

# Design Optimization to Analyze Elliptical Core Spiral Photonic Crystal Fiber with Improved Optical Properties

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**Abstract:** The aim of this chapter is to attempt an optimized design from horizontal and vertical core spiral photonic crystal fiber with the use of various photonic materials. Here we tried to design this spiral PCF for three PCF materials like chalcogenide glass, borosilicate crown glass and silica glass. The four designs have been proposed with all these selected materials to get the optimized result. The aim of the proposed design is to get low dispersion profile, low confinement loss and better transmission curve in both the spiral PCF structures. For this purpose we have used Opti Finite Difference Time Domain (FDTD) with transparent boundary conditions (TBC). In this design initially the core region is selected in horizontal elliptical shape, while the cladding part is maintained in circular shape. Later on the elliptically core is converted into vertical direction keeping the cladding region in circular shape. The core diameter is maintained at  $0.25\ \mu\text{m}$  and  $0.5\ \mu\text{m}$  with minor and major axes, while the cladding diameter varied from  $0.5\ \mu\text{m}$  to  $1.25\ \mu\text{m}$ . The design so obtained faced many conflictions during simulation process but after setting the parameters in appropriate manner, we got the optimized results and it also maintained the refractive index of the material selected using Sellmeier equation.

**Keywords:** FDTD, Core, Cladding, Dispersion, Refractive index, TBC, CVD

## I. BACKGROUNDS AND INTRODUCTION

In the ancient time human beings had the only means of communication, which was Dove. As the momentum grew, the humans also made some new inventions. If we talk about modern invention, human being has the best medium of communication, i.e. Optical fiber. Earlier, two scientists of Paris, Daniel Colladon and Jacques Babinet explained the propagation of light and the basic principal of optical fiber in 1840. After 12 years in 1852, John Tyndall again performed it publicly in London with a new research. Tyndall wrote a book in 1870, entitled "Nature of Light" in which he explained in detail about "Total Internal Reflection (TIR) principle" of light. Then there was a time when the light began to be passed from the Bent Glass Rods at the end of the 19th century and at the beginning of the 20th century. As time went ahead, technology also started moving forward. Moving forward this technology, radio experimenter Clarence Hansell and television pioneer John Logie Baird showed transmitting the image through optical fiber tube in 1920. In 1930, Heinrich Lamm used optical fiber in internal medical experiments. However, his contribution did not get any place in history.

"Necessity is the mother of invention" There were still many drawbacks in optical fiber technology; many research done to overcome these shortcomings. But in 1953, the research done by Dutch scientist Bram van Heel was the main one who introduced modern optical fiber technology. He transmitted the image using transparent cladding from the Bundles of optical fiber.

In the same year, Harold Hopkins and Narinder Singh Kapany at Imperial College London extended this research and in 1954 a research paper was published in the journal Nature, titled "A flexible fiberscope, using static scanning". But the main challenges facing the scientists were to reduce attenuation in optical fibers. To overcome this problem, two scientists working in England's company "Standard Telephones and Cables (STC)" gave an idea in 1965. In which they reported that the attenuation of optical fibers could be reduced to 20 decibels per kilometer (dB / km) by physical effects such as scattering.

Then they suggested using high purity silica glass as a core material in optical fiber. Due to this research, Kao was awarded the Nobel Prize in Physics in 2009. Subsequently, Robert D. Maurer, Donald Keck, Peter C. Schultz, and Frank Zimar collaborated with the American glassmaker Corning Glass Works to create a new core material, in which titanium was doped in silica glass. In this way a modern optical fiber was formed, whose attenuation was less than 4 dB / km. A revolutionary change occurred in this area in 1991. In 1991, Philip St. John Russell, Director of the Max Planck Institute for the Science of Light in Erlangen, Germany, gave the idea of photonic crystal fiber [1-9], which was published in the journal "Optics Letters" as a research paper in 1996.

## II. PHOTONIC CRYSTAL FIBER

Photonic crystal fiber is a type of optical fiber that is fully dependent on the properties of photonic crystals. In other words, we can say that photonic crystal fiber is a kind of optical fiber that is made of internal textured capillaries, which is a hexagonal lattice filled with air. Generally, photonic crystal fiber is made from fiber microstructure in cross-sectional; in which one or more material is used and which surrounds the core is called "Cladding". For example, the first time that Philip Russell gave the theory of photonic crystal fiber; the photonic crystal fiber is

made of hexagonal lattice air holes, whose core is either a solid or a hollow.

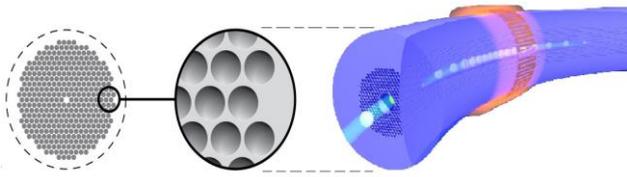


Figure 1: Basic Structure of hollow core photonic crystal fiber.

(Source: [https://commons.wikimedia.org/wiki/File:Photonic\\_crystal\\_fiber.jpg](https://commons.wikimedia.org/wiki/File:Photonic_crystal_fiber.jpg))

Therefore, photonic crystal fiber is also known as micro-structured fibers (MFs), holey fibers (HFs) or micro structured optical fibers (MOFs). In this way, combining the properties of optical fiber and photonic crystals, a series of new and unique properties has been prepared which cannot be obtained from traditional fiber. Although traditional optical fiber performs very well in telecommunications and other applications, but there are some limitations in designing and fabrication process (i.e limited material choice and modal cut-off wavelength). But on the other side in PCF we have the freedom to change many parameters (lattice pitch, air hole shape and diameter, type of lattice and refractive index of the glass), and this is the reason that the design of PCF is very flexible in comparison to the traditional optical fiber design. By changing the structure and materials in PCF it is possible to get desired dispersion properties.

Photonic crystal fiber has attracted significant attention towards researchers due to their design simplifications, their flexibility in withstanding with various applications and due to their excellent optical properties. Apart from them features like Endless Single Mode Operation, low confinement loss [37], high birefringence [38-39], high nonlinearity [40], ultra-flattened dispersion characteristics it is provided to be very useful in the field of communication.

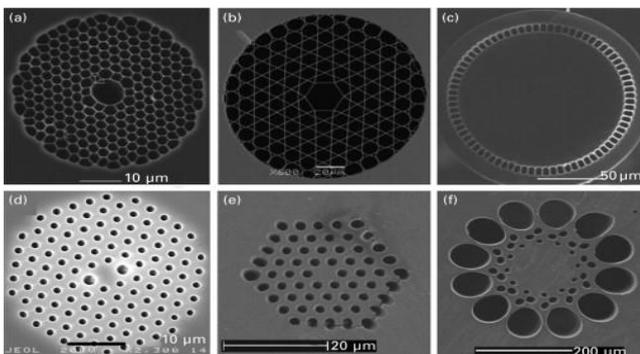


Figure 2: Different types of example of fabricated microstructure fibers (MF): (a) Silica hollow-core PCF

(b) Silica hollow-core kagome lattice fiber (c) silica hi-NA fiber (d) Silica birefringent fiber (e) single-mode microstructure polymer optical fibers (MPOF); (f) high bandwidth MPOF [27-28].

By the way, most photonic crystal fibers are made by silica glass, but other materials are also used to achieve particular optical properties (like high optical non-linearity and low or zero dispersion). Nowadays Researchers have more interested in using polymers. Where many types of structures have been explored includes ring-structured fibers, graded index structures and hollow core fibers. Such optical fibers are called “MPOFs” i.e. micro-structured polymer optical fibers.

### III. MAJOR TYPES OF PHOTONIC CRYSTAL FIBERS

Along with the increase in technology, many new types of PCFs have been researched. But here we will mainly study about two PCFs, which are as follows:

#### (a) Bragg fiber

If told in true sense, then Bragg Fibers is a special case of photonic crystal fiber, which is composed of the concentrated system of the dielectrics around the solid core or the hollow core. In such fibers, Bragg Mirror is used in cladding. Some theoretical research tells us that hollow core Bragg fibers can be feasible for achieve large refractive index contrasts and low dispersion. Although practically Hollow Core fibers have been tested and results have been received from the test, compared to conventional fiber, there are very little wavelength ranges losses in hollow core Bragg Fibers.

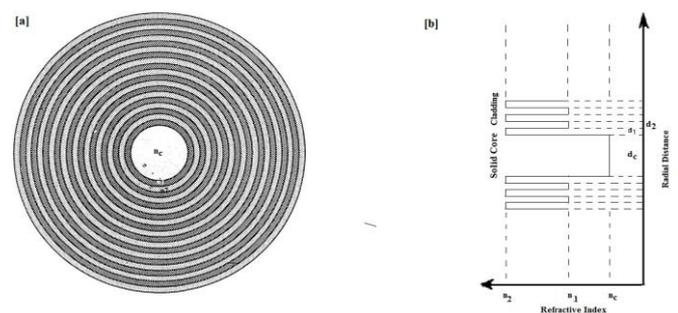


Figure 3: [a] Schematic of a Bragg fiber, [b] the radial index profile. (Source: DOI: 10.1109/JLT.2004.841260)

Here  $n_c$  is refractive index of Core,  $n_1$  is refractive index of even layers and  $n_2$  is refractive index of odd layers. Similarly  $d_c$  is diameter of core,  $d_1$  is diameter of even layers and  $d_2$  is diameter of odd layers.

#### (b) Hollow Core PCFs

The advantage of photonic crystal fiber after Bragg fiber

is that it requires less refractive index contrasts (such as air holes or vacuum holes in silica material) to obtain photonic gaps. The hollow-core photonic crystal fibers were divided into two parts from its first development. The first mechanism is photonic band gap (PBG) and the second mechanism is inhibited coupling between the cores and cladding (IC). By the way, both of the fibers have the same characteristics, guiding light in the hollow core and exhibiting microstructure cladding. But if you talk about specific differences, in case of confinement loss, both are different. Transmission losses in PBG HC-PCF can be less than the basic limits of the conventional optical fiber. However, its optical bandwidth is limited of the cladding PBG below the vacuum line in the effective index-frequency space. PBG guide HC-PCF also has a hidden passage that there is the existence of the interface modes (surface modes) located around the silica core. The guidance of light in the hollow core MOFs can be achieved only by the effect of photonic band gap.

### (c) Solid Core PCFs

As we already know that photonic crystal is a special type of fiber MOF. Due to easy fabrication, solid core PCF is a most common type of PCF. Like a conventional optical fiber, the core refractive index is always higher than the refractive index of cladding in solid core PCF. And that's why for solid core PCF is said that guidance is due to modified total internal reflection.

## IV. FABRICATION OF PHOTONIC CRYSTAL FIBERS

Traditional optical fiber is manufactured in two ways: First is fabrication of a fiber preform and second is drawing of this using a high temperature around 1900°C. In the last 3-4 decades, Fabrication Techniques that have been developed for traditional optical fibers have been proven relevant even today. Various types of vapor deposition techniques have also been developed in the last decades, in which vapor axial deposition (VAD) [33], modified chemical vapor deposition (MCVD) [26] and external vapor deposition (OVD) [29-32] are the main techniques. Doping of other metals in the silica glass can be controlled with the help of these techniques. Holes are made first by drilling process to add material in PCF. To provide an external abnormality, the cutting surface of the outer surface is processed, which gives rise to an asymmetric core. However, hundreds of holes are constructed in the drilling process, but in the last few years some simple and different work has been developed in comparison to it. These techniques, used in conjunction with solid silica rods and silica capillary tubes, are called hand-stacking techniques, which are comparatively faster, less costly and flexible than the earlier process.

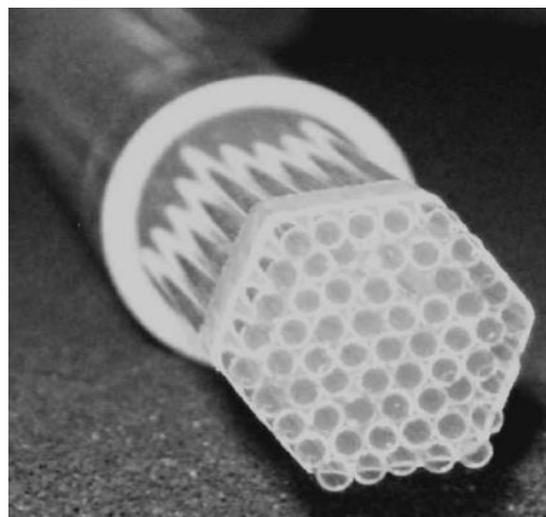


Figure 4: Image of a standard stacked preform photonic crystal fiber. (Source: DOI: 10.1016/j.electacta.2004.03.026)

It should be noted that the method employing circular elements, however, introduces additional air gaps in the fiber preform. These air gaps are located in the centers of three adjacent tubes / rods, so these are called interstitial holes.

The drawing of silica-based photonic crystal fibers are done at approximately 1900°C in the traditional drawing tower. The main reason for keeping temperature 1900 °C is to maintain surface tension or otherwise there is a risk of collapse of air holes. However, in some new research this temperature has been reduced. But it can definitely be said that there is an important role in properties like time dynamics and temperature variations in fabricating any PCF.

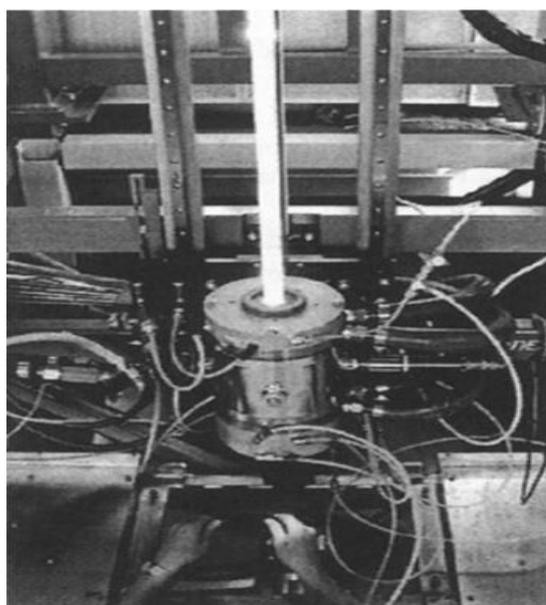


Figure 5: Drawing of a photonic crystal fiber from a preform at a temperature around 1900°C. (Copyright by Crystal Fiber AIS).

## V. COMPARATIVE STUDY OF COMMERCIAL PHOTONIC CRYSTAL FIBERS

Photonic crystal fiber is the best medium of digital communication in today's time. At present, there are a lot of companies in the market who make commercial PCFs and marketing them. These are: Thor labs, NKT photonics, Newport Optics, Coherent manufactures, Edmund Optics designs and manufactures, IPG Photonics develops and manufactures, Energetiq, ALIO, Ophir etc.

Parameter	F-AIR-11/1550	HC19-1550	HC-1550
Buffer Coating Material	Single Layer acrylate	Single Layer acrylate	Single Layer acrylate
Cable Diameter (mm)	2.5	2.5	2.5
Cladding Diameter ( $\mu\text{m}$ )	120	$115 \pm 3$	$120 \pm 2$
Coating Diameter ( $\mu\text{m}$ )	220	$220 \pm 30$	$220 \pm 30$ $\mu\text{m}$
Core diameter ( $\mu\text{m}$ )	10.9	$20 \pm 2$	$10 \pm 1$
Numerical aperture	0.12	$0.13 \pm 0.03$	0.12
Transmission loss (dB/km)	< 30 dB/km	< 20 dB/km	< 30 dB/km

Table 2: Properties of Commercial HC-PCF

## VI. REVIEW OF LITERATURE

The various issues which come under the Photonic crystal fiber will be the different properties of PCF under which the research papers are categorically arranged.

**[R. Buczynski, 2004]** Research paper written by R. Buczynski was published in Volume 106 Issue 2 by the journal "ACTA PHYSICA POLONICA A" in 2004. As this paper is titled, in this paper has given all important information about photonic crystal fiber. In this research paper, it has been explained in details about Introduction of PCFs, Development of PCFs, Types of PCFs, Fabrication and Modeling Methods of PCFs. In the introduction part, the author said that if some parameters (lattice pitch, air hole shape and diameter, refractive index of the glass, and type of lattice) are taken into account, then the PCF can be designed flexibly. Likewise, the author explained that there are two types of guiding mechanisms in the PCF, first index guiding mechanism and second photonic band-gap mechanism. Published with 55 references, this research paper is important for all those people who want to understand the PCF deeply.

**[Arti Agrawal et. al. 2008]** Aarti Agarwal and co Authors gave a new concept in 2008, regarding which a research paper has published in Volume 33 issue 22 of OPTICS LETTERS Journal. In this research paper, they explained how better results can be achieved by designing a golden spiral photonic crystal fiber. The fiber that is investigated shows a large modal birefringence peak value of 0.016 at an operating wavelength of 1.55 micrometer and exhibits highly tuneable dispersion with multiple zero dispersion wavelengths and also large normal dispersion. In this paper authors has discussed about birefringence and dispersion properties of the GS-PCF.

**[Muhammad Nazmul Hossain et. al. 2010]** Researchers designed a new PCF Structure in this research paper, and outputs were obtained by passing the Visible Light between 570 nm to 630 nm range. If we talk about structure design, Researchers have designed 11 Spiral Arms and 6 Air Ring's PCF in which 4 large elliptical air holes are designed surround the core and act as inner cladding. Due to low threshold damage in soft glass here the germanium-doped silica is used as the core material. In this research paper, the authors have explained the Basis of PCF and step by step design process very well. According to this paper, ultra flattened dispersion ( $-0.05064 \text{ ps} / \text{nm}^2 \cdot \text{km}$ ), high nonlinearity parameter ( $1433\text{W-1km-1}$ ), high Raman gain ( $698.478\text{W-1km-1}$ ) and very low confinement loss ( $0.00161 \text{ dB} / \text{km}$ ) at 600 nm outputs can be obtained by using same design and parameters. This research paper has published in 2010 by a world-famous journal "PHOTONICS LETTERS OF

POLAND" in its Volume 2 Issue 3. Although this paper is not about what other possibilities may have in future in this field, but we must know this new concept of PCFs design.

**[Pham Hong Thai et. al. 2014]** Moving forward the work of Aarti Agarwal in 2014, Pham Hong Thai et al. presented a research paper, which was published by the IEEE Digital Library. They designed a golden spiral photonic crystal fiber whose core was made by Germanium (GeO<sub>2</sub>) doping. This type of PCF called GGS-PCF. The purpose of designing such a PCF was to achieve very high nonlinear coefficient and flattened dispersion. If we pay attention to the conclusion of the paper, then it is clear that Researchers have achieved a very high nonlinear coefficient of about 108 W<sup>-1</sup>·km<sup>-1</sup> and dispersion flattened bandwidth of 170 nm. At center wavelength of 1.55 μm, dispersion and dispersion slope are calculated -0.322 [ps/(nm·km)] and -0.00086 [ps/(nm<sup>2</sup>·km)]. In this research paper, the authors have explained the dispersion, dispersion slope, the Effective area and the Confinement loss through the graph. The PCF designed by the researchers includes 24 air holes in which the first 8 holes are of equal size called "d1" and the remaining 16 air holes are of the same size called "d2". For the purpose of getting the best results, the size of 8 air holes was gradually reduced and the core size was increased. After this, the size of the outside 16 air holes was changed too. In this research paper, Sellmeier equation has been used to know the refractive index of silica and core material.

**[S. Revathi et. al. 2015]** In this research paper researchers designed and explained new structure of photonic crystal fiber called soft glass spiral photonic crystal fiber. We reviewed this research paper very well and received very important information, which we are sharing with you. In this paper, the authors successfully achieve high nonlinearity of 5828 W<sup>-1</sup>·km<sup>-1</sup> and High birefringence of  $2.96 \times 10^{-2}$  at 1.55 μm for the ellipticity ratio of 3.5 and high negative dispersion of -1546.6 ps/nm·km at 0.850 μm for the ellipticity ratio of 2. Authors have designed a new structure using software Comsol 3.5 and used FEM (finite element method) to find out boundary problems. By reading this paper, we find out that by designing this type of structure, excellent results can be obtained in comparison to conventional optical fibers. Here the author has designed eight arrays and five rings of photonic crystal fiber, which uses soft glass (SF-57) as the core material. In this paper, we found that the authors kept the constant core (1.05 micrometer) and air holes (0.21 μm) diameter. By the way, the authors analyzed the light passing between 0.65 μm to 1.95 μm Wavelength range, but they got good results on some Wavelength points. For example they got high negative

dispersion of -1546.6 ps/nm·km at 0.850 μm. Here Researchers have also explained the properties of PCFs as a great way. This research paper has published in 2015 by a world-famous journal "Optica Applicata" in its Volume 2015 Issue 1. This research paper can be further extended. In this research paper, the authors have used only one core material, but more core materials can be used and compared to each other.

We have reviewed a lot of research papers, but the main papers are being discussed in this book chapter. After reviewing the research papers, some of the key things have been revealed about which we are discussing here.

### ***1. Is Photonic Crystal Fiber Better than Optical Fiber?***

Although practically it is not correct to compare each other. Because the primary principle of both is the same but the secondary principle is different. According to today's time, photonic crystal fiber is undoubtedly better than optical fiber. And this is the reason to increase commercial use of photonic crystal fiber. Compared to optical fibers, the output of photonic crystal fiber (low dispersion, low confinement losses) is better.

### ***2. Can output results of the photonic crystal fiber be manipulated by changing the structure parameters?***

Yes, Changes to some parameters of PCF can change the results as well. For example, we can change size of air holes, number of rings, pitch, core size, material of core and methods of boundary condition.

### ***3. Can there be other core material rather than silica in PCF?***

Yes, In maximum case Silica is used as a core material, but some other materials have also been used in some papers (like Ge doped silica, germanium). But there are still many possibilities to use other materials like chalcogenide glass, borosilicate glass etc.

## **VII. ELLIPTICAL CORE SPIRAL PHOTONIC CRYSTAL FIBER**

The fastest developments in fiber optics communication compel the residual waveguide dispersion along the transmitting wavelength distance. Among all the optical sources available the photonic crystal fiber are widely used now a days in communication medium. So the elliptical core spiral photonic crystal fiber is the best approach to achieve nearly zero dispersion in the selected wavelength region. The various properties of Photonic crystal fiber like dispersion, confinement factor, transmission curve and effective refractive index have been analyzed for this structure. Here four different

designs have been proposed with varying parameters for different materials. Here we have considered Borosilicate crown glass [22], Chalcogenide glass [14-21] and Silica glass [23] as a PCF material. The proposed structure contains elliptical (Horizontal and Vertical) core of air holes which are surrounded by circular air holes.

As we know that an equiangular spiral PCF have higher nonlinearity at near infrared wavelength region of 1064 nm and show the potentials to be considered as pertinent in the fabrication of PCF through super-continuum generation (SCG) process.

This chapter includes four different designs of elliptical spiral PCF. In the first and second designs the core air hole is placed horizontally elliptical while in the third and fourth designs the core air hole is placed vertically elliptical. All the air holes of cladding have been arranged according to the center rings. The air hole in which the inner ring is the smallest, whose diameter has been named D1. In this way, the diameter of the air hole will be in increasing order i.e., the D4 will be larger than the D1. The spiral lattice has six arms, each containing four air holes; the first ring of circular holes has a radius of  $r_1$ . The diameter of the air holes is enlarged step by step with the aim of obtaining low dispersion and confinement loss. As previously mentioned, the silica is taken as the core material and the elliptical air hole made in the core is semi-minor axis of "a" and semi-major axis of "b".

The proposed design of elliptical spiral PCF is designed by keeping minor axes at  $0.25 \mu\text{m}$  and major axes at  $0.50 \mu\text{m}$  for the **elliptical** core. This elliptical slot in core region is used to provide better confinement modes. These elliptical core regions also offer increased freedom in modal distribution. After that the cladding air holes are used to vary with  $0.5 \mu\text{m}$  to  $1.25 \mu\text{m}$  range. It is varying as  $0.5 \mu\text{m}$ ,  $0.75 \mu\text{m}$ ,  $1.0 \mu\text{m}$  and  $1.25 \mu\text{m}$  respectively for increasing layers in circular shape.

In the proposed structure the angle between two rings can be maintained at  $180/N^\circ$ . Here N is known as the number of arms in the proposed structure. The value of N can be selected as that there should be no overlapping of air holes. In this way the distance between two adjacent air holes in each arm varies in term of geometric progression.

### 7.1 Final Structure Parameters-

For Vertical elliptical core

**Design 1:** D1 =  $0.5 \mu\text{m}$ , D2 =  $0.75 \mu\text{m}$ , D3 =  $1.0 \mu\text{m}$  and D4 =  $1.25 \mu\text{m}$  (When Pitch  $\wedge$  =  $2.0 \mu\text{m}$ )

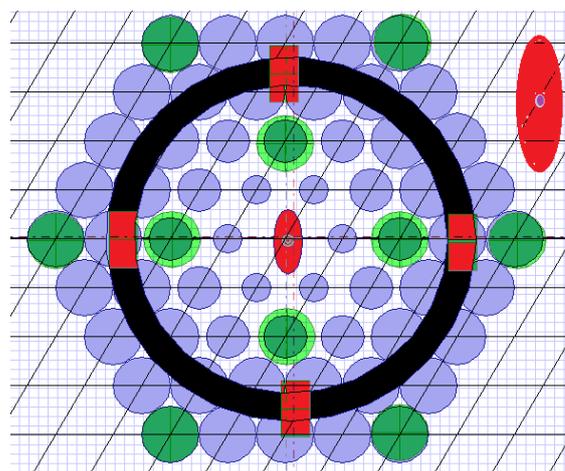
**Design 2:** D1 =  $0.5 \mu\text{m}$ , D2 =  $0.75 \mu\text{m}$ , D3 =  $1.0 \mu\text{m}$  and D4 =  $1.25 \mu\text{m}$  (When Pitch  $\wedge$  =  $1.0 \mu\text{m}$ )

For Horizontal elliptical core

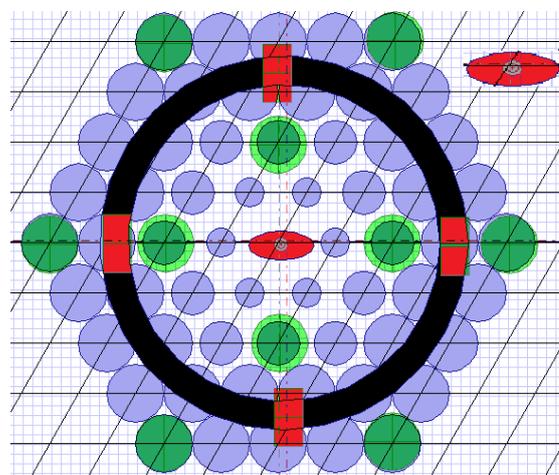
**Design 3:** D1 =  $0.5 \mu\text{m}$ , D2 =  $0.75 \mu\text{m}$ , D3 =  $1.0 \mu\text{m}$  and D4 =  $1.25 \mu\text{m}$  (When Pitch  $\wedge$  =  $2.0 \mu\text{m}$ )

**Design 4:** D1 =  $0.5 \mu\text{m}$ , D2 =  $0.75 \mu\text{m}$ , D3 =  $1.0 \mu\text{m}$  and D4 =  $1.25 \mu\text{m}$  (When Pitch  $\wedge$  =  $1.0 \mu\text{m}$ )

With the parameter selected we have designed elliptical spiral horizontal and vertical PCF of 5 layers, which is shown below in figure 6.



[a]



[b]

Figure 6: Designed Structure Photonic Crystal Fiber (a) Vertical Elliptical Core (b) Horizontal Elliptical Core

In the similar manner by considering same parameters we also proposed the same structures but for different materials. In the end the results so obtained on simulation have been compared and analyzed. All these results are plotted in term of graph and final comparison is tabulated below.

Figure 7 below shows the comparative analysis of total dispersion of silica material for all four designs. It gives that design three shows approximately equal to zero

dispersion between 0.5 to 1.2 micrometer wavelength regions.

Analysis of Total Dispersion in Chalcogenide Glass Photonic Crystal Fiber

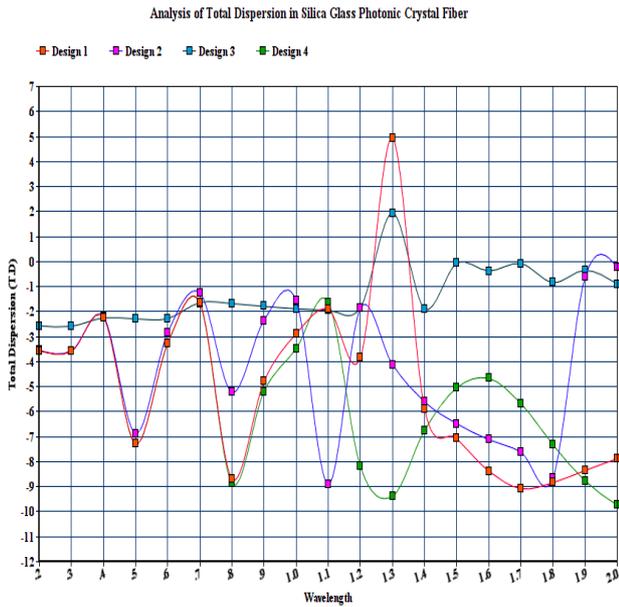


Figure 7: Analysis of Total Dispersion in Silica Glass PCF for various design

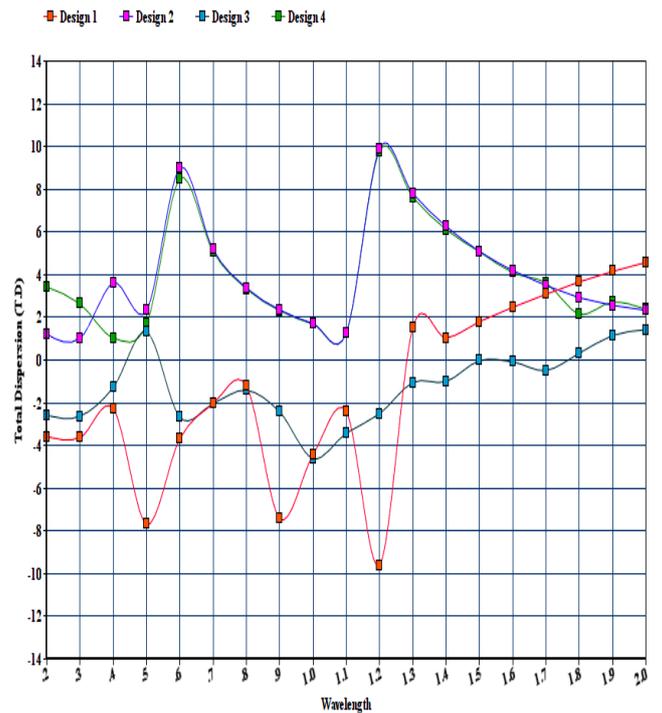


Figure 9: Analysis of Total Dispersion in Chalcogenide Glass PCF for various designs

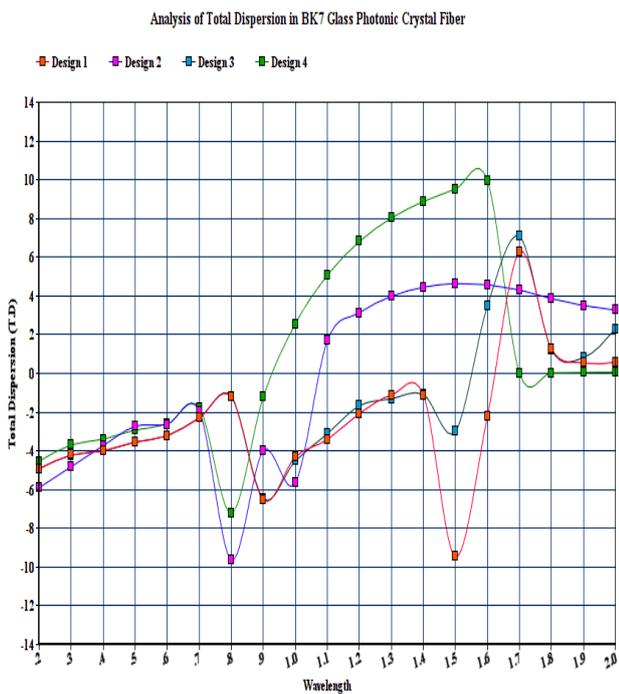


Figure 8: Analysis of Total Dispersion in BK7 Glass PCF for various designs

Figure 8 above shows the comparative analysis of total dispersion of BK7 material for all four designs. It gives that design four shows approximately equal to zero dispersion in the 1.7 to 2.0 micrometer wavelength region.

Figure 9 above shows the comparative analysis of total dispersion of chalcogenide glass material for all four designs. It gives that design three shows approximately equal to zero dispersion in the 1.3 to 2.0 micrometer wavelength region.

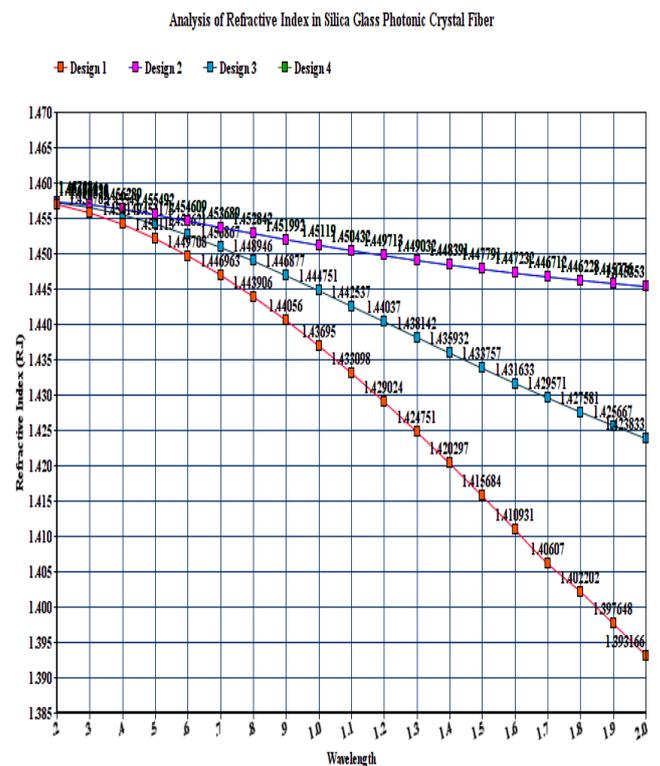


Figure 10: Refractive Index of Silica glass PCF for various designs

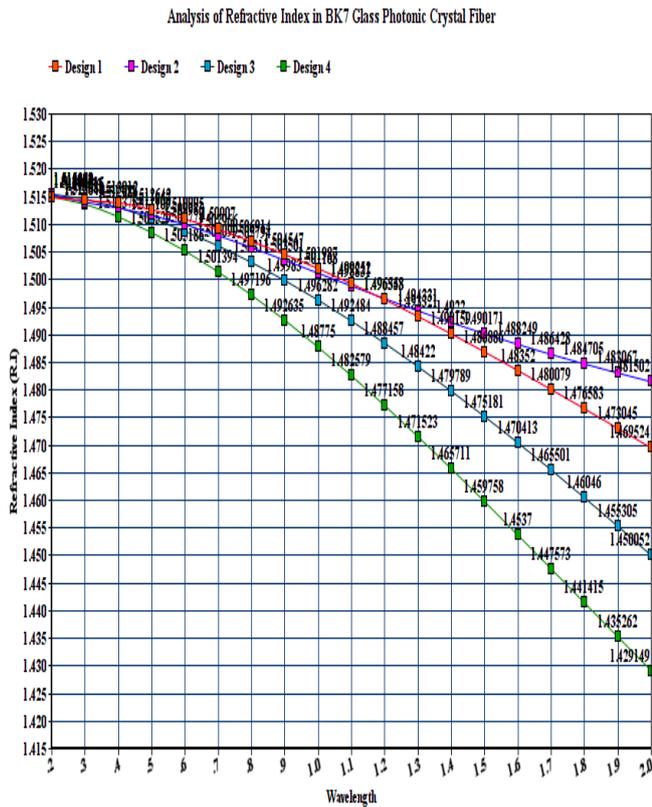


Figure 11: Refractive Index of BK7 glass PCF for various designs

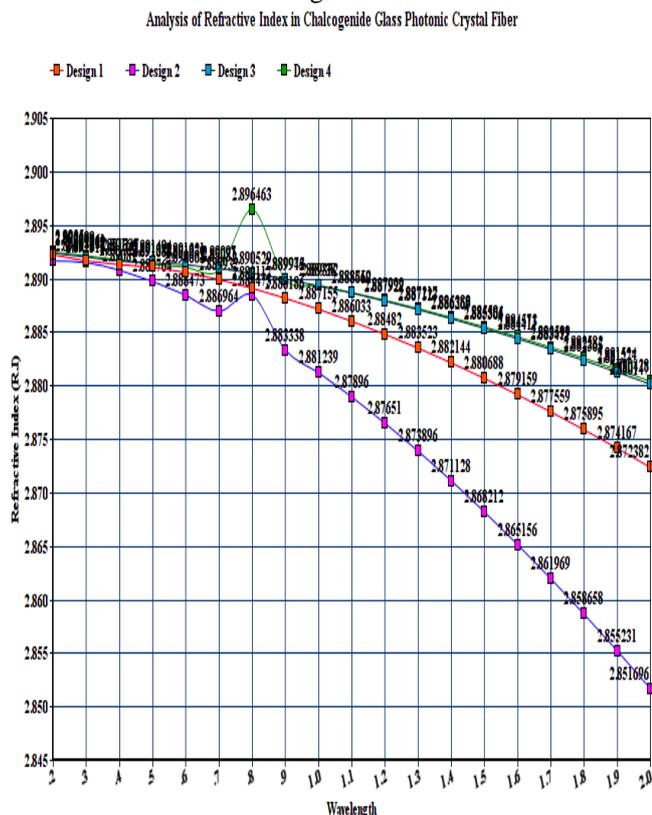


Figure 12: Refractive Index of Chalcogenide glass PCF for various designs

Above figures 10, 11, 12 represent the refractive index of all four designs for silica, BK7 and chalcogenide glass material respectively. It shows that refractive index of these materials can have approximately same value of refractive index as the material itself has.

On comparison in different material we found that Silica glass shows superiority due to its few order magnitude in the visible region. Therefore, in this chapter, we have emphasized that elliptical silica spiral PCF design architecture achieve nearly zero dispersion fiber (NZDF) with lower confinement factor and higher nonlinearity in the visible region. The proposed type of PCF offers homogeneity in output distribution over wide application in the 300nm to 2400nm wavelength region. It allows a greater coupling efficiency. The wavelength dependence of proposed spiral silica glass PCF is based on sellmeier's formula. This Sellmeier equation has been used to get the refractive index of material at selected wavelengths region to account for the material dispersion in computing the total dispersion of the fiber.

$$n^2 - 1 = \sum \frac{A_1(\lambda)^2}{(\lambda - \lambda_1)(\lambda + \lambda_1)}$$

All the comparison and analysis has been done on the microstructured fiber (MOFs) with hexagonal-lattice of elliptical air holes. But, here we have not considered the polarization issue anywhere. However, a negative average dispersion over the wavelength range of 1350 nm to 1550 nm has been reported for the proposed structure with a dispersion variation of about 5 ps/nm km, where one elliptical air hole is introduced in the core.

The proposed structure can be used as residual dispersion compensating fiber (RDCF), which is an EC-SPCF having air hole arrangement of silica glass. The angular position of each air hole in an arm is increased by than the previous one.

For this work, a Full-Vectorial Finite-Element Method (FVFIM) has been used to compute the birefringence. It can be defined as the difference in the effective refractive indices of the two orthogonal polarization modes of the EC-SPCF. The number of air holes is kept constant in five layers of rings. With this consideration the design is proposed being inspired by the asymmetric seed distribution pattern. Four elliptical air holes surrounding the core introduced and increasing radii of air holes towards the outer edge of cladding is considered. It allows the determination of optical mode field distributions of the pump and signal over the entire cross section of the fiber.

Tailoring the dispersion to achieve flat, anomalous dispersion with small slope and zero crossing near at the pump wavelength is an extremely important aspect in SCG. To obtain near zero ultraflattened dispersion in the middle of the visible region, we studied the tapering in and tapering out effect of the proposed geometry. Thus, we optimized the proposed fiber dimension to tailor both the ZDWs in the visible region along with its high nonlinearity parameter.

The main advantage of proposed silica spiral PCF is due to its compactness structure it gives us small core area which in turn results in large nonlinearity. A perfectly matched layer (PML) is created around the structure for perfect absorption of the waves. PML layer width which we used here is 1  $\mu\text{m}$ . We tailor the semi-major axis and semi-minor axis of the elliptical defect air hole. The main advantage of using this spiral lattice is that the number of air holes we use here gets reduced by a large number when compared to the normal triangular lattice structure which leads to a small core area. Because of this small core area, the effective mode area will be less.

## 7.2 Key data for the micro structured optical fiber is listed in below table.

Average pitch:	1.5 $\mu\text{m}$
Average hole diameter:	2.3 $\mu\text{m}$
Core diameter:	1.0 $\mu\text{m}$
Splice loss:	0.3 dB
Numerical aperture:	$\sim 0.5$
Birefringence:	$1.1 \cdot 10^{-4}$
Nonlinear coefficient:	$\sim 20 (\text{Wkm})^{-1}$

Several properties of PCF like birefringence, dispersion, effective mode area, splice loss and nonlinearity are discussed.

### A. Birefringence

Birefringence plays an important role in fiber optics and various sensing applications where light has to converse a linear polarization, generally high birefringence are required. Linearly polarized light rays in both (parallel and perpendicular) direction show uneven effective refractive indices i.e.  $n_e$  and  $n_o$  for unexpected and regular emerging rays respectively. When an beam of light of un-polarized ray passes through the material with a non-zero acute angle to the optical axis, then the perpendicularly polarized vector faces the refraction at an angle as per the normal law of refraction and its opposite component at a non-standard angle shown by the difference between the two effective refractive indices called as the birefringence magnitude.

$$\Delta n = n_e - n_o$$

The difference between the real part value of the effective indices of the pronounced fundamental core Eigen modes along x and y axis LP01x and LP01y

$$B = | \text{Re}(n_{x_{\text{eff}}}) - \text{Re}(n_{y_{\text{eff}}}) |$$

### B. Confinement Loss

The occurrence of finite air holes in the core region causes leakage of optical mode from inner core region to exterior air holes and that is unavoidable which results in confinement losses. Fundamental mode is used to calculate confinement loss from the imaginary part of the complex effective index  $n_{\text{eff}}$ , using

$$\text{Confinement loss} = (40\pi/\ln(10)) \text{Im}(n_{\text{eff}}) [\text{dB/km}]$$

Where  $\text{Im}$  is the imaginary part of the  $n_{\text{eff}}$  Confinement loss is the leaking of light from core to exterior matrix material. Confinement loss can be changed according to the parameters like number of air holes, number of layers, air hole diameter and the pitch.

**C. Chromatic Dispersion** The sum of waveguide and material dispersion contributes to the chromatic dispersion or total dispersion. The material dispersion is characteristic to the material used to fabricate the fiber whereas the waveguide dispersion can be varied by changing the design parameter of the waveguide thus total dispersion is allowed to be altered. The material dispersion can be neglected when  $nm(\lambda)$  becomes constant and the real part of the effective index of refraction  $n_{\text{eff}}$  contains the dispersion information  $D$ .

$$D = -(\lambda/c) (d^2 \text{Re}(n_{\text{yeff}}) / d\lambda^2)$$

Where  $c$  is the speed of light in vacuum and  $\lambda$  is the operating wavelength.

**D. Nonlinearity** High optical power density is provided by a small effective area for which the nonlinear effects would be significant. The nonlinear effective or nonlinearity is closely related with the effective area and also nonlinear coefficient of the PCF background material in associated with the operating wavelength  $\lambda$ .

**E. Splice Loss** Splice loss is another important parameter for fiber design consideration. Generally, for longer distance signal carrying or longer distance optical communication aspect two fibers are experienced by joining or splicing. It is very sensitive issue because due to small mismatch of the fibers during the splicing will led to the large signal attenuation. Splice loss occurs during the splicing between PCF and the single mode fiber.

## VIII. RESULTS & DISCUSSION

We found various losses in the proposed structure and they occur due to various reasons like absorption, due to intrinsic material, due to fabrication and due to confinement loss. We can overcome this fabrication loss by carefully optimization of the fabrication process. The confinement loss is use to quantify the light with minimum loss. It can be view as an additional form of loss occurred in PCFs. By increasing the number of air holes in cladding region we can overcome this type of loss. As shown in the figure, for optimized design the value of the confinement loss is about 0.00111 dB/km at 1.50  $\mu\text{m}$ . The obtained confinement loss is more than approximately 355 times greater than the fundamental modes, which shows that only the fundamental mode can be used to guide in the elliptical core design. Therefore, we can say that the proposed PCF can be effectively operates as a single-mode fiber.

Finally is it assumed that due to exponentially advancements in PCFs fabrication technologies, it is

possible to fabricate our proposed structure of spiral Elliptical core PCF without any major complications. The proposed PCF can be fabricated by using improved stacking and center vacuuming method of fabrication.

Someone can use this method of fabrication as follows: Firstly, a PCF with a single elliptical air hole in the core region can be fabricated. Then, magnetron sputtering technology can be used. At last, the chemical vapor deposition (CVD) method can be used to deposit glass material in the elliptical air hole.

## IX. CONCLUSION

It is concluded that a simple elliptical spiral PCF has been proposed which shows an average dispersion of  $1.4 \text{ ps nm}^{-1} \text{ km}^{-1}$  with ultra flattened dispersion between  $1.2$  and  $1.9 \text{ ps nm}^{-1} \text{ km}^{-1}$  over the wavelength range of  $20 \mu\text{m}$ . It has been discussed that the spiral PCF gives confinement loss about  $0.0011 \text{ dB km}^{-1}$  for five rings at  $1.0 \mu\text{m}$  wavelength. The refractive index of various material so calculated is approximately equal to the material itself. The Transmission factor curve shows that it is approximately  $0.36$  at  $50 \text{ nm}$  ranges. Among all four designs it is clear that silica glass shows approximately nearly zero dispersion for design three between  $0.5$  to  $1.2$  micrometer wavelength ranges. Similarly Silica glass again shows approx  $1.456$  refractive index for design three between  $0.2$  to  $0.9$  micrometer ranges. So we can consider this design as shown above in the figure for practical applications in photonic crystal fibers. So finally it is concluded that apart from all the materials available for PCF Silica photonic crystal fibers is mostly used as a material for the PCF due to its properties and behavior shown above.

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