Analysis of Dispersion and Confinement Loss in Photonic Crystal Fiber

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***Abstract*—Chromatic dispersion and confinement loss are two significant issues in the design of photonic crystal fiber. This paper presents a systematic study of these two issues for five rings hexagonal photonic crystal fiber along with its dependence on structure and material used. The values of these two propagation characteristics obtained for different refractive indices and hole diameters reveal that optimization of these two characteristics depend on the application requirements, but not for determining which fiber structure is the best. Photonic crystal fiber structure is modeled using OPTI FDTD 8 simulation software and dispersion as well as loss is plotted by MATHCAD 2000i Professional tool.**

Keywords*— Chromatic dispersion; Confinement loss; Impurity; lattice pitch; Photonic crystal fiber

I. INTRODUCTION

Photonic crystal fiber (PCF) is a particular class of fiber which is made of a solitary substance having air holes in the cladding. All the propagation characteristics, such as, effective index mode, confinement loss, chromatic dispersion, mode field diameter are measured by varying the structural parameters (hole diameter, lattice pitch, doping for example). PCF have involved in an extensive amount of attention recently, because of their unique properties that are not realized in conventional optical fibers [1]. PCFs are also called endlessly single mode fibers [2], which are separated into two special kinds of fibers [3]. The first one guides light by total internal reflection between a solid core and a cladding region with multiple air-holes. On the other hand, the second one uses a absolutely periodic structure exhibiting a photonic band gap effect at the operating wavelength to guide light in a low index core region [3], which is also called photonic band gap fiber. The distance between the holes is known as lattice pitch which is denoted by Λ and the diameter of the air holes is indicated by d and is termed as the structural parameter of the PCF [4] and the ratio d/Λ is called air filling fraction. All the circulation uniqueness can be prescribed by the dissimilarity of the structural parameters. Structural parameter plays a significant function of confining the light in the core which affects the propagation characteristics. Because of its capability to confine light in hollow or solid cores, PCF is now finding applications in fiber optic communications, fiber lasers, nonlinear devices, high-power transmission, and highly sensitive gas sensors. In this paper, we have explained the propagation characteristics, such as, chromatic dispersion and confinement loss of five rings hexagonal PCF with different hole diameter and refractive indices (by adding impurity). The result reveals the highly non-linear consequence of PCF which is very much essential for the applications in the fields of communication and medical technology.

II. MATERIALS AND METHODS

A. Electromagnetic Mode Theory for Optical Propagation

To get a better model for the propagation of light in a PCF/optical fiber, electromagnetic wave theory must be considered. The basic foundation for the study of electromagnetic wave propagation is provided by Maxwell's equations. For a medium with zero conductivity these vector connection may be written in terms of the electric field E, magnetic field H, electric flux density D and magnetic flux density B as the curl equations [5]:

$$\nabla \times E = -\frac{\partial B}{\partial t} \text{ and } \nabla \times H = \frac{\partial D}{\partial t} \tag{1}$$

and the divergence conditions:

$\nabla.D = 0$ and $\nabla.B = 0$, where ∇ is a vector operator.

The four field vectors are correlated by the relationships: $D = \varepsilon E$ and $\mathrm{B} = \mu\mathrm{H}$, where μ is the magnetic permeability and ε is dielectric permittivity of the medium. Now substituting for D and B in equation (1) and using divergence conditions, we have found the nondispersive wave equations:

$$\nabla^2 E = \mu\varepsilon \frac{\partial^2 E}{\partial t^2} \text{ and } \nabla^2 H = \mu\varepsilon \frac{\partial^2 H}{\partial t^2} \tag{2}$$

where ∇^2 is the Laplacian operator. For rectangular Cartesian and cylindrical polar coordinates, equations (1) and (2) hold for each factor of the field vector, every component satisfying the scalar wave equation:

$\nabla^2\psi = \frac{1}{v_p^2}\frac{\partial^2\psi}{\partial t^2}$, where ψ may signify a component of the E or H field and v_p is the phase velocity. If the planner waveguides described by rectangular Cartesian coordinates (x, y, z) or circular fibers described by cylindrical polar coordinates (r, ϕ, z) are considered, then the Laplacian operator takes the form:

$$\nabla^2\psi = \frac{\partial^2\psi}{\partial x^2} + \frac{\partial\ \psi}{\partial y^2} + \frac{\partial^2\psi}{\partial z^2} \quad (3)$$

The basic explanation of the wave equation is a sinusoidal wave, the most imperative form of which is a uniform plane wave given by:

$$\psi = \psi_0 \exp j(\omega t - k.r) \quad (4)$$

where ω is the angular frequency of the field, t is the time, k is the propagation vector which gives the route of propagation and the rate of alter of phase with distance, r is the coordinate point at which the field is observed. When λ is the optical/center wavelength, then $k = 2\pi/\lambda$ is the vacuum phase propagation constant.

B. Chromatic Dispersion

The group-velocity dispersion $D(\lambda)$ is defined as the transform in pulse width per unit distance of propagation (i.e., ps/(km-nm)). It means that $D(\lambda)$ causes a short pulse of light to extend in time as a result of different frequency components of the pulse roving at different velocities. This can be calculated from the following equation (5).

$$D(\lambda) = \frac{d}{d\lambda}\left(\frac{1}{v_g(\lambda)}\right) = -\frac{2\pi c}{\lambda^2}\beta_2 = -\frac{4\pi^2 cn}{\lambda^3} = -\frac{\lambda}{c}\frac{d^2 R_e[n_{eff}]}{d\lambda^2} \quad (5)$$

where β_2 is the propagation constant, v_g is the group velocity, λ is the operating wavelength in µm, c is the velocity of the light in a vacuum, $Re[n_{eff}]$ is the real part of the effective index. Since the total chromatic dispersion is the summing up of material dispersion $D_m(\lambda)$ and waveguide dispersion $D_w(\lambda)$. The material dispersion quantified from the Sellmeier equation is frankly included in the FDM computation process. The reason for this, $D_m(\lambda)$ is mostly determined by the wavelength dependence of the fiber materials and for this reason it cannot be altered drastically in the engineering procedure. On the other hand, $D_w(\lambda)$ is powerfully reliant to the silica-air structure. Therefore, in our calculation chromatic dispersion $D(\lambda)$ [6] corresponds to the total dispersion of the PCF.

C. Confinement Loss

The attenuation caused by the waveguide geometry is called confinement loss L_c. This is an extra form of loss that occurs in single-material fibers predominantly in PCF because they are usually made of pure silica and given by [6]

$$L_c = -20\log_{10}\varepsilon^{-k_0 \operatorname{Im}[n_{eff}]} = 8.686 k_0 \operatorname{Im}[n_{eff}] \quad (6)$$

Where, k_0 is the propagation constant ($k_0 = 2\pi/\lambda$) in free space, λ is the operating wavelength in µm, and $Im(n_{eff})$ is the imaginary part of the effective refractive index n_{eff}.

D. Simulation Method

The main objective of simulation is to review chromatic dispersion and confinement loss characteristics of five rings hexagonal PCF. The structural parameters considered for simulation purpose are given below:

Hole diameter, d = 0.6 µm
Lattice pitch, Λ = 2.3 µm
Normalized hole diameter, d/Λ = 0.26
Air-fraction refractive index, n_{air} = 1.0
Core/cladding refractive index, n = 1.46
Number of ring in the cladding = 5

Figure 1 shows the structural view of five rings hexagonal shape PCF. The red color indicates the refractive index whose value is 1.46, whereas the blue color indicates the same with value of 1.00. The figure clarifies that the core shape is almost hexagonal.

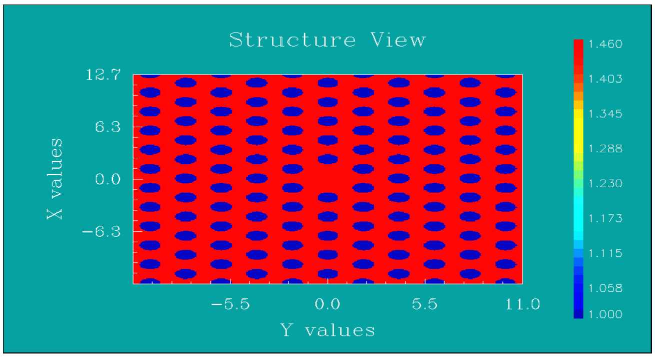

Fig. 1 Structural view of hexagonal PCF.

III. RESULTS AND DISCUSSION

Simulation is carried out in two consecutive parts. In the first part of the simulation, we have used OPTI FDTD 8 software. The basic flow of simulation is executed with several iterations to calculate the number of parameters and to obtain precise results. The simulation algorithm for parameters sweeping contains few steps: once the physical structure is created, the simulation parameters and mesh are set- mesh delta X (µm) = 0.08, mesh delta Z (µm) = 0.08, number of mesh cells X = 273 and Z = 316, where the wafer dimension is 25.30 µm length and 21.91 µm width, the simulation is run for 840 time steps (auto). For simulation, the wavelength of 1.3 µm is used as center wavelength with TBC boundary condition. After simulation the confinement of electric field in the core region and elliptic waveguide pattern are shown in Figs. 2 and 3, respectively. In Fig.2, the electric filed is confined mostly in the core region (red), and in the next consecutive figure (Fig. 3), the pattern of the waveguide is shown (elliptic).

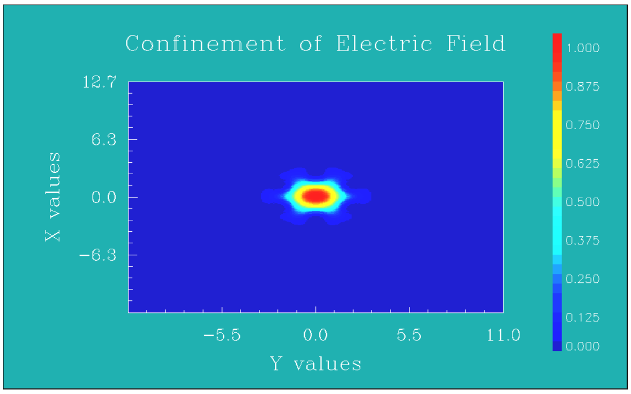

Fig. 2 Confinement of electric field in core region.

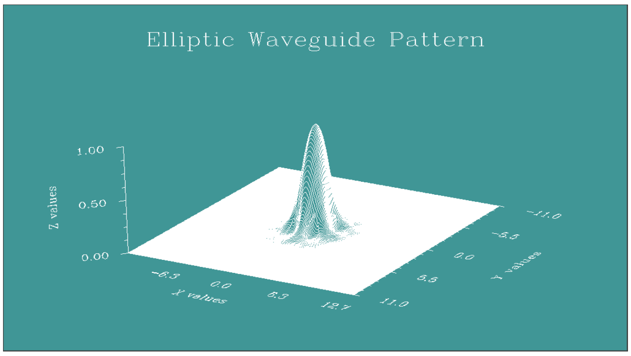

Fig. 3 Elliptic waveguide pattern.

After simulation we have found modal index where the real part of the effective refractive index is 1.4407166 and the imaginary part is 0.00000102. Using this index value we have plotted chromatic dispersion and confinement loss by using MATHCAD 2000i Professional software, as shown in Figs. 4 and 5, respectively.

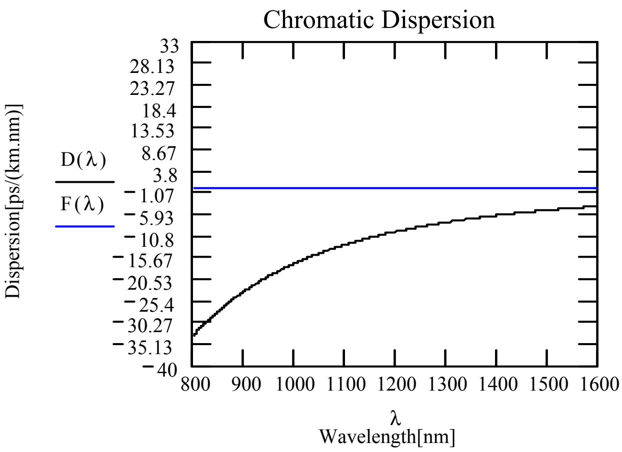

Fig. 4 Chromatic dispersion of five rings hexagonal PCF (flattened and negative dispersion).

Figure 4 shows that chromatic dispersion for 1.3 µm is 1.05 ps/[km-nm] (flattened) and -5.93 ps/[km-nm] (negative), respectively. The figure also shows that more negative dispersion is achieved in shorter wavelength.

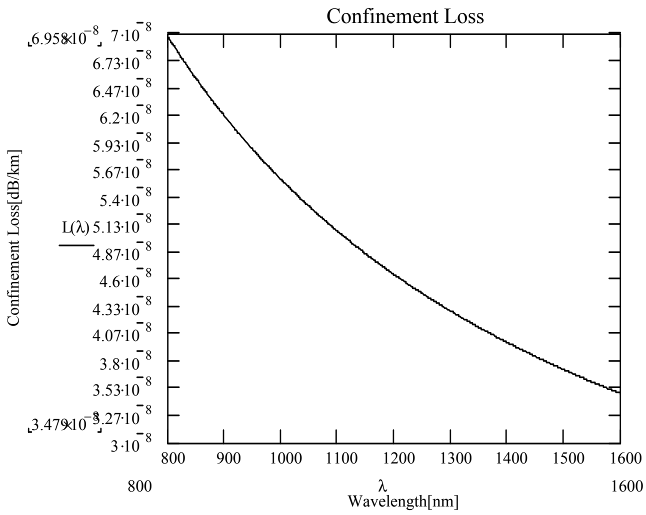

Fig. 5 Confinement loss of five rings hexagonal PCF.

It is clear from the Figure 5 that the confinement loss is increased when wavelength is decreased gradually but minimum in longer wavelength, that is, at 1600 nm, the loss is 3.5×10^{-8} dB/km. Changing the hole diameter from 0.6 µm to 0.8 µm, the chromatic dispersion as well as the confinement loss is also plotted, as seen in Figs. 6 and 7, respectively.

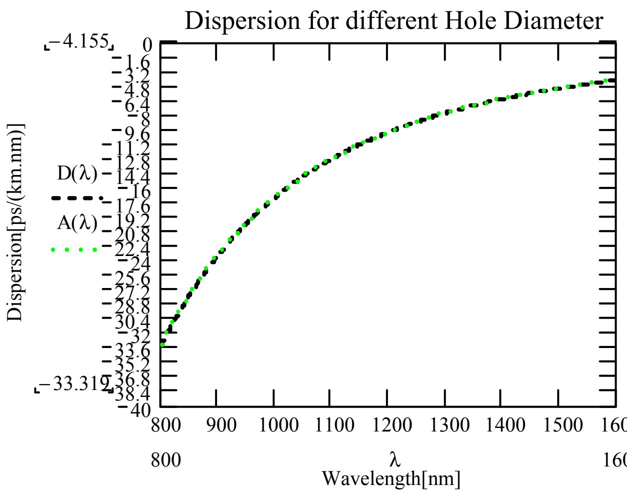

Fig. 6 Chromatic dispersion (hole diameter: 0.6 µm and 0.8 µm) for five ring hexagonal PCF.

In Fig. 6, we have compared the dispersion for two different hole diameters, that is 0.6 µm and 0.8 µm and found that very small percentage of dispersion changes. But, it is clear from this figure that more negative dispersion is found in case of 0.6 µm hole diameter. So, if we want to reduce dispersion, we must reduce the hole diameter. On the other hand, low confinement loss is found in case of 0.8 µm hole diameter, as seen in Fig. 7. Confinement loss is compared in 1300 nm wavelength and found 5.4×10^{-8} dB/km for 0.6 µm when it is found 2.6×10^{-8} dB/km for 0.8 µm.

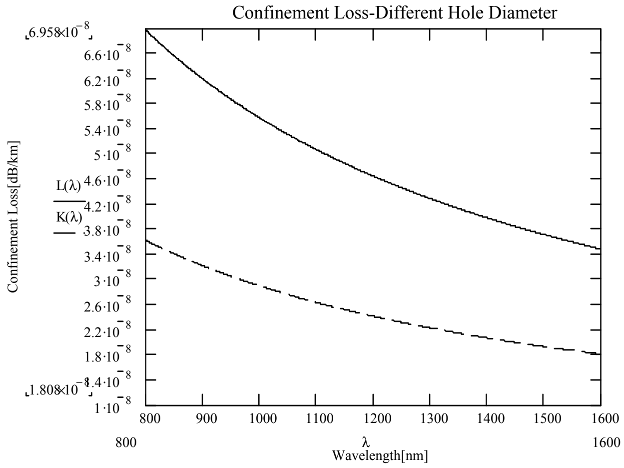

Fig. 7 Confinement loss (different hole diameters) for five rings hexagonal PCF.

By using different doping level (adding GeO_2) the effective refractive index is found which is given in the TABLE I, and the consequential chromatic dispersion and confinement loss effect is shown in Figs. 8 and 9, respectively.

TABLE I. EFFECTIVE REFRACTIVE INDEX FOR DIFFERENT DOPING LEVEL

Refractive Index(n)	Effective Refractive Index(real)	Effective Refractive Index(imaginary)
1.46 (pure silica)	1.44037166	.00000102
1.48	1.46048416	.00000123
1.49	1.47054253	.00000132
1.60	1.58124464	.00000197

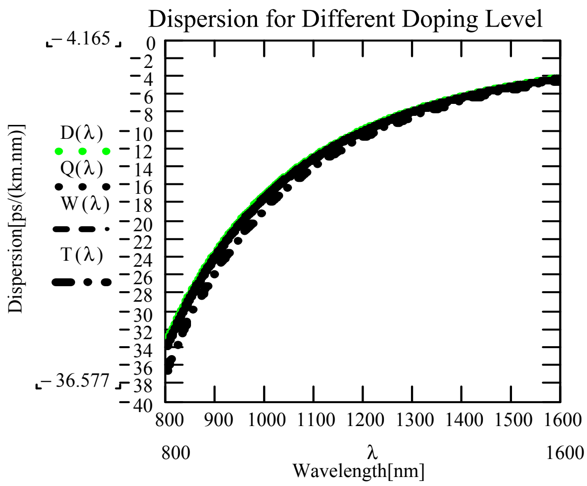

Fig. 8 Chromatic dispersion (different doping Level) of five rings hexagonal PCF.

As seen in Fig. 8, chromatic dispersion is plotted at different effective refractive indices. It is clear that more negative dispersed pulse is found when the impurity level is maximum (refractive index is 1.60). But interesting result is found in confinement loss analysis (Fig. 9). Lowest confinement loss is found in 1.48 refractive index impurity materials. In addition, no loss is found in when refractive index is 1.49. From 1300 to 1600 nm, the loss is almost constant and it is decreased by reducing the wavelength.

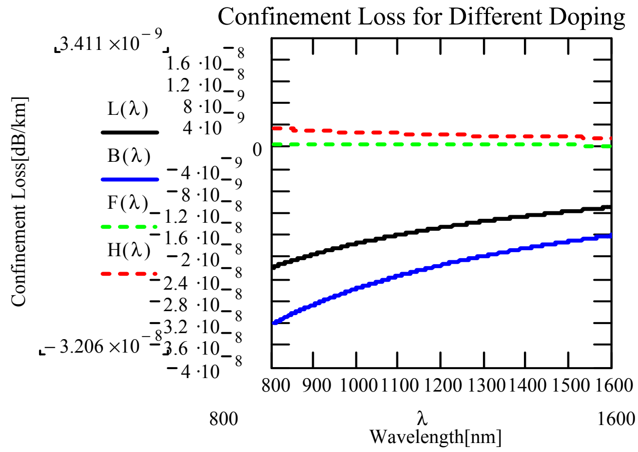

Fig. 9 Confinement loss (different doping level) for five rings hexagonal PCF.

IV. CONCLUSION

In this paper, our intension was to vary the structural parameters (hole diameter and refractive index) and to analyze the propagation characteristics, such as, chromatic dispersion and confinement loss. We changed hole diameter, and also refractive index by adding impurity in pure silica. The result shows that when the hole diameter is increased, the effect of chromatic dispersion is almost identical but the confinement loss reduces significantly. On the other hand, when the impurity is added, the confinement loss increases but low chromatic dispersion is achieved. The result implies the highly non-linear effect of PCF which is very useful for the applications in optical sensing, medical equipment, optical parametric amplification, display device, etc.

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