Hollow Core Fiber Design with Ultimate Low Confinement Loss and Dispersion

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Abstract

Secure and uninterruptable data communication is one of the most important requirements in telecommunication sector. Research is being done in the field of telecommunication in order to provide secure data to customers by reducing dispersion and confinement losses within an optical fiber. Photonic crystal fiber is a new technology of optical fibers which has provided secure and managed data transfer with low dispersion properties and confinement loss. In this paper we studied Hollow Core Photonic Crystal Fibers (HC-PCF) to reduce the dispersion and losses through the fibers. We presented different designs of HC-PCF and selected one design with reduced dispersion and confinement loss. The main purpose of this study was to develop a design that can be utilized in Wavelength Division Multiplexing Systems (WDM). In WDM systems we can only use a fiber that has low material dispersion and low confinement loss. The wavelength range for a WDM system is from 1300nm to 1550nm. So, we studied HC-PCF designs and calculated the confinement loss and dispersion within this range.

Index Terms—Hollow Core Fibers, Photonic Crystal Fibers, Confinement Loss, Dispersion, Wavelength Division Multiplexing Systems.

I. INTRODUCTION

Photonic Crystal Fiber (PCF) is a two dimensional fiber made up of a dielectric material such as silica. Latest trends of PCF show that they successfully replaced the conventional optical fiber in telecommunication sector. Two types of PCF have been reported in literature, Solid Core PCF (SC-PCF) and Hollow Core PCF (HC-PCF) [1]. Research is being done on both these fibers and it is expected that both of these types of PCF should propagate light with minimum losses and dispersion to fulfill the requirements of the customers.

Like conventional optical fibers, PCF also consist of a core that is surrounded by a cladding. The cladding of PCF is much different than the cladding of optical fiber. It consists of periodic air hole rings that sometimes make the refractive index of core smaller than that of the cladding. In conventional optical fibers the refractive index of core is greater than the refractive index of cladding due to which light is guided through the core because of Total Internal Reflection (TIR) [2]. In PCF light is guided through the core due to Total Internal Reflection (TIR) and also due to Photonic Band Gap effect (PBG) that is generated by the periodic air hole rings in the cladding. If the refractive index of core of PCF is greater than that of cladding, light guidance is due to TIR, and if the refractive index of core is smaller than the combined effect of air hole rings of cladding, light is guided due to PBG effect. In HC-PCF light guidance is mainly due to PBG effect. The Fig. 1 shows the difference between SC-PCF and HC-PCF [2].

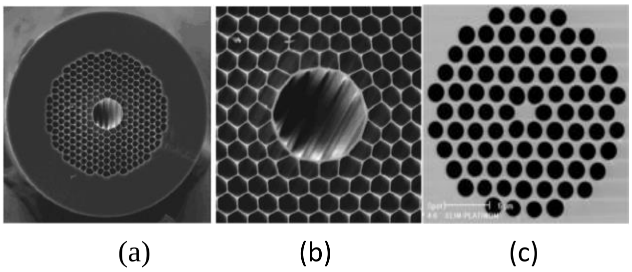

Fig.1: (a) Hollow Core PCF (b) Core of HC-PCF (c) Solid Core PCF

An SC-PCF propagates light using the air holes of cladding that runs down the entire fiber length [3]. These fibers are made up of a material commonly known as silica and consist of a core surrounded by a cladding made up of periodic air hole rings [4]. In SC-PCF, core is simply a region without an air hole. If we introduce an air hole in the core region of PCF then it becomes another important and useful form of PCF known as Hollow Core Photonic Crystal Fiber (HC-PCF). Presence of air holes in such fibers opens up a variety of potential applications ranging from small mode area for highly non-linear fibers for non-linear devices to large mode area fibers for high power delivery [5]. When we arrange large air-holes in the form of a periodic network, light propagation can be achieved through PBG effect. Literature Review shows that a band gap is only produced when the airholes are quite large. When a defect is established in such a structure, as large airhole in center of figure 1(a) and (b), a localization mode excitation is established in Photonic Band Gap region, and it is then possible for the PCF to direct light inside an air core along the entire length of the fiber. This new mechanism of light propagation within HC-PCF leads to a large number of useful applications such as, these fibers are used to deliver large amount of power, and they are also used as sensing elements in gas sensors [6].

II. Theoretical Discussion

Propagation through a Photonic Crystal Fiber requires the solution of Maxwell's equations. To solve the Maxwell's equations we assume a lossless and source free medium for convenience. The Maxwell's equations for such medium are given by Eq. (1-4) [7]

$$\nabla \times \boldsymbol{H} = \epsilon . \frac{\partial \boldsymbol{E}}{\partial t} \quad (1)$$

$$\nabla \times \boldsymbol{E} = -\mu . \frac{\partial \boldsymbol{H}}{\partial t} \quad (2)$$

$$\nabla . D = \nabla . \epsilon \boldsymbol{E} = \boldsymbol{0} , \quad (3)$$

$$\nabla . B = \nabla . \mu \boldsymbol{H} = \boldsymbol{0} \quad (4)$$

The normalized frequency V for a conventional step index fiber is given by Eq. 5

$$V = k_0 \rho \sqrt{n_{co}^2 + n_{cl}^2} \qquad (5)$$

Where ρ is the core radius, k_0 is the wave number, n_{co} and n_{cl} are the refractive indices of the core and cladding respectively [8]. The smaller is the V number, the fewer guided modes are handled by the core. If for a given wavelength V < 2.405, fiber will only support a single mode for propagation of light and that fiber is simply a single mode fiber. The normalized frequency for a PCF is given by Eq. 6

$$V_{eff}(\lambda) = k_0 2\Lambda \sqrt{n_{silica}^2 + n_{eff}^2(\lambda)} \qquad (6)$$

Where 2Λ is the core diameter [8]. A PCF with $d/\Lambda \leq 0.4$ do not support higher order modes because for them $V_{eff}(\lambda) \leq 2.405$ for a given wavelength with d being the hole size.

As in this paper we are concentrating more on the losses and dispersion effects occurring within HC-PCF so we will now describe the spectral density $S_z(\kappa)$, as $S_z(\kappa)$ and the transverse overlap of modes at glass surfaces determine the strength of coupling and loss is calculated from power coupled to the modes [9]. $S_z(\kappa)$ is given by Eq. 7

$$S_z(\kappa) = \frac{k_B T_g}{4\pi\gamma\kappa} \coth\left(\frac{\kappa W}{2}\right) \qquad (7)$$

Where T_g is glass transition temperature, k_B is the Boltzmann constant, γ is surface tension and κ is the spectral frequency and is given by Eq. 8

$$\kappa = \frac{2\pi}{\lambda} |n - n_0| \qquad (8)$$

where n and n_0 are the mode index and the effective mode index respectively. The normalized field intensity is given by Eq. 9 [9]

$$F = \left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2} \frac{\oint^0_{hole\ perimeters} dl|E|^2}{\int^0_{cross-section} dA|E \times H^*| \cdot \hat{z}} \qquad (9)$$

Where **E** and **H** are the Electric and Magnetic fields. $\hat{z}$ is the unit vector along the direction of fiber. The air filling fraction f of air holes of HC-PCF is directly related to the hole parameters and is given by Eq. 10 [8]

$$f = \left(\frac{d}{\Lambda}\right)^2 \left[1 - \left(1 - \frac{\pi}{2\sqrt{3}}\right)\left(\frac{d_c}{d}\right)^2\right] \qquad (10)$$

To obtain hexagonal holes we have to set $\frac{d_c}{d}$ = 0, and for circular holes we have $\frac{d_c}{d}$ = 1, where d is the hole size, d_c is the curvature at corners and Λ is the pitch (distance between two adjacent holes) [9].

For simulation purpose, we used Perfectly Matched Layer (PML) boundary conditions for which we selected an anisotropic material whose permittivity and permeability tensors are given by [9]

$$\varepsilon = \varepsilon_0 n^2 S \quad ; \quad \mu = \mu_0 S \qquad (11)$$

with

$$S = \begin{bmatrix} s_x/s_y & 0 & 0 \\ 0 & s_x/s_y & 0 \\ 0 & 0 & s_x/s_y \end{bmatrix} \qquad (12)$$

s_x and s_y are the components of S and are given in the following Table 1

TABLE I
PML PARAMETERS

PML Parameters	PML Region		
s_x	1	s_2	s_2
s_y	s_1	1	s_1

values of s_i (i = 1,2) are given by the formula

$$s_i = 1 - j\alpha_i \left(\frac{\rho}{d_i}\right)^2 \qquad (13)$$

Here d is the distance from start of PML and d_i is the PML width in both horizontal and vertical directions, α_i is the attenuation [10].

Confinement loss L_c occurring within HC-PCF is due to finite number of air holes and is given by Eq. 14

$$L_c = 8.680\, k_0\, I_m \eta_{eff}$$

Where

$$\eta_{eff} = \eta_{material} + \eta_{eff,\, bandstructure} - \eta_{constant} \qquad (15)$$

Dispersion is the combined effect of material dispersion and waveguide dispersion and is given by Eq. 16 [8]

$$D(\lambda) = -\frac{\lambda}{c} \times \left(d^2 Re[\eta_{eff}]\right) / d\lambda^2 \qquad (16)$$

Dispersion is basically the second derivative of propagation constant β i.e $\beta_2(\omega) = \frac{\partial^2 \beta}{\partial \omega^2}$ [8]

$$\beta(\omega) = \frac{n_{eff}(\omega)\omega}{c} = \sum_m \frac{1}{m!} \beta_m (\omega - \omega_0)^m; \quad \beta = \frac{\partial \beta}{\partial \omega}\Big|_{\omega = \omega_0} \qquad (17)$$

III. Simulation and Results

In this paper we proposed a design for a Hollow Core Photonic Crystal Fiber through which light can be propagated with minimum confinement loss and dispersion. We designed this fiber in order to utilize it in wavelength division multiplexing systems where it is mandatory to minimize both the loss and dispersion for secure and uninterruptable transmission of light from one terminal to the other. In this paper we did the modal analysis of our proposed HC-PCF designs, to calculate the Electric Field intensity through the fundamental mode of the fibers and then calculated the dispersion and confinement loss through the proposed designs of HC-PCF using the formulas given in theoretical discussion. In WDM systems, wavelength range of operation is from 1300nm to 1550 nm [11]. So we analyzed our designs of HC-PCF over this range and calculated the dispersion and confinement loss for both the lower limit and upper limit of the wavelength i.e at 1300nm and 1550nm. Using the technique given earlier in this paper we designed three different designs of HC-PCF and then compared them with each other as well as compared them with the designs available in literature and found a design with lowest possible loss and dispersion. For this purpose we used five layered model of HC-PCF which means that the cladding of the fiber contained five rings of periodic air holes. The following Table II shows the comparison between three designs we made:

In this table pitch is the distance between the two consecutive air holes. Radius R_1, R_2, R_3, R_4, R_5 is the radius of the air holes indexing from the inner ring. The first two designs are made by making the radius of air holes of all the rings equal and in the third design; radius of air holes of all the rings is different. We were supposed to find a design in which both dispersion and confinement loss should be kept in mind. We cannot select a design with low loss and high dispersion or vice versa. So, by comparing the designs given in table, design 3 is providing the best design with low loss and low dispersion. The following figure 2 shows the Electric Field intensity through HC-PCF designs.

TABLE II

SIMULATION PARAMETERS

Design	Pitch (μm)	Radius R1,R2,R3,R4,R5 (μm)	Core Dia (μm)	Loss at 1300nm (dB/cm)	Loss at 1550nm (dB/cm)	Dispersion at 1300nm (ps/nm/km)	Dispersion at 1550nm (ps/nm/km)
1	1.6	0.5	2.5	0	$3x10^{-7}$	45	65
2	1.6	0.3	1.5	0	17	− 100	− 160
3	1.6	0.25,0.29,0.32, 0.33,0.69	1.5	0	$4x10^{-9}$	− 4	− 38

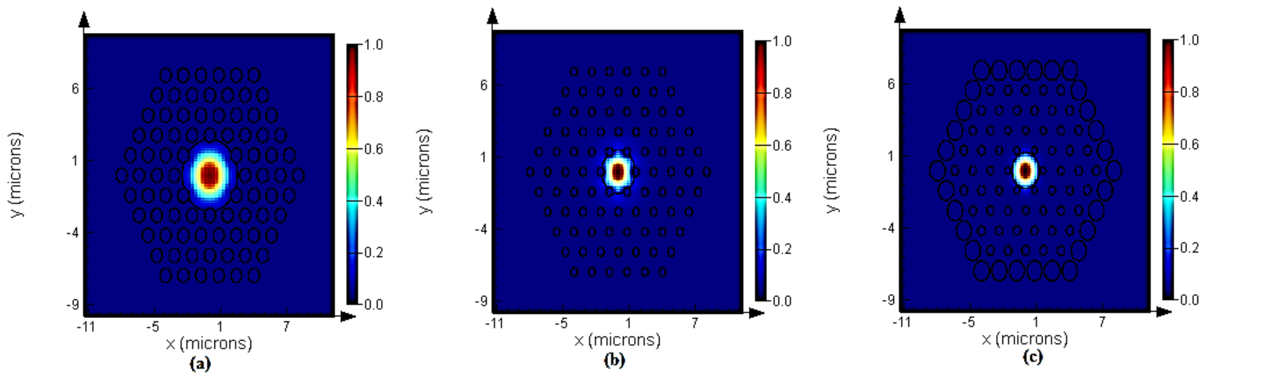

Figure 10: Electric field intensities through the fundamental mode for designs of HC-PCF

The following Figure 3 shows the confinement loss through the fiber designs presented above

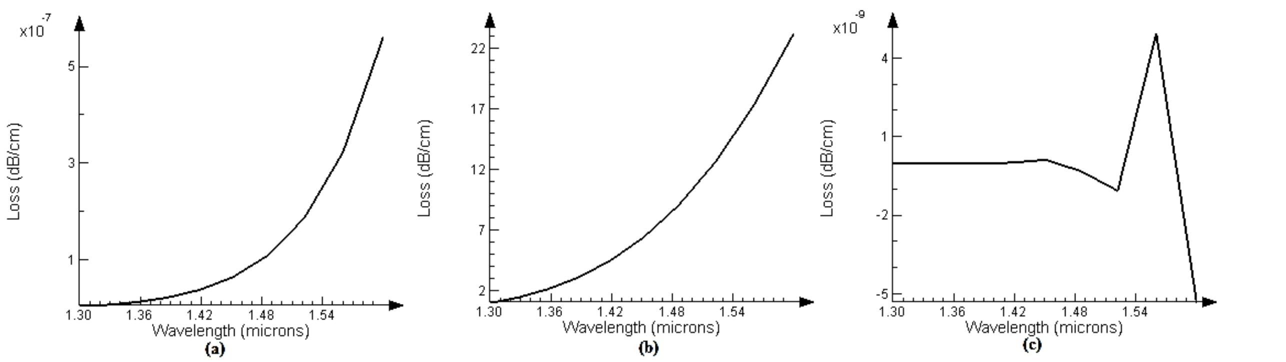

Figure 11: Comparison of confinement losses for the three designs of HC-PCF

The dispersion obtained through the three given designs is presented in the Figure 4

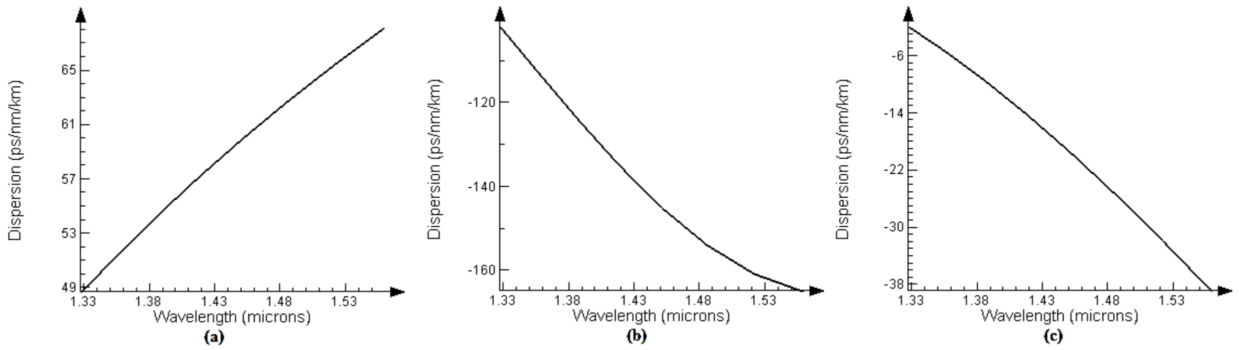

Figure 12: Comparison of dispersion for the three designs of HC-PCF

IV. Conclusions

In this paper, we studied the transmission properties of HC-PCF fiber so that it can be utilized in WDM systems. We have focused much on the confinement loss and dispersion properties occurring within the fiber. We first analyzed the three different designs to find their fundamental mode through which light passes more efficiently, and then compared these designs with each other to select the best design having lowest possible loss and dispersion. By looking at Table 1, we found that the Design 3 of HC-PCF is the best possible design having lowest possible loss and dispersion. The fiber of design 3 has a confinement loss of 4×10^{-9} dB/cm and dispersion of -38ps/nm/km at 1550nm. These three designs were made after having a thorough look at literature; we found that these three designs were a better option. Among these three designs, design 3 was chosen to be the one with minimum possible confinement loss and dispersion.

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