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DESIGN AND SIMULATION OF PHOTONIC CRYSTAL FIBERS TO EVALUATE DISPERSION AND CONFINEMENT LOSS FOR WAVELENGTH DIVISION MULTIPLEXING SYSTEMS

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Photonic Crystal Fiber (PCF) is the innovative and vital advancement in the field of optical communication. Research is being carried out in this field to study the transmission properties of PCF and how these properties can be improved to get the most optimum design. In this paper, two different categories of PCF are used (i) single solid-core PCF and (ii) multi solid-core PCF. We evaluated the confinement loss and dispersion properties for different designs of PCF to find an appropriate design for effective propagation of light in wavelength division multiplexing (WDM) systems. For WDM systems, both the confinement loss and dispersion of the fiber should be minimized for effective propagation of light. We made different designs of PCF and compared them to achieve the best possible design. The wavelength range for WDM systems is from 1300nm to 1500nm. We studied the confinement loss and dispersion for this range of wavelengths.

Keywords: Photonic Crystal Fibers, Micro-structured fibers, Confinement loss, Dispersion, Wavelength Division Multiplexing.

1. Introduction

Photonic Crystal Fiber (PCF) is a 2-Dimensional periodic structure of dielectric material [1]. Two types of PCF are defined in literature (1) hollow-core PCF and (2) solid-core PCF. The most common PCFs reported in the literature have structure that takes the form of hexagonal, honeycomb, or cobweb geometry as shown in Figure 1 [3]. Solid-core PCF and hollow-core PCF have a hexagonal lattice structure. PCFs are further subdivided into two categories, one is index-guiding PCF in which light is guided due to Total Internal Reflection (TIR) and the other is perfectly periodic structure exhibiting a Photonic Band Gap effect (PBG) in a low index core region [2]. First solid core PCF was developed in 1995. It was made up of thin silica glass having periodic array of circular air holes [3].

The arrival of PCF in field of optics has tremendously increased the demand of the fiber for active transmission of information without any significant loss of data. PCF has successfully replaced the use of conventional optical fiber for the purpose of light propagation.

In conventional optical fiber, there is a core surrounded by a cladding with the refractive index of core greater than that of cladding. In PCF, there is a high refractive index core surrounded by cladding that has periodic arrangement of air holes.

Due to periodic arrangement of air holes in the cladding, light can be propagated due to either Photonic Band Gap (PBG) effect or Total Internal Reflection (TIR). In Conventional optical fibers light only be propagates due to TIR effect [4].

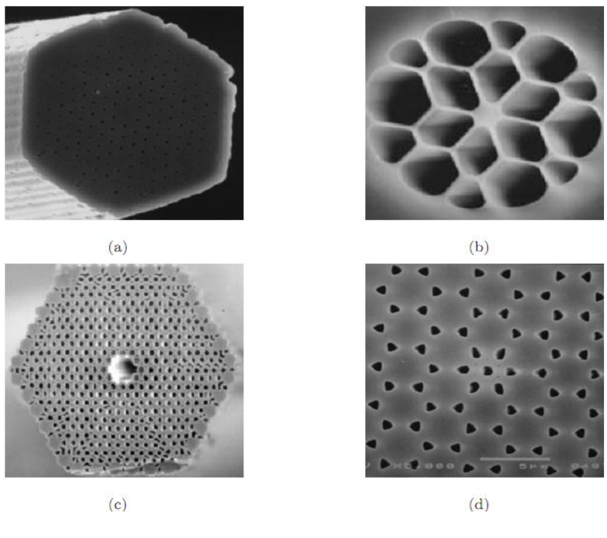

Figure 1. Various PCF structures reported in the literature: (a) hexagonal solid-core PCF, (b) cobweb PCF, (c) hexagonal hollow-core PCF, and (d) honeycomb PCF.

In this paper we concentrated more on finding an optimum design of PCF by minimizing the confinement loss and dispersion within the fiber. This was achieved by changing the parameters of PCF such as core diameter, radius of air holes and pitch presented in simulations.

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2. Theoretical Disucssion

For the propagation of light through PCF, we assume that the waveguide consist of source-free materials [5]. It has been reported that if a source-free material is used, lossless propagation in PCF is possible only if the air hole arrangement is infinite [6]. Practically, it is not possible to design a PCF with infinite air holes. In a homogeneous medium the dispersion relation between wave vector $\boldsymbol{k}$ and frequency ω of the propagating light is given through the refractive index of the material $\omega = c|\boldsymbol{k}|/\eta_{eff}$. The effective mode index of a PCF is $\eta_{eff} = \beta / k_0$. For this source-free medium, Maxwell's equations are given by Eq. (1-4)

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

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

$$\nabla . D = \nabla . \in E = 0 \quad (3)$$

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

Where k_0 is the wave number, β is the propagation constant and **E** and **H** are Electric and Magnetic field vectors respectively. μ and $\in$ are the permeability and permittivity constants. If the band structure of the fiber is taken into account then the effective refractive index is given by $n_{eff,bandstructure} = c\beta/\omega$. The frequency dependence of the refractive index arising from the silica is subsequently included using Eq. (5).

$$n_{eff} = n_{material} + n_{eff,bandstructure} - n_{constant} \quad (5)$$

Where $n_{material}$ has been calculated from the Sellmeier relationship using Eq. (6).

$$n^2_{material}(\lambda) = 1 + \sum_{j=1}^{p} \frac{\beta_j^2}{1-\left(\frac{\lambda_j}{\lambda}\right)^2} \quad (6)$$

In a PCF, the material dispersion and band structure of the fiber determine the dispersion characteristics of the fiber. To get the dispersion characteristics (ω versus β) of the structure, Maxwell's equations have to be solved. If we assume linear response of the medium and no losses then the wave equation for the $\boldsymbol{H_\omega}(\boldsymbol{r})$ field is given by Eq. (7).

$$\boldsymbol{\nabla} \times \left[\frac{1}{\varepsilon(\boldsymbol{r})} \nabla \times H_\omega(r)\right] = \left(\frac{\omega}{c}\right)^2 H_\omega(r) \quad (7)$$

where ε is the dielectric function. Here the fields have been expanded into a set of harmonic modes $\boldsymbol{H_\omega}(\boldsymbol{r}, t) = Re(H_\omega(r) e^{-j\omega t})$ with frequency ω. Because of translational symmetry along the z-axis, the dielectric function only depends on (x, y), consequently the harmonic modes are expressed in Eq. (8).

$$H_\omega(r) = \sum_m a_m \, h_m(x, y) e^{j\beta^{(m)}(\omega) z} \quad (8)$$

Where m denotes the m^{th} eigen-mode with transverse part $h_m(x, y)$ and propagation constant $\beta^{(m)}(\omega)$.

Dispersion is the second derivative of the propagation constant β, so in order to calculate dispersion we have to calculate the propagation constant β. For testing purpose, an arbitrary Taylor expansion for the propagation constant is applied. The theoretical propagation constant is given by [3] Eq. (9).

$$\beta(\omega) = \frac{n_{eff}(\omega)\omega}{c} = \sum_m \frac{1}{m!} \beta_m (\omega - \omega_0)^m;$$

$$\beta = \frac{\partial \beta}{\partial \omega}|_{\omega = \omega_0} \quad (9)$$

The experimentally measured quantity $\beta_2(\omega) = \frac{\partial^2 \beta}{\partial \omega^2}$ is integrated to give Eq. (10).

$$\beta(\omega) = \int_0^\omega \int_0^{\omega'} \beta_2(\omega") + \beta_1 \omega + \beta_0 d\omega" d\omega' \quad (10)$$

The integration constant β_0 does not influence the dynamics therefore we set $\beta_0 = 0$. The constant β_1 corresponds to a velocity, but the actual value of β_1 is not important since it is compensated for the moving frame of reference. The detail of the derivations can be found in [3, 4].

As discussed earlier that we can only have finite number of air holes due to which confinement loss occurs. Material also produces some losses due to absorption and Rayleigh scattering. Confinement loss is the combination of these two losses. The confinement loss is represented by Lc and is due to the finite number of air holes and is given by Eq. (11).

$$Lc = 8.686 k_0 I_m[\eta_{eff}] \quad (11)$$

where I_m is the imaginary part of wavelength λ.

Research is being conducted to study the dispersion properties of PCF and in [7] the authors obtained flattened dispersion characteristics near wavelength of 800nm and a nearly zero flat dispersion around 1130 nm. Total dispersion of 2000 ps/nm/km at 1550 nm has been achieved in [8]. The total dispersion is sum of the material dispersion and the waveguide dispersion. The chromatic dispersion, $D(\lambda)$ of a PCF is easily calculated from the second derivative of the real part of the effective mode index and is given in Eq. (12).

$$D(\lambda) = -\frac{\lambda}{c} \times (d^2 \; Re[\eta_{eff}])/d\lambda^2 \quad (12)$$

Table 1. Solid Core PCF: Comparison of solid core PCF designs.

Design	Pitch	Radius (μm)	Core Dia	Loss at 1300nm (dB/cm)	Loss at 1550nm (dB/cm)	Dispersion at 1300nm (ps/nm/km)	Dispersion at 1550nm (ps/nm/km)
1	2.3	0.9	2μm	$5.5*10^{-13}$	$0.5x10^{-13}$	27.8	30.8
2	2.3	0.7	1μm	0	$0.5x10^{-8}$	67	59
3	2.3	0.7	2μm	$0.5x10^{-12}$	$0.5x10^{-12}$	23.7	26.1
4	2.3	0.7	3μm	0	$0.4x10^{-11}$	11.1	12.6
5	2.3	0.4	2μm	0	$2.5x10^{-5}$	15.6	15
6	1.6	0.4	2μm	0	$0.3x10^{-5}$	32.8	31.3

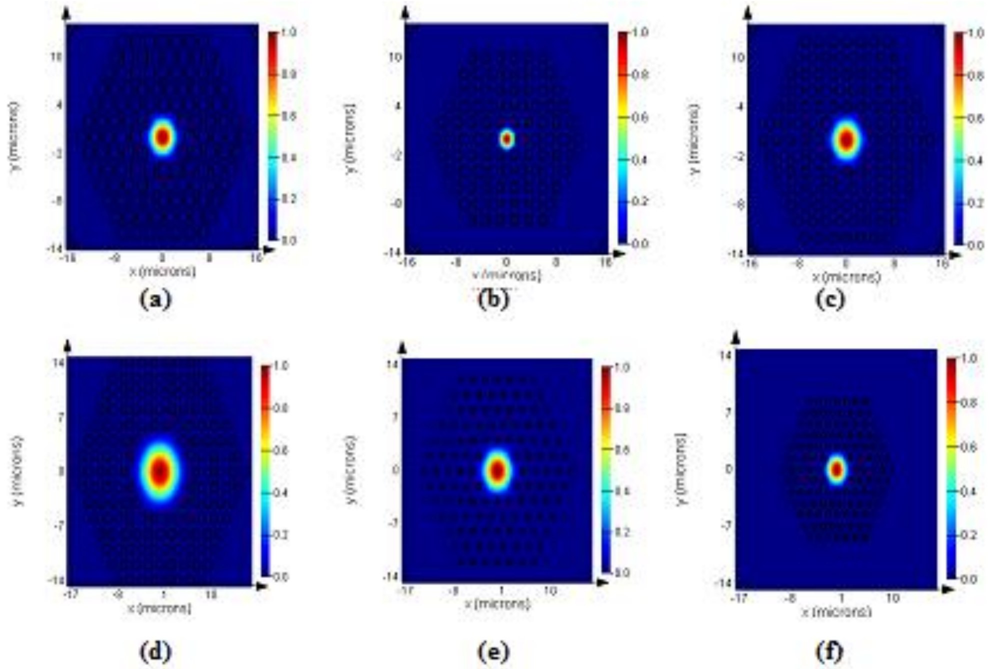

Figure 2. Electric Field Intensity through the fundamental mode of PCF for designs 1, 2, 3, 4, 5 and 6 respectively.

3. PCF Design, Analysis and Results

We studied two categories of PCF, single solid-core and multi solid-core. Simulation of these fibers is carried out using mode solutions 5.0.6. Comparison has been made between different designs and the best possible designs are selected and presented in Table 5.

3.1. Solid Core Photonic Crystal Fiber

In this section, we present six designs of solid-core PCF. A five layer PCF was used whose operating wavelength range is 1300nm to 1550nm for WDM applications. We studied these fibers over a wavelength range of 1200nm to 1700nm. We have done modal analysis and frequency analysis on different PCF designs to get the results. In these designs, pitch i.e. distance between adjacent air-holes was kept constant, radius of air holes and core diameter were made variable. Table 1 shows the comparison between these fibers.

The above table shows that as we kept on increasing the core diameter along with the limitations of the parameters described in the Table 1, the confinement loss and dispersion is decreased. An optimum design with acceptable low loss and low dispersion is needed. Therefore, by comparing the above designs it is deduced that design 4 would be a better choice with acceptable low confinement loss and dispersion.

Figure 2 shows the Electric field intensity of the above mentioned designs through the fundamental mode. Figures 3 and 4 show the confinement loss and dispersion for the mentioned designs respectively.

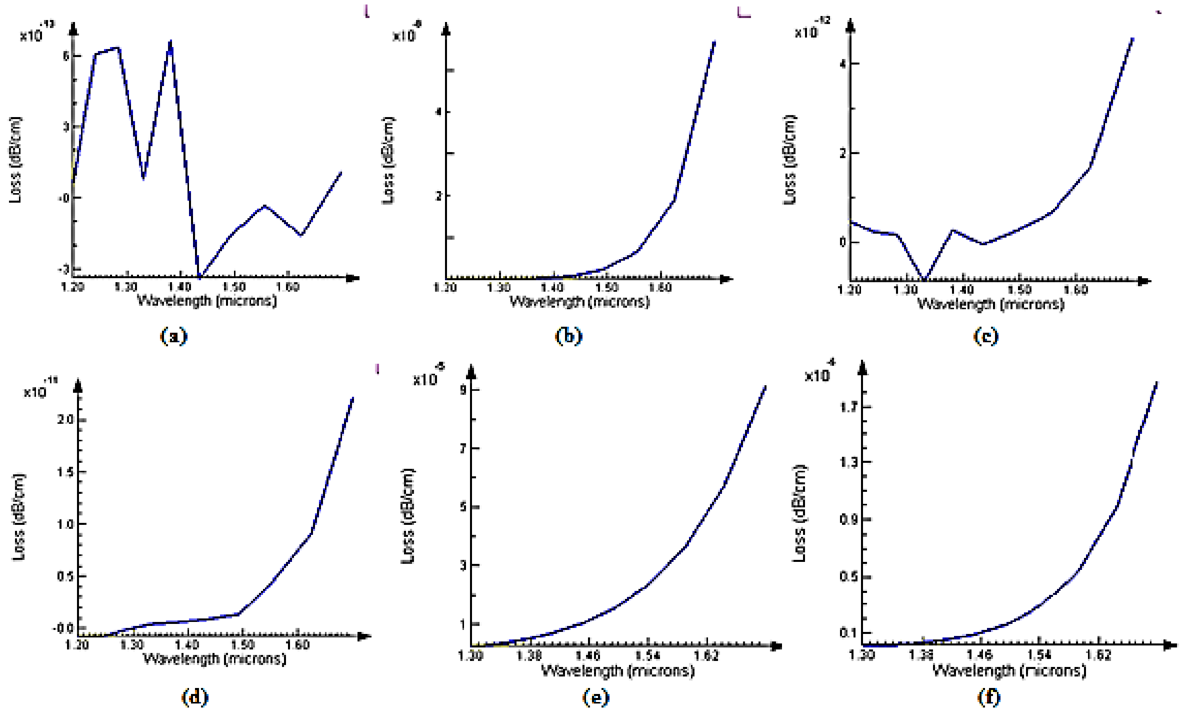

Figure 3. Confinement Loss of PCF for design 1, 2, 3, 4, 5 and 6 respectively.

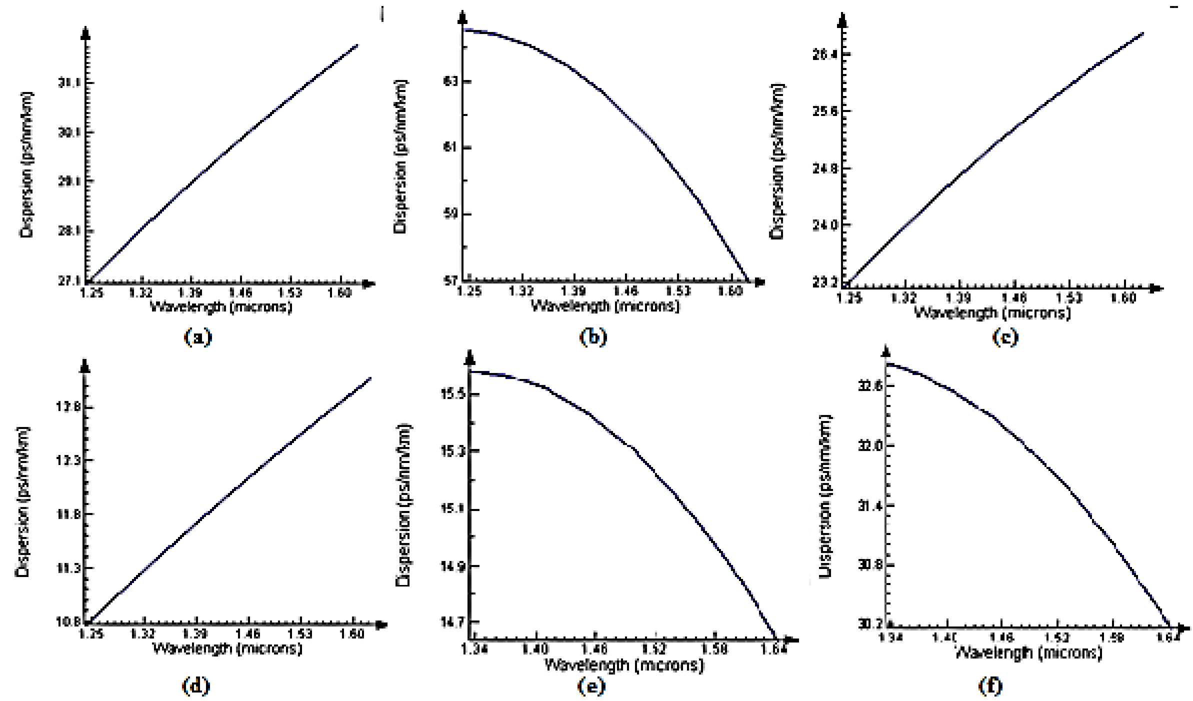

Figure 4. Dispersion of PCF for design 1, 2, 3, 4, 5 and 6 respectively.

The comparison is made with respect to both the loss and dispersion. We cannot select a design with low loss and high dispersion or vice versa. Therefore, keeping this in mind, design 4 gave the best possible results. Now we are changing the radius of inner and outer rings in such a way that only R1 and R2 values are changed and R3, R4, R5 remain equal.

R1 = Radius of 1st ring starting from inside, R2 = Radius of 2nd ring, R3 = Radius of 3rd ring, R4 = Radius of 4th ring, R5 = Radius of 5th ring.

a1 = Pitch of inner 1st ring and a2 = Pitch of other rings

For design 4 it is seen that the radius and pitch for ring 1 and 2 are changed. Figures 5 to 7 show the Electric field intensities, Confinement loss and dispersion for the above PCF designs respectively.

Now observe the designs given in Table 3.

Table 2. Study of PCF by changing R1 and R2.

Design	Pitch a1, a2 (µm)	Radius R1, R2, R3, R4, R5 (µm)	Core Dia (µm)	Loss at 1300 nm (dB/cm)	Loss at 1550nm (dB/cm)	Dispersion at 1300nm (ps/nm/km)	Dispersion at 1550nm (ps/nm/km)
1	2.3,2.3	0.4,0.4,0.9,0.9,0.9	2	0.1×10^{-12}	0.3×10^{-12}	15.8	15.5
2	2.3,2.3	0.2,0.2,0.7,0.7,0.7	2	0.1×10^{-8}	1.1×10^{-8}	2.7	3.6
3	2.3,2.3	0.2,0.35,0.7,0.7,0.7	2	0	0.2×10^{-8}	6.4	5.8
4	3.45,2.3	0.2,0.35,0.7,0.7,0.7	2	0	0.4×10^{-8}	4.27	4.25

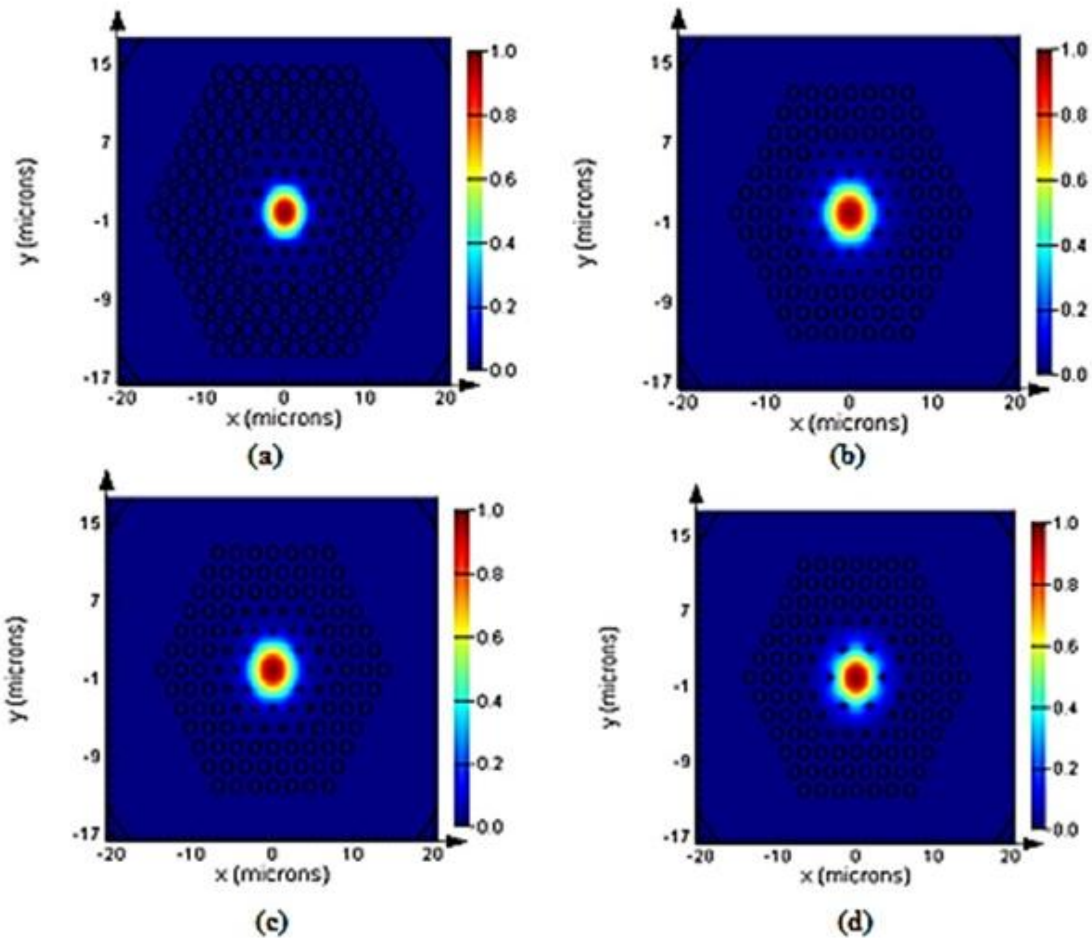

Figure 5. Electric Field Intensity within PCF fundamental mode for design 1, 2, 3 and 4 respectively.

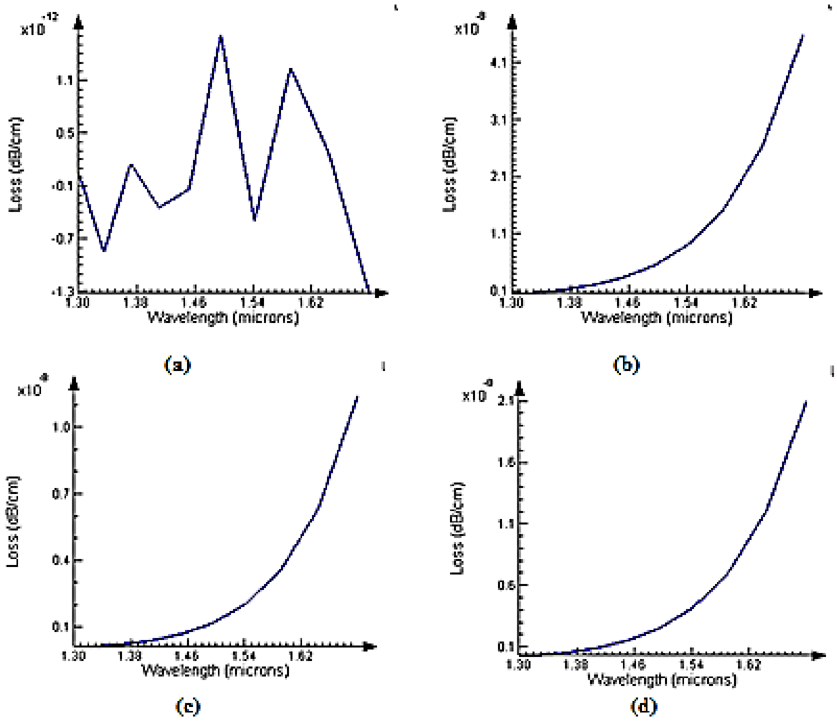

Figure 6. Confinement Loss of PCF for design 1, 2, 3 and 4 respectively.

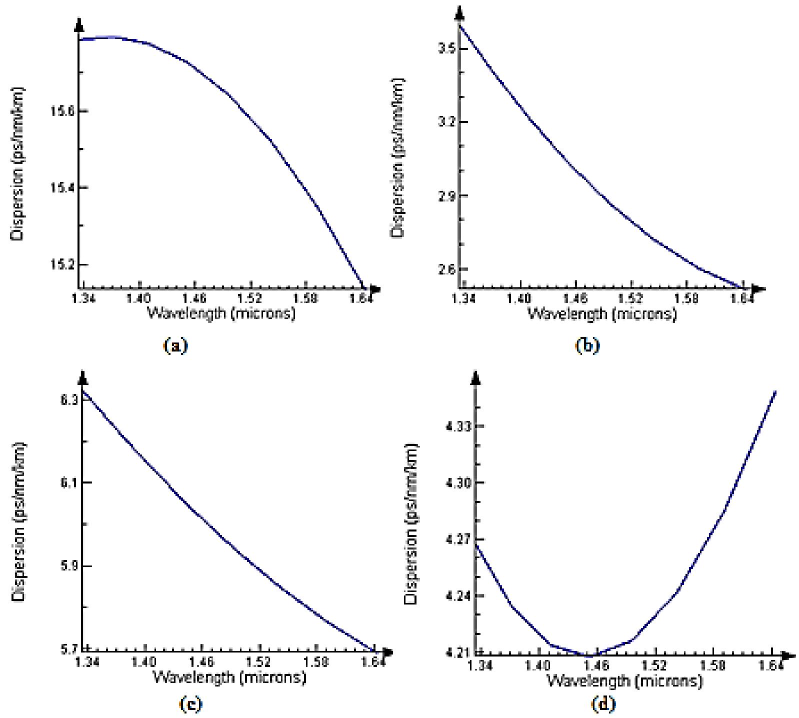

Figure 7. Dispersion of PCF for design 1, 2, 3 and 4 respectively

It can be observed by comparing the above designs, that by reducing the diameter of first ring as compared to other rings we can have a design with low loss and dispersion. So keeping this in mind, the better values came out for design 4.

In this design the pitch of the fiber has been reduced from 2.3μm to 1.6μm, and it is observed that the radius of all the air hole rings is different in such a way that as we go nearer to the core the radius of rings goes on decreasing. The following are the results for the above mentioned designs. Figures 8 to 10 show the electric field intensity, confinement loss and dispersion of these designs respectively.

Table 3. Study of PCF by changing R1, R2, R3, R4, R5.

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	0.4	1	0	$0.5x10^{-2}$	32	−9
2	1.6	0.2,0.23,0.26,0.29,0.4	1	0	0.2	−29	−33.6
3	1.6	0.15,0.19,0.22,0.26,0.4	1	0.1	0.26	−15	−14.3
4	1.6	0.15,0.19,0.22,0.23,0.4	1	0	0.3	−15.6	−15.2

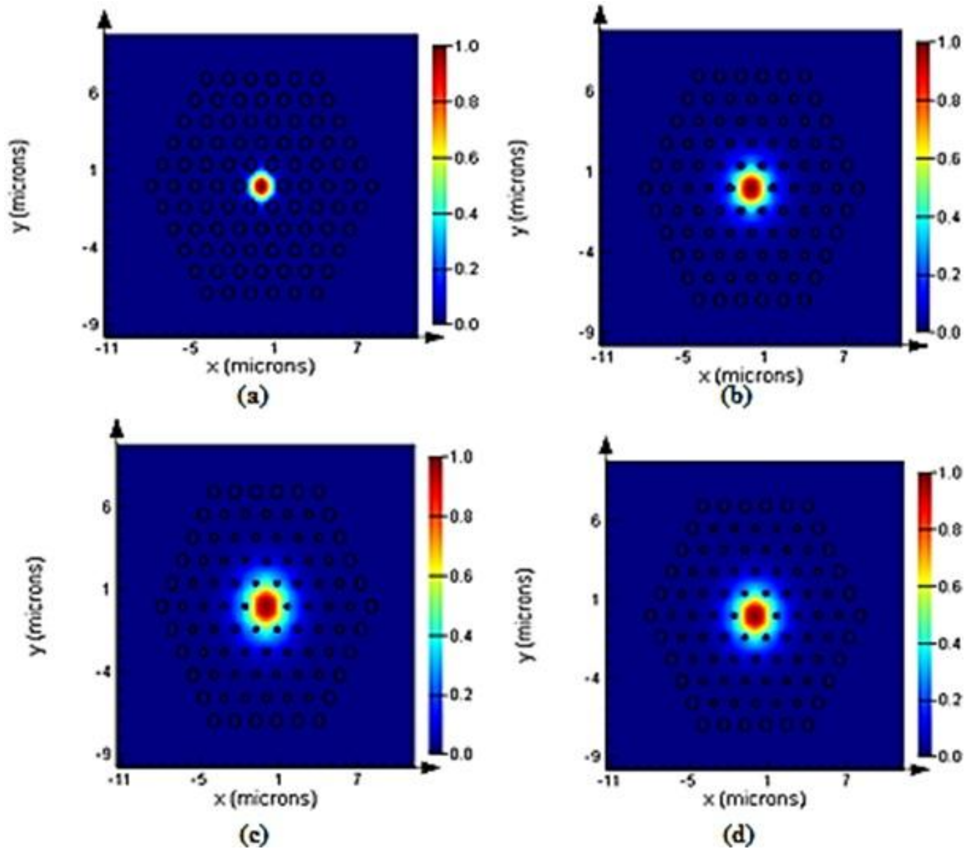

Figure 8. Electric Field Intensity within PCF fundamental mode for design 1, 2, 3 and 4 respectively.

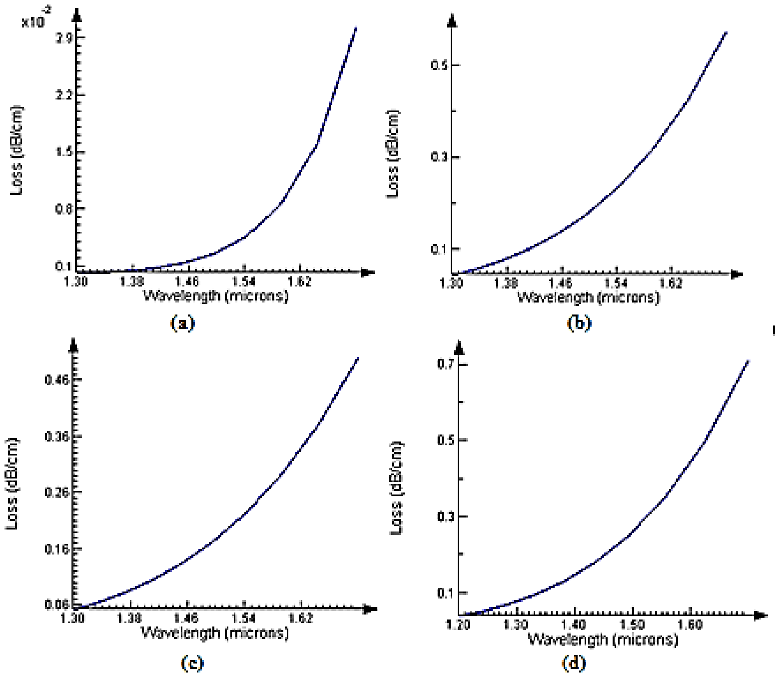

Figure 9. Confinement Loss of PCF for design 1, 2, 3 and 4 respectively.

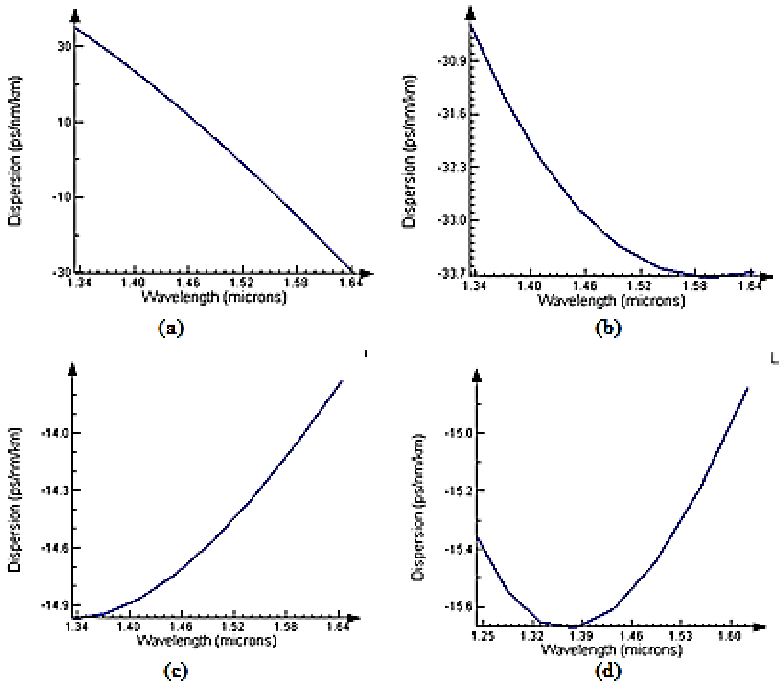

Figure 10. Dispersion of PCF for design 1, 2, 3 and 4 respectively.

3.2. Solid Multi-core PCF.

Now we consider that our fiber consist of two cores. The wavelength range is from 1300 to 1700nm. We have taken the same five layer PCF. Table 4 shows three different designs for multi-core fiber.

Table 4. Comparison of designs of solid multi-core PCF.

Design	Pitch a (µm)	Radius R (µm)	Core Dia D1, D2 (µm)	Loss at 1300nm (dB/cm)	Loss at 1550 nm (dB/cm)	Dispersion at 1300nm (ps/nm/km)	Dispersion at 1550nm (ps/nm/km)
1	1.6	0.6	1,1	0	1	110	70
2	1.6	0.6	2,2	0	0.5×10^{-10}	48.7	51.1
3	1.6	0.3	2,2	0	0.4×10^{-2}	22	15

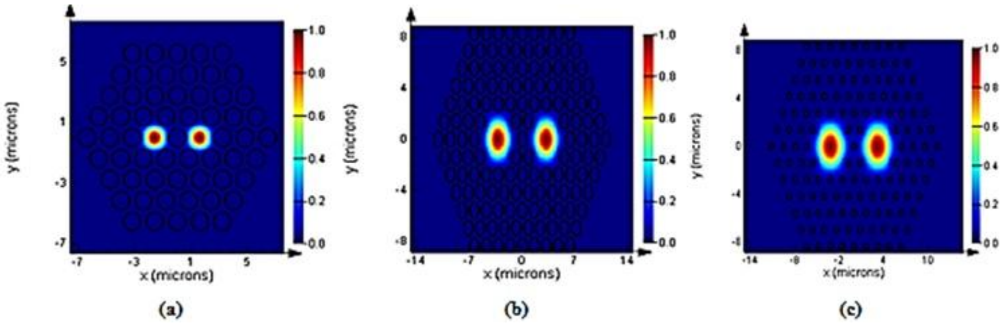

Figure 11. Electric field intensity within PCF core for designs 1, 2 and 3 respectively.

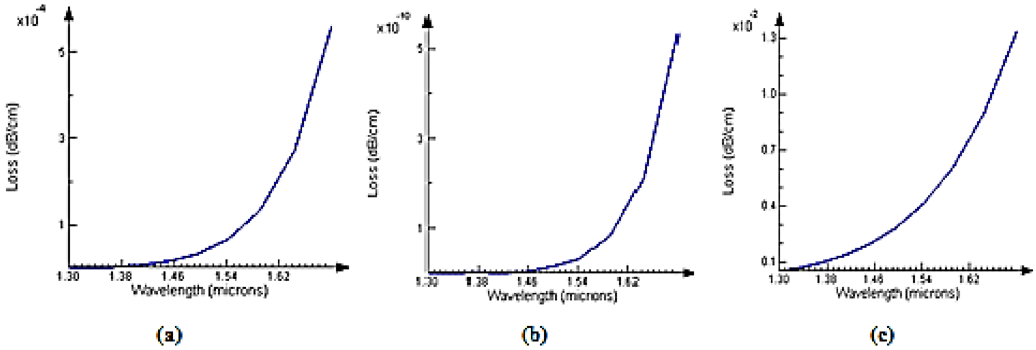

Figure 12. Confinement loss of PCF for designs 1, 2 and 3 respectively.

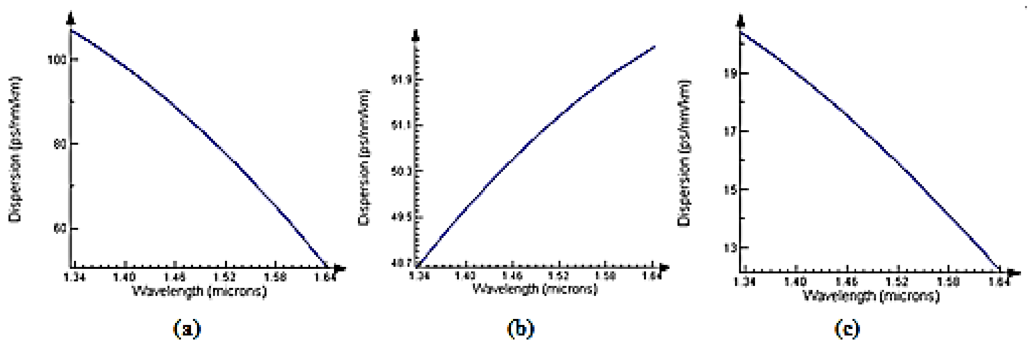

Figure 13. Dispersion of PCF for designs 1, 2 and 3 respectively.

By summarizing all the designs mentioned in Tables 1-4 provided above, Table 5 has been created having the best designs regarding low confinement loss and dispersion from the different categories of PCF.

Table 5. Best designs from different categories of PCF.

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)
Table 1	2.3	0.7	3μm	0	$0.4x10^{-11}$	11.1	12.6
Table 2	3.45,2.3	0.2,0.35,0.7,0.7,0.7	2	0	$0.4x10^{-8}$	4.27	4.25
Table 3	1.6	0.15,0.19,0.22,0.23,0.4	1	0	0.3	−15.6	−15.2
Table 4	1.6	0.3	2,2	0	$0.4x10^{-2}$	22	15

4. Conclusion

In this paper, we studied the confinement loss and dispersion properties for different designs of PCF in order to minimize these losses so that it can be utilized as an application in WDM systems. In order to use a PCF for WDM system, the wavelength range is from 1300nm to 1500nm. Two different categories of PCF were presented in this paper, solid single-core and solid multi-core. From the comparison given in Table 5, it is clearly seen that by reducing the pitch and core diameter of PCF to a certain limit, dispersion and losses started to decrease and this is the requirement for propagation of light through PCF in WDM systems. First three designs of solid single-core PCF were obtained by changing the radius of fiber and core diameter. By comparing these designs we found that by reducing the radius of fiber and other parameters, dispersion has been reduced to-15.2 ps/nm/km. Fourth design was of solid multi-core PCF. The best possible design came out to be the one from Table 2 with confinement loss of $0.4x10^{-8}$and dispersion of 4.25 ps/nm/km at 1550nm. These designs can be utilized in WDM Systems.

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