Estimation of Low Loss and Dispersion of Hollow Core Photonic Crystal Fiber Designs for WDM Systems

M. Khalid[1], I. Arshad[2]

[1,2]Electrical Engineering Department, University of Engineering and Technology, Taxila, Pakistan
[1]mamoona.khalid@uettaxila.edu.pk

***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 produced different designs of Hollow Core Photonic Crystal Fibers (HC-PCF) with reduced dispersion and confinement losses through their core. We presented different designs of HC-PCF and selected one design with reduced losses. 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 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.

***Keywords*-**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 have 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) [i]. Research is being done on both these fibers and they are expected to propagate light with minimum losses and dispersion in order 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 that of an optical fiber. It consists of periodic air hole rings that sometimes make the refractive index of core smaller than the refractive index 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 by the effect known as Total Internal Reflection (TIR) [iii]. In PCF light is guided through the core using Total Internal Reflection (TIR) and also the Photonic Band Gap effect (PBG) that is generated due to the periodic air hole rings in the cladding [iv]. 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 structure of HC-PCF [ii].

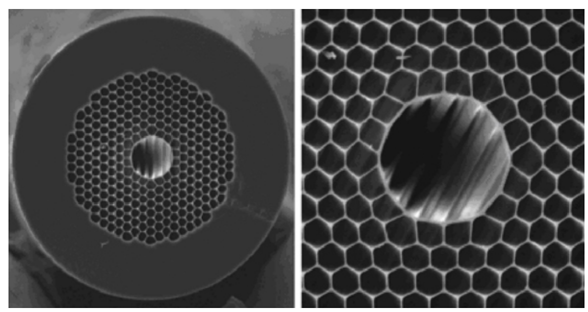

Fig.1. (a) Hollow Core PCF (b) Core of HC-PCF (c) Solid Core PCF

If an air hole is introduced in the core region of PCF then it becomes an important and useful form of the fiber 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 of highly non-linear fibers for non-linear devices to large mode area fibers for high power delivery [v]. For the analysis of low loss and dispersion properties, HC-PCF has been found to be one of the promising fibers in telecommunication sector. The construction of HC-PCF is such that the core is created by introducing air-holes in the center of a photonic band gap of the fiber. The core forms the shape of a cylinder that runs down the entire fiber which is surrounded by cladding with periodic arrangement of air holes. When we arrange large air-holes in the form of a periodic network, light propagation can be achieved using PBG effect. Literature Review shows that a band gap is only produced when the air-holes are quite large.

When a defect is established in such a

structure as a large air-hole in center of Fig. 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 the air core through the entire length of the fiber. This 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 [vi].

II. Theoretical Discussion

Propagation of light through HC-PCF 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 referred by (1-4) [vii]

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

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

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

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

The normalized frequency V for a conventional step index fiber is given in (5).

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

Where ρ is the core radius, $\boldsymbol{k_0}$ is the wave number, $\boldsymbol{n_{co}}$ and $\boldsymbol{n_{cl}}$ are the refractive indices of the core and cladding respectively [viii]. 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 one mode for propagation of light and that fiber becomes a single mode fiber. The normalized frequency of a PCF is given in (6)

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

Where 2Λ is the core diameter [viii]. A PCF with d/Λ $\leq$ 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 [ix]. $S_z(\kappa)$ is referred to (7).

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

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

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

Where n and n_0 are the simple mode index and the effective mode index respectively. The normalized field intensity is given by (9) [ix].

$$F = \left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2} \frac{\oint_{hole\ perimeters}^{0} dl|\boldsymbol{E}|^2}{\int_{cross-section}^{0} dA|\boldsymbol{E}\times\boldsymbol{H}^*| . \hat{z}} \quad (9)$$

Where **E** and **H** are the Electric and Magnetic fields respectively. $\hat{z}$ 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 parameter and is given by (10) [viii].

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

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) [ix].

For simulation purpose we used Perfectly Matched Layer (PML) boundary conditions for which we selected an anisotropic material whose permittivity and permeability tensors are referred to (11-12).

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

with

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

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

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) is as in (13).

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

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 [x].

Confinement loss L_c occurring within HC-PCF is due to finite number of air holes and are referred to (14-15).

$$L_c = 8.680\, k_0 \quad I_m \eta_{eff} \tag{14}$$

Where

$$\eta_{eff} = \eta_{material} + \eta_{eff,\ bandstructure} - \eta_{constant} \tag{15}$$

Dispersion through the entire fiber is the combined effect of material dispersion and waveguide dispersion and is as in (16) [viii]

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

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

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

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 fiber and then calculated the dispersion and confinement loss through those designs of HC-PCF. After this a comparison was made between proposed designs and the design of HC-PCF commercially available.

In WDM systems, wavelength range of operation is from 1300nm to 1550 nm [xi]. 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 and also 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 the 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	$3\text{x}10^{-7}$	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	$4\text{x}10^{-9}$	-4	-38

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 produced 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 with minimum dispersion and confinement loss. 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 reflecting the best design with low loss and dispersion. The following Fig. 2 shows the cross sectional view and the Electric Field intensity through HC-PCF designs.

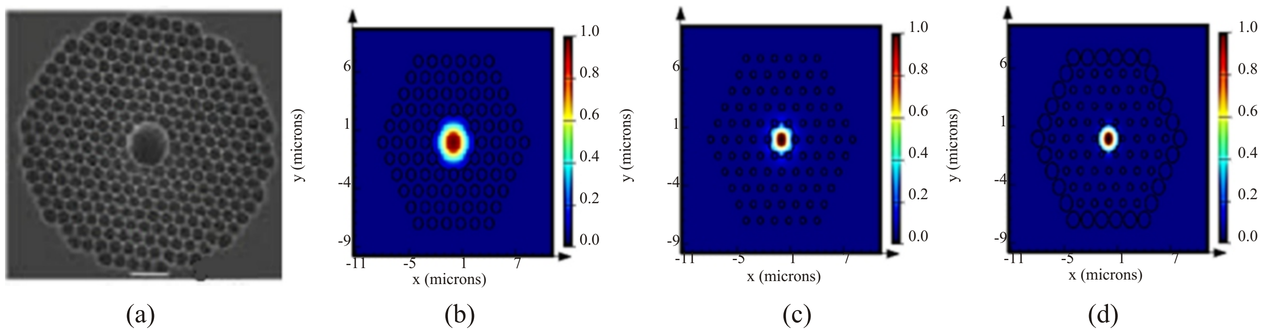

Fig. 2. (a) Cross-sectional view of HC-PCF. (b,c,d) Electric field intensities through the fundamental mode for different designs of HC-PCF given in table

Fig. 3 shows the confinement loss through the fiber designs presented above.

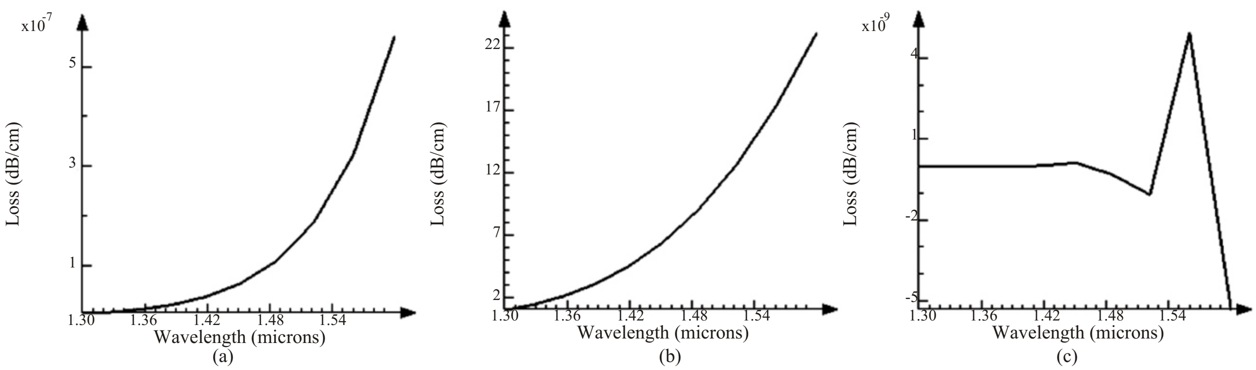

Fig. 3. Comparison of confinement losses for the three designs of HC-PCF

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

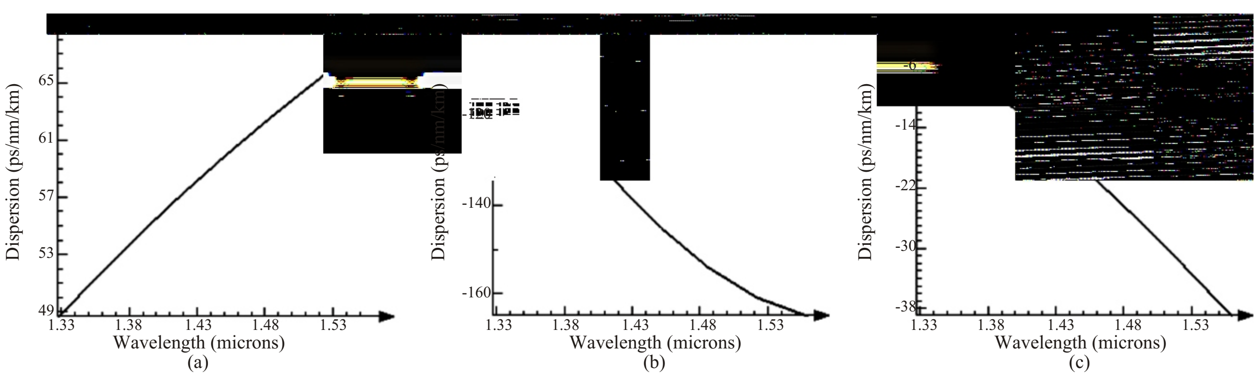

Fig. 4. Comparison of dispersion for the three designs of HC-PCF

IV. Conclusions

In this paper, we studied the transmission properties of HC-PCF fiber so that it can be utilized in WDM systems. We focused our study on the confinement loss and dispersion properties occurring within the fiber. We first analyzed different designs of the fiber to calculate 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 I, 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 x 10^{-9} dB/cm and dispersion of -38ps/nm/km at 1550nm. These three designs were made after having a thorough look at literature; it was found that these designs were a better option. Among these three designs, design 3 was chosen to be the one with minimum possible confinement loss and dispersion.

REFERENCES

[i] P. J. Brown, Stephen H Foulger, "Photonic Crystal-Based Fibers" Project M02-CL06.Annual Report 2005.

[ii] P. J. Roberts, F. Couny, H. Sabert, B. J. Mangan, D. P. Williams, L. Farr, M. W. Masonand A. Tomlinson, "Ultimate low loss of hollow-core photonic crystal fibres" *OPTICS EXPRESS*, vol 13. No.1, 2005.

[iii] R. F. Cregan, B. J. Mangan, J. C. Knight, T. A. Birks, P. St. J. Russell, P. J. Roberts and D. C. Allan, "Single-mode photonic band gap guidance of light in air," *Science* 285, 1537-1539 (1999).

[iv] A. Khetan, A. Momenpour, T. Monfared, S. Tiwari, H. Anis, "Hollow core photonic crystal fiber as a robust Raman biosensor" *Optical Fibers and Sensors for Medical Diagnostics and Treatment Applications* XIII, Proc. of SPIE Vol. 8576,85760F.

[v] S. O. Konorov, C. J. Addison, H. G. Schulze, R. F. B. Turner, and M. W. Blades, "Hollow-core photonic crystal fiber-optic probes for Raman spectroscopy," *Opt. Lett*. 31, 1911-1913 (2006).

[vi] X. Yang, C. Shi, R. Newhouse, J. Z. Zhang, and C. Gu, "Hollow-Core Photonic Crystal Fibers for Surface-Enhanced Raman Scattering Probes," *International Journal of Optics*, vol. 2011, Article ID 754610, (2011).

[vii] M. R. Albandakji, "Modeling and Analysis of Photonic Crystal Waveguides", PhD Dissertation submitted to the Faculty of the Virginia Polytechnic Institute and State University (2006).

[viii] R. A. Correa, "Development of Hollow Core Photonic Band Gap Fibers Free of Surface Modes" PhD Dissertation submitted to Faculty of Engineering, Science and Mathematics, Optoelectronics Research Center, University of Southampton (2009).

[ix] F. Benabid, "Hollow-core photonic bandgapfibre: new light guidance for new science and technology" Philosophical Transactions, *The Royal Society* (2006).

[x] S. Gowre, S. Mahapatra, and P. K. Sahu "A Modified Structure for All-Glass Photonic Bandgap Fibers:Dispersion Characteristics and Confinement Loss Analysis" ISRN Optics, Volume 2013, Article ID 416537, (2013).

[xi] M. Khalid, I. Arshad, M. Zafrullah "Design and Simulation of Photonic Crystal-Fibers to Evaluate Dispersion and Confinement Loss for WDM Systems" accepted, The Nucleus 51, No.2, 2014.