A Novel design of Photonic Crystal Fiber with Flattened Dispersion and Reduced Confinement Loss

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Abstract

Data transmission with low losses and dispersion is one of the biggest challenges for optical communication. Light should be transmitted through a fiber that has the most optimum condition for the losses and dispersion. A lot of research is being conducted on optical fibers to improve the transmission properties of the fiber so that maximum data should travel through the fiber. Photonic Crystal Fibers (PCF) have resolved this issue of data transfer from one terminal to the other with minimum losses and dispersion, moreover the transmission properties of PCF are far better than optical fibers. The purpose of the study in this paper is to find an optimum design for a PCF in which we reduce both the dispersion and confinement losses. We studied these transmission properties of PCF over a wavelength range of 1300 nm to 1550 nm. The biggest application of this design is in Wavelength Division Multiplexing (WDM) systems in which the losses and dispersion should be minimized for better transmission of data.

Key Words: *Photonic Crystal Fibers; Micro-structured Fibers; Confinement loss; Dispersion.*

1. Introduction

Photonic Crystal Fiber (PCF), a completely new class of Micro-structured Fibers, is of great importance now a day. The study of transmission properties of PCF is now being one of the most popular topics among the researchers all around the world [1]. Due to the beneficial properties of Photonic Crystals, PCFs are now being utilized in many applications of optical communication such as WDM and DWDM systems where these transmission properties allow most of the data to travel through it without much losses and dispersion [2].

Dielectric materials are formed in such a way to produce a two dimensional structure which has been given the name PCF. This fiber is supposed to be uniform in z direction [2]. PCFs are divided into two forms (i) Hollow Core PCF and (ii) Solid Core PCF. These two types are again subdivided into two more types (i) Index Guiding PCF and (ii) Photonic Band Gap Fibers (PBG). This division of PCF into subdivisions is done because of the effect through which light propagates through the fiber. In index Guided PCF, light propagates through the PCF due to Total Internal Reflection (TIR) and in Photonic Band Gap fibers light propagates through an effect commonly known as Photonic Band Gap effect [3].

The structure of Conventional Optical Fiber consists of simply a core surrounded by a cladding. The refractive index of core is greater than that of the cladding in such fibers. When the refractive index of core is greater than that of the cladding, light is confined to the core of the fiber due to TIR effect [2]. These fibers are single-mode step index fibers, multi-mode step index fibers and single-mode graded index fibers. In these fibers, losses occur due to scattering, dispersion, confinement loss, absorption by the material, bending losses and Rayleigh scattering [3].

The structure of Photonic Crystal Fiber (PCF) consists of a core that is surrounded by a cladding. In this case cladding is not like that of conventional optical fiber, but it is a periodic structure of air holes that allows the light to confine to the core of the fiber. In Photonic Crystal Fibers, light is propagated through the core due to TIR effect as well as due to PBG effect. Photonic Band Gap structure of fiber is produced due to the periodic arrangement of air holes in the cladding. If the index of refraction of core is greater than the effective refractive index of cladding, light will be guided through the core due to TIR effect. If the refractive index of core is smaller than that of the effective refractive index of cladding, light will be propagated due to PBG effect [3].

In this paper we proposed a new model of PCF in which we studied low confinement losses as well as low dispersion for WDM and DWDM systems. The main concern for the design of a PCF was to reduce dispersion and confinement loss, as it is the main requirement of a WDM system.

In this research we made a novel design for PCF by reducing the radius of air holes in such a way that the radius of holes in the inner ring is smaller as compared to the outer rings. In addition to this, hexagonal structure has been used and a five layer PCF is assumed. This proposed design is compared with the design already available in literature [4], after comparing the results of this design with the available design it is seen that both the confinement loss and dispersion have been reduced to a much lower value. Simulations have been done using mode solution 5.0.6 software.

The rest of the paper is organized as: Section 2 contains the theoretical discussion containing the equations utilized for this paper. Section 3 describes the proposed model of Photonic Crystal Fiber and Section 4 gives the concluded result.

2. Theoretical Discussion

A dielectric material is used for the fabrication and designing of a PCF [6]. For the guidance of light through a PCF we first solved the Maxwell's Equations. For this purpose we first assumed a source free, loss-less and homogeneous dielectric medium having linear response for simplicity. For this assumption the wave equation took the form of Eq. 1

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

Here ε is the dielectric function. Moreover **E** and **H** are the Electric and Magnetic Fields respectively. The field expansion has been done in to a set of harmonic modes $H_\omega(r,t) = \mathrm{Re}(H_\omega(r)e^{-j\omega t}$ with ω being the frequency. μ and ϵ are the permeability and permittivity factors respectively [7].

For the simulation of wave propagation, only the fundamental mode is utilized. To find out the fundamental mode of the PCF, we first have to define the normalized frequency, the V number. The V number for single mode step index fiber is given by

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

With k_0 being the wave number, ρ the radius of the core, n_{co}^2 is the index of refraction for the core and n_{cl}^2 is the index of refraction of cladding.

In case of Photonic Crystal Fibers, it is a little bit changed due to the changed structure of cladding of PCF as compared to the single-mode step index fiber. The V number for PCF is given by

$$V_{eff}(\lambda) = k_o 2\Lambda \sqrt{n_{silica}^2 + n_{eff}^2(\lambda)} \quad (3)$$

With 2Λ being the diameter of the core. Here $n_{eff}^2(\lambda)$ is the effective index of refraction for the cladding. To make the fiber single mode the following condition must be satisfied

$$V \le 2.405 \text{ and } V_{eff}(\lambda) \le 2.405 \quad (4)$$

$V_{eff}(\lambda)$ will be less than or equal to 2.405 only when $d/\Lambda < 0.4$, with d being the dimension of the waveguide and Λ is the pitch. The effective index of refraction for PCF is given by

$$\eta_{eff} = \beta / k_o \quad (5)$$

with β being the propagation constant [8].

Confinement loss can be completely removed if we have infinite number of air holes in the cladding of the PCF. It is noticeable with finite number of air holes. If we increase the number of air holes, we can significantly reduce the confinement loss.

The confinement loss is represented by *Lc* and occurs mainly due to the finite number of air holes. L_c is given by

$$Lc = 8.686 k_o l_m [\eta_{eff}] \quad (6)$$

A lot of research is being conducted to evaluate the transmission properties of PCF specially the dispersion and confinement loss. In [9] the researchers got a flattened dispersion characteristics around wavelength of 800nm and a nearly zero flat dispersion near 1130nm. A total dispersion of 2000ps/nm.km at 1550nm was achieved by the researchers, detail can be found in [10]. The total dispersion is basically the sum of the dispersion occurred by the material and the dispersion through the waveguide. The chromatic dispersion, represented by $D(\lambda)$ of a PCF is normally evaluated from the second derivative of the real portion of the effective mode index:

$$D(\lambda)=\frac{\lambda}{c}\times\frac{d^2 Re[\eta\_eff]}{d\lambda^2} \quad (7)$$

Dispersion is basically the second derivative of the propagation constant β, so the theoretical propagation constant found by applying arbitrary Taylor expansion is given by the following equation

$$\beta(\omega)=\frac{\eta_{eff}(\omega)\omega}{c}=\sum_m \frac{1}{m!}\beta_m(\omega-\omega_o)\ m; \quad (8)$$

$$\beta=\left.\frac{\partial\beta}{\partial\omega}\right|_{\omega=\omega_o}$$

Integration of experimentally measured quantity $\beta_2(\omega)=\frac{\partial^2\beta}{\partial\omega^2}$ takes the following form

$$\beta(\omega)=\int_o^{\omega}\int_o^{\omega_r}\beta_2(\omega^2)+\beta_1\omega+\beta_o d\omega'' d\omega' \quad (9)$$

Constant β_0 can be set to zero as it does not affect the dynamics and β_1 corresponds to velocity but the actual value of β_1 is not important as it compensates for the moving frame of reference.

Different numerical, theoretical and experimental approaches are being made to minimize both the dispersion as well as the confinement losses in order to pass light through PCF without much distortion [11]. In this paper we provided the comparison between different designs of PCF in order to find out a design with lowest confinement loss and dispersion properties to find an application in WDM systems. Moreover we also introduced a novel design with ultra-flattened dispersion characteristics at 1.45 microns. In WDM systems wavelength ranges from 1300 nm to 1550 nm for PCFs. In WDM systems the best design of PCF is supposed to be the one in which we have low confinement loss and low dispersion [10].

3. Proposed Design

Before the propagation of light through any fiber, it is first compulsory to analyze that fiber to find its fundamental mode. In this work we did the modal analysis of PCF, found its fundamental mode, its dispersion and the confinement loss which could have been produced due to particular parameters applied such as core radius, Pitch, and size of air holes. After this analysis we compared that design with the one already available in literature [4].

Figure 1 shows simple design for PCF in which pure silica with background index 1.45 is utilized. This design is already available in literature [4]. Similar work is done by Vineet Agrawal et. al., [5]. In this design [4] the following parameters are used.

Table 1 Parameters of already available design[4]

Diameter of air holes numbered from the rings starting from the Core Region	
D1	0.4μm
D2	0.76μm
D3, D4, D5	1.8μm
Pitch of the air holes (distance between the adjacent holes)	
Λ1=1.5Λ	3.45μm
Λ	2.3μm

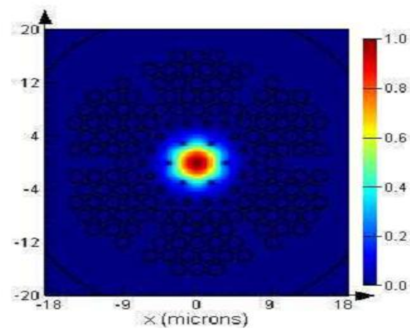

Fig. 1 Cross section of available PCF structure

Figure 2 represents the result of the above mentioned PCF showing effective refractive index graph, confinement loss and the dispersion produced by the fiber design available. In this design triangular lattice of the PCF has been utilized. Different lattice structures for PCF can be established but the most popular lattice structures are the triangular, hexagonal and square lattice structure. All these structures have different transmission properties.

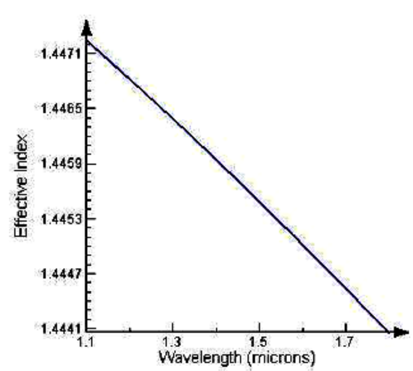

Fig. 2(a) Effective mode index

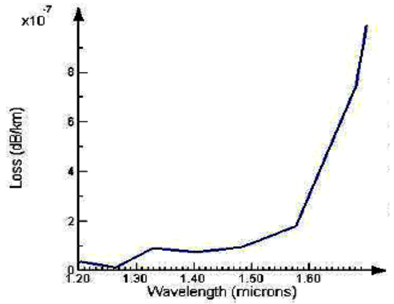

Fig. 2(b) Confinement loss-wavelength graph

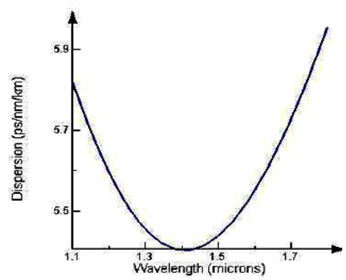

Fig. 2(c) Dispersion- wavelength graph

In our proposed designs we utilize the hexagonal lattice structure for the Photonic Crystal Fiber. Hexagonal lattice structure is the first and the most important structure for a PCF. In our designs 5 layered PCFs have been utilized. Five layered PCF means that the cladding of PCF is surrounded by five hexagonal layers of air-holes. The refractive index for air-holes is 1 and the refractive index of the silica background has been selected to be 1.45.

In order to have low losses and dispersion, the number of air-holes that surround the core should be increased. Secondly, if the air-holes of inner ring have smallest diameter as compared to the others than these targets can also be achieved.

In our new design we reduced the diameter of the inner holes in order to achieve low confinement loss as well as low dispersion. The parameters which were taken to design the PCF are given below:

Table 2 Parameters of Proposed Design 1

Diameter of air holes numbered from the rings starting from the Core Region	
D1	0.35 µm
D2	0.7 µm
D3, D4, D5	0.14 µm
Pitch of the air holes (distance between the adjacent air holes)	
Λ1=1.5Λ	3.45 µm
Λ	2.3 µm

The hole size in the rings is reduced in our proposed design, because it is observed that as we go on reducing the inner hole radius the loss as well as the dispersion reduces. Secondly, we used hexagonal lattice for PCF rather than triangular approach presented in Figure 1 that was the design already available in literature. Figure 3 shows the Electric field intensity in the fundamental mode which resulted due to the modal analysis of our design. The wavelength range used is from 1.3 to 1.7µm.

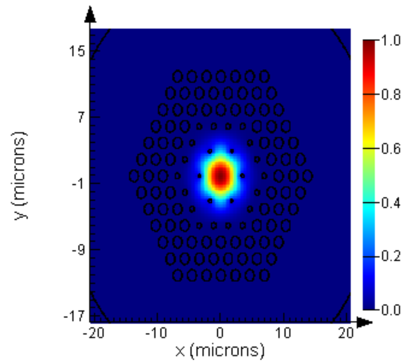

Fig.3 **El**ectric field intensity in fundamental mode

Figure 4a, 4b, 4c respectively show the effective mode index, confinement loss and dispersion of the new proposed design. This result was achieved by doing frequency analysis of the proposed PCF structure.

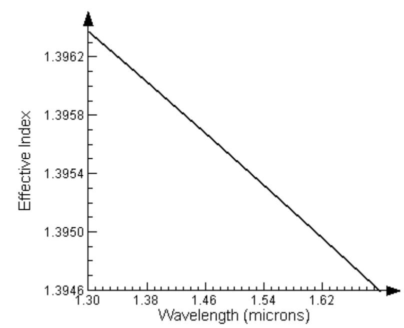

Fig.4(a): Effective index-wavelength graph

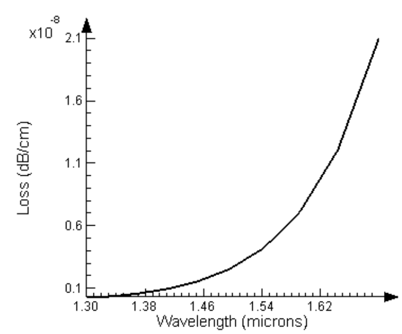

Fig.4(b): Confinement loss- Wavelength graph

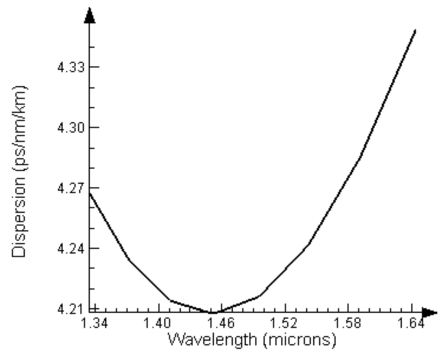

Fig.4(c): Dispersion-Wavelength graph

It can be observed from above figure that this design gives a flattened dispersion for a wavelength range from 1.44μm to 1.46μm.

Now moving further apart, we present another new design of Photonic Crystal Fibers for which we achieved negative dispersion and also obtained flattened dispersion for a range of 1.36 μm to 1.39 μm, much less than the previous design and less than already available in literature [2]. Negative dispersion for PCF designs have also been presented in literature [3-5]. This structure is achieved by changing the air hole sizes for all the five layers of air holes with layer 5 having largest air hole ring size, layer 4 having second largest and so on towards the ring 1 which has the smallest air hole size. The parameters are given as follows.

Table 3: Parameters of Proposed Design 3

Diameter of air holes numbered from the rings starting from the Core Region	
D1	0.3 μm
D2	0.38 μm
D3	0.44 μm
D4	0.46 μm
D5	0.8 μm
Pitch of the air holes (distance between the adjacent air holes)	
Λ	1.6 μm

Figure 5 shows the Electric Field intensity through the fundamental mode of this new design, figure 6(a) gives its confinement loss and figure 6(b) gives the dispersion through the fiber.

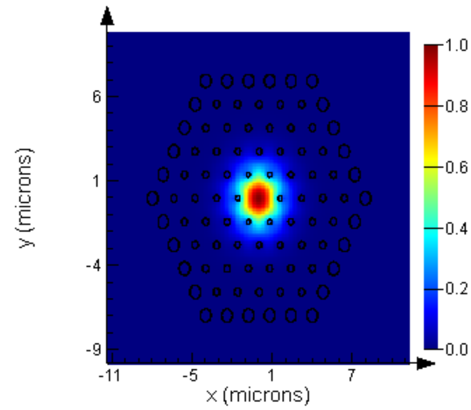

Fig. 5 Electric Field Intensity through the fundamental mode.

The next figure 6 shows the confinement loss and dispersion properties for the second new design presented in this paper.

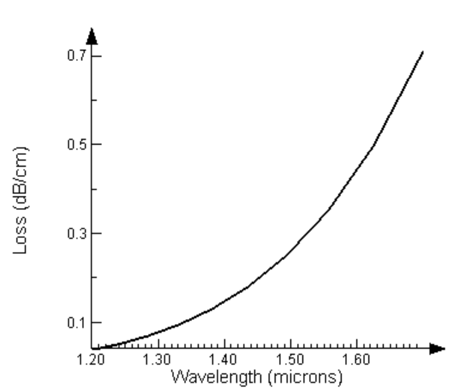

Fig. 6(a): Confinement loss for the new design

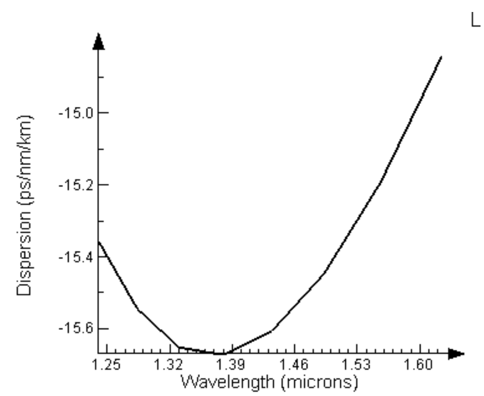

Fig.6(b): Dispersion for the new design

4. Conclusions

In this paper we have presented a new design of a Photonic Crystal Fiber with the one already available in literature. Purpose of such type of comparison was to achieve a design that is more reliable and has less dispersion and confinement loss as compared to the one already available.

It was observed during our research that as we go on increasing the diameter of the air holes with the first ring which is nearest the core having smallest diameter, the second ring that surrounds the first ring has air-hole diameter greater than the first ring, the third ring air-hole diameter greater than second ring and so on up to the fifth ring, improved transmission properties are achieved. That is why the PCF design given in Figure 5 gives the best results as in this design all the air-hole rings have different diameters, so in this case we achieved the flattened dispersion characteristics of PCF.

Comparing the first two designs given in figure 1 and figure 3 it can be noted that both the confinement loss as well as the dispersion have been reduced in the design of figure 3. In case of design 1 which was already available in literature, the confinement loss is $0.5*10^{-7}$at 1.3µm and at 1.55µm it is $0.9*10^{-7}$dB/cm but in the proposed design given in figure 3 the confinement loss has been reduced to 0 at 1.3µmand at 1.5µm it is $0.4*10^{-8}$dB/cm (Figure 4b). The dispersion in case of design 1 for 1.3µm and 1.55µm is 5ps/nm.km but in case of design 3 at 1.3µm dispersion is 4.27ps/nm/km and at 1.55µ it is 4.24ps/nm/km (figure 4c) with a flattened dispersion of 1.44 microns. So, the proposed design is suitable for use in WDM and DWDM applications where low loss and dispersion are needed.

Another design is also presented in this paper with an improved flattened dispersion property plus negative dispersion and much less confinement loss as presented in figure 6(a) and 6(b). In this design, flattened dispersion is achieved at 1.38 microns and a confinement loss of 0.3 dB/cm which is much more computable as compared to the design given in Fig.4.

In short, by looking at both new designs presented in this paper, design given in figure 5 is more appropriate model to be used which provides a negative dispersion of approximately -15.2 ps/nm/km at 1.55 microns.

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