i \neq j \neq k$ with x_i and y_i as Cartesian co-ordinates of the i[th] vertex. Whereas, A_e is considered to be as area of the triangular element and is given by:

$$A_e = (\beta_2 \gamma_3 - \gamma_2 \beta_3)/2 \tag{10.2}$$

By solving the aforementioned equations, each of the modal properties can be studied by combining the subdivided segments of the PCF in finite element method [46].

2.4 Plane wave expansion (PWE):

Plane wave expansion can be applicable for predicting the birefringence as well as the dispersion characteristics of PCF. The geometry of PCF is considered as an impact on this approach while evaluating the mentioned modal properties [47]. Basically Bloch's theorem is used in plane wave expansion method. By utilizing three components of magnetic field, this approach can be proceeded to evaluate the well-known modal properties of PCF and this is the reason it has been widely used by the researcher [48]. Besides, in this approach the dielectric constant is conveyed as Fourier series expansion. As it is known that PCF is formed by spatial defect in core region and to analyze that defect, a superperiodicity in defect is introduced onto the whole structure of the PCF. The propagation constants and the modal fields in PCF can be found by solving a matrix eigenvalue problem which can be solved by using variational method. The matrix can be solved based on minimization of functional corresponding to the wave equation.

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This can be utilized in both index guiding and air guiding photonic crystal fibers [47, 48].

2.5 Finite difference time domain (FDTD):

Finite difference time domain technique is widely used to study the distributed diffraction and reflection of light at arbitrary angle. Owing to the versatile technique and powerful PCF [49-51]. Moreover, FDTD technique is also known as Yee algorithm as it was introduced by Kane Yee in 1996 which was further improved by Allen Taflove in 1970 [52] to improve the solutions of modal properties of photonic crystal fiber. Basically, Yee algorithm is considered to be the second order finite difference time domain method which can be utilized for simple geometries and can also be utilized for PCF. To analyze the modal behavior of PCF, Maxwell's equations is used in time domain. The finite difference time domain technique is capable only for geometries that are simple, small or moderate dimension that lack dielectric interfaces [52]. This is the reason it has been highly applicable in developing the modal characteristics of PCF.

2.6 Multipole method (MM):

The modal fields of PCF can be expanded in cylindrical harmonic functions only when the air holes are circular. Based on this approach, local circular geometry of air holes can be exploited during the study of modal properties, this technique is called multipole method [1], [23-25]. This can also describe the leaky nature of PCF which is composed of a finite number of air holes in cladding. In multipole method two longitudinal axial components of electromagnetic fields is used and the fields in proximity to

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the air holes is expressed in terms of Hankel and Bessel functions by using local cylindrical co-ordinates. Whereas, the axial electric and magnetic fields inside the air holes the can be expressed only in terms of regular Bessel function. Additionally, boundary condition is being used to obtain the relations between all the expansion coefficients [1], [23-25].

2.7 Beam propagation method (BPM):

Beam propagation method is used basically for characterization of longitudinally varying PCF. Moreover, it can also be used to define certain features of PCF by utilizing scalar approximation of beam propagation method by exploiting fast Fourier transform beam propagation method (FFT-BPM) [26-28]. In beam propagation technique the wave propagation splits into homogeneous medium and phase correction of inhomogeneous index distribution in PCF structure. By using FFT technique, it is possible to carry the spectral domain of wave propagation in homogeneous medium. Besides, to avoid the polarization effect in PCF, a weakly guiding structure is assumed in FFT-BPM. Other than that, to compute the modal properties as well as the propagation constants of high contrast PCFs, full vector beam propagation method is used on finite element method (FE-BPM) [53] and FD-BPM [28]. The leakage arising due to array of air holes in PCF can be investigated by FE-BPM [53].

2.7.1 Mathematical formulation:

The mathematical formulation of beam propagation method can be evaluated in three different approximation techniques. The approximations has been elaborated as follows:

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1. Slowly varying envelope approximation:

By using the reference refractive index to be n_0 the formulation for approximation of modal characteristics is given as follows [53]:

$$\phi(x,y,z)=\phi_t(x,y,z)\exp(-jk_0n_0z)+\phi_z(x,y,z)\exp(-jk_0n_0z)i_z \qquad (11)$$

$$\left.\begin{aligned}&\Delta_t\times(ps_l^{-1}\Delta_t\times\Phi_t)+\Delta_z\left\{p[s_t]^{-1}(\Delta_t\Phi_z-\Delta_z\Phi_t)\right\}=k_0^2q[s_t]\Phi_t\\ &\text{And}\\ &\Delta_t\times\left[\left\{p[s_t]^{-1}(\Delta_t\Phi_z-\Delta_z\Phi_t)\right\}\times i_z\right]=k_0^2qs_l\Phi_zi_z\end{aligned}\right\} \qquad (12)$$

By substitution of Eq. (11) to Eq. (12), fundamental equations of beam propagation method for slowly varying complex amplitudes such as ϕ_t and ϕ_z respectively is given by [53]:

$$\begin{aligned}&\Delta_t\times(ps_l^{-1}\Delta_t\times\Phi_t)+(\Delta_z^2-2jk_0n_0\Delta_z-k_0^2n_0^2)p[s_t]^{-1}\Phi_t-k_0^2q[s_t]\Phi_t\\ &+(\Delta_z-jk_0n_0)p[s_t]^{-1}\Delta_t\Phi_z=0\end{aligned} \qquad (13)$$

$$\Delta_t\times\left[p[s_t]^{-1}\Delta_t\Phi_z\times i_z\right]-\Delta_t\times\left[\left\{p[s_t]^{-1}(\Delta_z-jk_0n_0)\Phi_t\right\}\times i_z\right]-k_0^2qs_l\Phi_zi_z=0$$

(14)

These are the equations that can be used for beam propagation method by exploiting slowly varying envelope approximation.

2. Finite element discretization:

By subdividing the structure of PCF into curvilinear hybrid nodal element, one can expand the transverse components of electromagnetic fields i.e. ϕ_x and ϕ_y along with longitudinal components ϕ_z in each segment. These can be expressed as follows [53]:

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$$\Phi = \begin{bmatrix} \Phi_x \\ \Phi_y \\ \Phi_z \end{bmatrix} = \begin{bmatrix} \{U\}^T \{\Phi_t\}_e \\ \{V\}^T \{\Phi_t\}_e \\ j\{N\}^T \{\Phi_z\}_e \end{bmatrix} \tag{15}$$

Here, for each edge segment, $\{U\}$ and $\{V\}$ are the shape function vectors and $\{N\}$ is the shape function for nodal segment. Whereas, $\{\phi_t\}_e$ and $\{\phi_z\}_e$ are the edge and nodal variables for each segment.

Thereafter by substituting Eq. (15) into Eq. (13) and (14) the longitudinal field transformation can be obtained by applying Fresnel approximation and finite element technique to transverse *xy* plane and is expressed as follows [52]:

$$\Phi_z(x, y, z)\exp(-jk_0 n_0 z) = j\frac{d}{dz}\{\Phi'_z(x, y, z)\exp(-jk_0 n_0 z)\} \tag{16}$$

Besides, the matrix equation for the approximation is given as follows:

$$-2jk_0 n_0 [M]\frac{d\{\Phi\}}{dz} + ([K] - k_0^2 n_0^2 [M])\{\Phi\} = \{0\} \tag{17}$$

3. Crank-Nicholson Method:

The crank-Nicholson algorithm is applying to the propagation direction z which can be expressed as follows [52]:

$$[A]_i \{\Phi\}_{i+1} = [B]_i \{\Phi\}_i \tag{18}$$

Whereas,

$$\left.[A]_i = -2jk_0 n_{0,i}[M]_i + 0.5\Delta z([K]_i - k_0^2 n_{0,i}^2 [M]_i)\right\}$$

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$$[B]_i = -2jk_0 n_{0,i}[M]_i - 0.5\Delta z([K]_i - k_0^2 n_{0,i}^2 [M]_i)$$

These are the three basic approximations that can be taken during the study of modal properties of photonic crystal fiber exploiting beam propagation method.

3. PRACTICAL APPLICATIONS OF PHOTONIC CRYSTAL FIBER:

Due to the enormous variety in air-holes arrangements, PCF offers an extensive possibility to control the refractive index difference between the core and cladding that brings certain novel and unique optical properties. Owing to their unconventional structures, it has been under huge research interest in ever-widening areas of science and technology. Moreover, PCF is basically found to follow endlessly single mode-operation, this feature of PCF can be utilized for long term communication system. The tunable single mode wavelength range, low loss and optimized or large optical nonlinearity make them better candidates than conventional fibers for many applications. There are certain advantages of PCF based on their propagation characteristics and are given below:

3.1 Advantages of solid core photonic crystal fiber:

- Highly birefringent fiber
- Dispersion tailoring
- Ultrahigh nonlinearity
- Large mode area

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3.2 Advantages of solid core photonic crystal fiber

- Low nonlinearity
- For delivering high-power continuous wave (CW), nanosecond and sub-picosecond laser beams
- Terahertz generation

The use of PCFs can be done in various applications related to supercontinuum generation, four-wave mixing and hollow-core PCF technology that could possibly bring breakthroughs in science particularly in medicine and microscopy. Moreover, PCF has certain tunable parameter by controlling which the losses arising during communication can be controlled. By reducing losses of PCF, we can develop attenuation free communication. Fabrication of PCF that can operate in highly tunable single mode operation can help in exploiting long-distance communication system like in telecommunication.

4. CONCLUSION:

Conclusively, the techniques that has been described in this chapter would be beneficial for the researcher to design photonic crystal fiber. In addition to that these aforementioned techniques can also be utilized to analyse the modal charateristics of photonic crystal fiber. Out of the aforementioned techniques EIM techniques is considered to be ease in computation than that of the other mentioned techniques. Other than EIM technique FEM is also widely used in designing and modal parameter analysis of photonic crystal fiber. Besides, the other mentioned techniques such as FDTD, BPM, MM

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and the rest are also utilized extensively to improve the design of photonic crystal fiber.

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