A

DISSERTATION REPORT

ON

DESIGN AND ANALYSIS OF SPIRAL PHOTONIC CRYSTAL FIBER WITH CIRCULAR AND ELLIPTICAL AIR HOLES FOR FLATTENED DISPERSION AND BIREFRINGENCE PROPERTIES

is submitted as a partial fulfillment of the

MASTER OF TECHNOLOGY IN ELECTRONICS AND COMMUNICATION ENGINEERING

BY

JULIE DEVI

(2015PEC5306)

UNDER THE GUIDANCE OF

Dr. RITU SHARMA

(Assistant Professor, ECE, MNIT, Jaipur)

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY JAIPUR

JUNE 2017

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY

JAIPUR (RAJASTHAN)-302017

CERTIFICATE

This is to certify that the dissertation report entitled "**DESIGN AND ANALYSIS OF SPIRAL PHOTONIC CRYSTAL FIBER WITH CIRCULAR AND ELLIPTICAL AIR HOLES FOR FLATTENED DISPERSION AND BIREFRINGENCE PROPERTIES"** submitted by **JULIE DEVI** (2015PEC5306), in partial fulfilment of Degree **Master of technology** in **Electronics and Communication Engineering during** academic year 2016-2017. To best of my knowledge and belief that this work has not been submitted elsewhere for the award of any other degree.

The work carried out by her has been found satisfactory under my guidance and supervision in the department and is approved for submission**.**

Date:

Place:

Dr. Ritu Sharma

Assistant Professor

Department of electronics and communication

MNIT Jaipur

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY

JAIPUR (RAJASTHAN)-302017

DECLARATION

This is to certify that the dissertation report entitled "**DESIGN AND ANALYSIS OF SPIRAL PHOTONIC CRYSTAL FIBER CIRCULAR AND ELLIPTICAL AIR HOLES FOR FLATTENED DISPERSION AND BIREFRINGENCE PROPERTIES"** being submitted by me in partial fulfilment of degree of **Master of Technology** in **Electronics & communications** during **2016-2017** in a research work carried out by me under supervision of **Dr. Ritu Sharma**, and content of this dissertation work in full or in parts have not been submitted to any other institute or university for award of any degree or diploma. I also certify that no part of this dissertation work has been copied or borrowed from anywhere else. In case any type of plagiarism is found out. I will be solely and completely responsible for it.

Place: **JULIE DEVI**

Date: M.Tech.(ECE)

2015PEC5306

MNIT Jaipur

Acknowledgement

This Dissertation report on "**DESIGN AND ANALYSIS OF SPIRAL LATTICE PHOTONIC CRYSTAL FIBER CIRCULAR AND ELLIPTICAL AIR HOLES FOR FLATTENED DISPERSION AND BIREFRINGENCE PROPERTIES"** is carried out under the valuable guidance of supervisor Dr. Ritu Sharma (Assistant professor, ECE, MNITs, Jaipur).

It is my privilege to express my deep sense of gratitude to her for her great efforts, ever helping attitude, critical and valuable comments and constant inspiration with a keen interest in making this dissertation report.

I am highly thankful to all faculty members of Electronics and communication department for having their direct and indirect co-operation.

Finally, I gratefully acknowledge my parents and all my friends for their support and co-operation.

Julie Devi

(2015pec5306)

Table of Contents

List of Figures **Page No.**

List of tables

List of Abbreviations

PCF	Photonic Crystal fiber
FEM	Finite Element Method
PBGF	Photonic Fiber Bragg Grating
LFM	localized Function Method
SIF	Step Index Fiber
HC-PCF	Hollow Core Fiber
FDTD	Finite Difference Time Domain
TIR	Total Internal Reflection
FBG	Photonic Brag grating
PMF	Polarization maintaining fiber
DCF	Dispersion Compensation Fiber

Abstract

In this thesis, spiral PCF with circular and elliptical air hole is designed and analysed for various optical properties. All layouts are simulated by Comsol 5.1 software. In this report, spiral type photonic crystal fiber (PCF) designed by varying diameter of air hole and arrangement of air hole in cladding region. Two types of layouts **1)** circular air hole spiral PCF **2)** elliptical air hole spiral PCF designed and reported in this thesis. In the first layout, the diameter of air hole is changed and all other parameters are kept constant. In this layout three different dimension configurations are considered with a) d=0.6µm b) d=0.8µm c) d=1µm of air holes. Low dispersion examined as compared to conventional PCF.

The second layout consists elliptical arrangement of air holes. This design is optimized for large flattened dispersion and high birefringence. Three configurations have been designed with three different dimensions. a) minor axis diameter =0.55µm, major axis diameter=0.45µm b) minor axis diameter=0.62µm, major axis diameter=0.40µm c) ellipticity ratio vary from first to last ring. These two designs have been compared with each other and examined for different propagation property of light waves such as dispersion, effective area, effective refractive index, and birefringence.

these layouts, silica is used as a substrate material having refractive index 1.45. It has been analysed that as we change the geometry of PCF all properties get changes. It has been observed that as the diameter of the air hole is changed, dispersion changes with wavelength and very high birefringence is obtained for elliptical air hole arrangement as compared to circular air hole PCF. Thus, the optimized design can be used as low flattened dispersion PCF for sensing application.

CHAPTER – 1

INTRODUCTION

1.1 Introduction

Since the introduction of conventional step index fibers, optical fibers have evolved into many forms in the 70s and later single material fiber where effective cladding structures determined the propagation of light. The principle objective was the transportation of light from one point to another whether by step index confinement or by band-gap confinement such as in Bragg fiber. We can use optical fiber in many applications like transporting high speed data, bio sensors Etc. the optical fiber can also use in Gas sensing application, strain or pressure measurement in bridges and high-power amplifier. Photonic Crystal Fibers (PCF) is a variant of the micro structured fibers with greater control of guiding properties. Such a vital Photonic Crystal fiber have large application area in nonlinear devices and high power optical fiber amplifier.

1.2 History of PCF

Optical fibers were discovered in the 1970s and are now the backbone of opticalcommunication systems due to a large amount of information they can handle. Particularly designed optical fibers are also used for many optical applications, including sensors, medicine, illumination and much more. Standard step-index optical fibers guide light through total internal reflection, which occurs only if the core has a larger refractive index than the outer cladding. The optical signal propagates in the core is completely reflected at the interface core/cladding and is, therefore guided in the core. First fiber is fabricated by Russell consist hexagonal lattice in silica fiber. These novel periodic structures were called photonic crystals. Only light with certain wave vectors can propagate in the structure If a defect or periodic structure is introduced in the is in the structure, the wavelengths forbidden in the periodic structure are now allowed to “stay” in the defect as the photonic crystal running along the air hole prevents them from “escaping”. The refractive index is not required to be higher than that of the periodic material. By using this idea light can be trapped inside a hollow core (defect). Therefore, light can even be guided in the air.[8]

1.3 Theory of PCF

In the last decade, photonic crystal fibers have been under rigorous study and due to the development of PCF and unique application, attracted huge research interest. PCF is a fiber which contains its different optical properties from particularly varying the design and arrangement of air holes in fiber which run through the length of the fiber, not from different glass composition. The simplest type of PCF has triangular lattice. Photonic crystal fiber is categorized into two types of mechanism 1) Photonic band Gap 2) Total Internal reflection

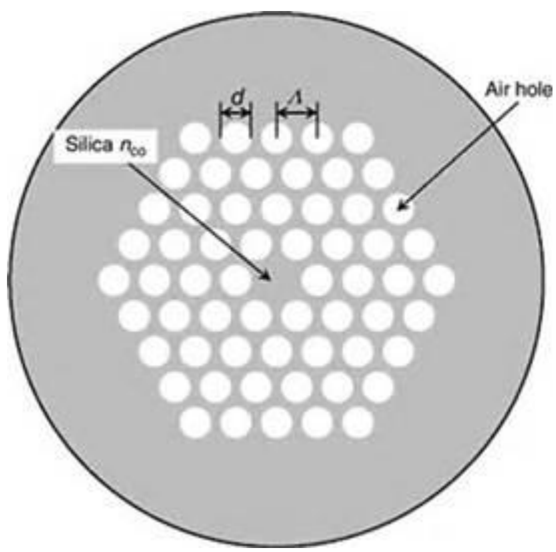

Fig 2.1 geometry of hexagonal PCF

1.3.1 Advantage of Photonic Crystal Fiber

- Better light confinement than conventional fibers
- Low dispersion
- Very low attenuation (holey fiber)
- More flexible than conventional fibers
- Many core fiber

1.3.2 Basics equations

Propagation of light in PCFs is described by Maxwell's equations. For no free charge or current, the following equations become applicable

$$\nabla . D = 0 \qquad \text{(a)}$$

$$\nabla \times H = \frac{\partial D}{\partial t}$$

$$\nabla . B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad (2.1)$$

$$\varepsilon(\mathrm{r},\omega) \;=\; \varepsilon(\mathrm{r}) \in R$$

$$\mathrm{D(r)} = \varepsilon(r) \times \varepsilon o \times E(r)$$

$$\mathrm{B} = \mu o \times H \qquad (2.2)$$

Inserting equation b into a

$$\nabla . \varepsilon(r) \times \epsilon o \times E(r,t) = 0$$

$$\nabla \times H(r,t) = \varepsilon(r) \times \varepsilon o \times \frac{\partial E(r,t)}{\partial t}$$

$$\nabla . \mu o . H(r,t) = 0 \quad (2.3)$$

$$\nabla \times E(r,t) = -\mu o . \frac{\partial H(r,t)}{\partial t}$$

Since Maxwell's equations are linear we can separate out the time dependence by expanding into

a set of harmonic modes

$$H(r,t) = H(r) . e^{j\omega t}$$

$$E(r,t) = E(r) . e^{j\omega t}$$

To obtain coupled equations we need the following ones

$$\nabla.\varepsilon(r).E(r) = 0 \quad (2.4)$$

$$\nabla \times H(r,t) = j\omega\varepsilon(r)\varepsilon o E(r)$$

$$\nabla.H(r) = 0$$

$$\nabla \times E(r) = j\omega.\mu o.H(r) \quad (2.5)$$

1.4 Guiding mechanism in PCF

1.4.1 Total internal reflection

In solid core PCF light, is comes from high refractive index core to lower refractive index cladding. Light is kept in the core by total internal reflection in photonic crystal fiber. In PCF, When the angle of incident is greater is greater than the critical angle, total internal reflection takes place in solid core fiber.

1.4.2 Photonic bandgap in photonic crystal fiber defects is created by introducing air hole in fiber and the photonic band gap is created.in this case light guidance mechanism is like electron conduction mechanism in solid-state physics. Photonic band gap structure offer opportunity to design new optical property in existing fiber. Due to the presence of air hole, light is confined in the core region and these modes guided along the defect through the fiber.

1.5 Properties of PCF

1.5.1 Confinement loss

The losses in PCFs occur for many reasons, such as Rayleigh scattering loss, intrinsic material absorption loss, macro and micro binding loss, and so on. Fabrication related losses can be reduced by carefully optimizing the fabrication process. The Periodic arrangement of air holes in PCF causes a decrease in optical confinement, is called Confinement loss. PCF is made by single material and so guided mode is leaky. The region of loss is that the refractive index of the core is same the refractive index of the cladding. Confinement loss depends on the structure and arrangement of air holes in PCF. We can alter the value of loss by changes the geometry of fiber. For analyzing the confinement loss, PML layer is applied to PCF. With the help of PML layer, we find the value of the imaginary refractive index and find the confinement loss.

$$\text{Confinement loss} = 8.686\times10^{6}\times ko\times im(n_{eff}) \qquad (dB/m)$$

1.5.2 Normalized frequency

The V parameter (normalized frequency) is commonly used in the design of conventional SIFs and is given by

$$V = \frac{2\pi a}{\lambda}\times\sqrt{n_{co}^2 - n_{cl}^2}$$

To finding the V parameter for PCF, its different nature is considered. V parameter of PCF given as

$$V_{PCF} = \frac{2\pi a}{w}\times\sqrt{n_{FM}^2(w) - n_{FSM}^2(w)}$$

Where $n_{FM}(w)$ is wavelength dependent refractive index of fundamental mode and n_{FSM}^2(w) is fundamental space filling factor. For single mode fiber V_{PCF} should be equal to π.

1.5.3 Effective modal area

The effective mode area A_{eff}, is computed using transverse electric or magnetic field vector of the whole cross-sectional area of the fiber. The effective area of the of the fiber core $A_{eff}$is defined as [2]

$$A_{eff} = \frac{(\iint|E_{t|}^2 dxdy)^2}{\iint|E_{t|}^4 dxdy}$$

Or

$$A_{eff} = \frac{(\iint|H_{t|}^2 dxdy)^2}{\iint|H_{t|}^4 dxdy}$$

where E_t and $H_t$is the transverse electric field vector and magnetic field vector respectively and the integration is done through the whole cross-sectional area of the fiber.

1.5.4 Chromatic dispersion

Effective refractive index of mode profile depends on wavelength. Relation between wavelength and refractive index is given by equation below

$$v=\frac{c}{n}$$

All optical source used for optical transmission emit light, in the band of spectral width $\Delta\lambda$, distributed around λ.so individual frequency component experienced different velocity so different frequency component travel with different speed and pulse get dispersed. The speed at which light travel through fiber rely on its wavelength and design of fiber thus some wavelength of band of which the pulse is embraced may be delayed compared with other, leading to pulse spreading with time after traversing a significant length of fiber called chromatic(Total) dispersion. Total dispersion is the sum of two form of dispersion (1) material dispersion (2) waveguide dispersion. The chromatic dispersion D of a PCF is calculated from given formula [18-20]

$$D = -\frac{\lambda}{C} \times \frac{d^2_{neff}}{d\lambda^2}$$

where c is the velocity of light in a vacuum n_{eff} is effective refractive index of PCF.

1.5.4.1 Material dispersion

The material refractive index depends on the value of wavelength. Material dispersion is calculated by a sellmeier equation which gives the relation between refractive index and wavelength. Usual form of equation is given as [22]

$$n^2(w)= 1+\frac{B_1 w^2}{w^2-C_1} + \frac{B_2 w^2}{w^2-C_2} + \frac{B_3 w^2}{w^2-C_3}$$

where n is refractive index of material and w is operating wavelength. Coefficient $B_{1,2,3}$ and $C_{1,2,3}$ is experimentally examine. The coefficient of the sellmeier equation is different for different material.

1.5.4.2 Waveguide dispersion

Waveguide dispersion depends on the fiber refractive index profile. Waveguide dispersion is significant for the fiber having small effective area. Altering the refractive index profile will alter the waveguide dispersion.

$$D = \frac{\lambda}{c}\frac{d^2 n}{d\lambda^2}$$

1.5.5 Modal birefringence

Effective index profile sometimes depends on the polarization and propagation direction of optical signal. So the refractive index of the two fundamental modes (x and y mode) will not be same. Birefringence is the difference of effective refractive index between these two-fundamental modes. Birefringence can be calculated using the equation [9]

$$\text{Birefringence} = [n_{eff}(X\text{ mode}) - n_{eff}(Y\text{ mode})]$$

1.5.6 Non-linearity

The nonlinear effect in optical fiber occurs due to intensity dependence of refractive index in medium or different scattering phenomenon. Nonlinearity is a most important phenomenon in optical fiber communication and used in various applications such as four-wave mixing, Supercontinuum generation and self-phase modulation. Nonlinearity depends on the type of material and design of fiber. Nonlinearity is calculated with the help of nonlinear coefficient that is different to different materials. [12]

$$\gamma = \frac{2\pi}{\lambda} \times \frac{n_2}{A_{eff}}$$

where n_2 is nonlinear coefficient

1.6 Applications of PCF

1.6.1 Dispersion compensation Fiber

DCF is a simple and developed technology used in optical communication system. Commercially available DCF can compensate the dispersion of all transmission fiber even for high bit rate and long distance. The newest development in DCF reduced losses and length of optical fiber. This fiber can also be used as dispersion shifted fiber. [33]

1.6.2 Polarization maintaining PCF

Optical fiber always shows some amount of birefringence even if PCF has a circular design because in fabrication process there is always some stress or pressure which breaks the symmetry of fiber because of this polarization of light propagating in the fiber regularly changes in an uncontrolled manner. To remove this problem PMF is used. PMF has a high value of birefringence. The polarization of light launched into the fiber is aligned with one of the birefringence axes and polarization is maintained even if the fiber is bent. Due to strong birefringence, the propagation constant of two polarization modes is different so the relative phase of such copropagating modes rapidly drift away so any disturbance in giber does not affect large enough on polarization direction. [32]

1.6.3 Hollow core fiber

Hollow core fibers light is guided by using a photonic bandgap structure in place of a traditional total internal reflection. Since most of the optical power propagates through the core region, not cladding region, these fibers are particularly unaffected by nonlinear optical effects. Hollow core fibers can offer other advantages like extremely low loss bends, extreme dispersion values and the ability to modify the core material properties by exchange air for some other gas and HC-PCF can be used as microcell.

1.6.4 Fiber laser amplifier

Fiber amplifiers are one of the key components of modern telecommunication. Also, fiber lasers are starting to be more and more important in medicine, spectroscopy, and industry. Compared to conventional solid-state lasers, the great advantage of fiber lasers is their outstanding heat dissipation capability. The fiber laser is insusceptible to thermal lensing and all other temperature properties. The one most important advantage of fiber laser amplifier than a conventional laser is the quality of stream of light which is close to the diffraction limit.

CHAPTER 2

ANALYSIS METHOD

2.1 Methodology

In general, three methods are utilized to analyze the structure and the properties of photonic crystal fibers. They are

- Effective refractive Index Approach
- Basis-Function Expansion Approach
- Numerical Approach

2.1.1 Effective Index approach

The first approach developed for PCFs was the effective index approach based on a very simple scalar model using an effective cladding index. In this approach propagation of light is through slab like PCF is commonly describe in terms of refractive indices , we can replace 3D structure by an effective 2D refractive index profile .first, an effective index for the periodically repeated hole-in-silica structure is evaluated and then the microstructured cladding region is replaced by a uniform medium with a properly chosen effective index, resulting in an equivalent step index fiber (SIF) consisting of a core and a cladding region. Using this simple model and the well-established fiber theory, we can obtain a qualitative information about PCFs with perfect hexagonal symmetry. The core is pure silica, but the effective cladding index is determined by using the propagation constant of the lowest-order fundamental mode propagating in the periodically repeated hole-in-silica structure without any defects. The propagating modes in such an infinite cladding material are called space filling modes, the propagation constants of which are strongly dependent on the operating wavelength λ. The propagation constants of the space-filling modes are usually calculated by solving an approximate scalar-wave equation within a unit cell centered on one of the air holes. By reflection symmetry, the Neumann condition is enforced on each cell edge, namely, the normal derivative of the cladding mode field to the edge must be zero.

2.1.2 Basic Function Expansion approach

Although the effective index approach can provide good qualitative information about PCFs, this approach is unable to accurately predict modal properties such as dispersion or birefringence. These quantities depend critically on PCF geometries. An early full-vector model for PCFs has been based on a modal decomposition technique using various basis functions such as sinusoidal functions, Hermite–Gaussian functions and cylindrical functions. The PWE has been effectively applied not only to index guiding PCFs but also to PBGFs. PWE involves defining the supercell over a restricted region and using periodic boundary conditions to extend the structure spatially, and therefore, the applicability to PCFs that do not need to be periodic is somewhat restricted. An alternative approach is a localized-function method (LFM). As the guided modes in PCFs are localized in the defect core region, their modal fields are well described using localized Hermite–Gaussian functions. The LFM takes advantage of mode localization, and thus, a modest number of functions are required to accurately model the guided modes, resulting in less computational efforts, compared with the PWE.

2.1.3 Numerical approach

Although the basis-function expansion approach can accurately predict the modal properties such as dispersion and birefringence, it is difficult to apply it to more complicated fibers with noncircular air holes and/or longitudinally varying structures. Recently, published models utilize other direct numerical analysis techniques such as BPM, FDM, FDTD, BEM, and FEM. In the FEM, instead of solving the wave equation, the corresponding functional to which a variational method is applied is set up, where the fiber cross section is divided into the so-called elements, an equivalent discretized model for each element is constructed, and then all the element contributions to the whole fiber cross section are assembled.

2.2 Full Vectored Finite Element Method

- A finite element optical mode solver is the most popular method to thoroughly analyze photonic crystal fibers. The finite element method is a numerical approximation process used for the solution of boundary and initial value problems for differential equations
- The FEM produces approximate solutions by writing them as linear combinations of simple basis functions and test functions equal to the basic functions and introducing these into the variational formulation of the problem
- The final FEM equations that must be solved are systems of linear algebraic equations
- COMSOL is modern software embedding the FEM with a cleverly designed user interface designed to increase the applicability and ease of use of mathematical modeling methods

There is different matched layer condition in finite element method.

2.2.1 Perfect Magnetic conductor: -

This boundary condition can be expressed as

$$n.D = 0$$

$$n \times H = 0$$

According to this condition, tangential components of H and normal components of D is continuous across any interface

2.2.2 Perfect Electric conductor

This boundary condition can be expressed as

$$n.B = 0$$

$$n \times E = 0$$

Here, n is the unit normal vector to the boundary. According to this condition, tangential components of E and normal components of B is continuous across any interface.

2.3 Comsol Multiphysics

COMSOL MULTIPHYSICS software is used to simulate different properties of PCF which is based on finite element method. COMSOL software (5.1) is used for the numerical answers & graphs of different parameters of spiral PCF and the results are reported in this thesis.

2.3.1 Design of PCF using COMSOL

- Open software COMSOL 5.1. A window named **Model Wizard** will be opened
- Then following steps are followed: **optics Module>Wave optics>Electromagnetic, frequency domain Waves>Mode analysis**
- The software is opened with working window.

To design the structure of a PCF first set it at appropriate modal analysis, then draw the structure of PCF and give input for geometrical properties, initialize mesh and then solve the structure. The procedure for this work is given bellow

2.3.1.1Setting appropriate parameter and study

- We Select Physics in the Physics menu to open the Application Mode Properties dialog box**.**
- We select the correct study using **Add study** dialog box
- We select the appropriate parameter for our geometry and define all the parameter in setting window of the parameter.

2.3.1.2 Geometry Modeling

- On geometry, toolbar click **primitive** and choose circle
- In **setting window** of circle locate size and shape
- We start by drawing a circle with the radius and the center at desired values with right click in geometry icon.
- In geometry tool bar click **transforms** and select **rotate.**
- Click the build all object button.

2.3.1.3 Material setting

- After making the geometry of PCF we add material in our geometry.
- First, click on **material toolbar** and select blank material and write the refractive index of material in material setting window
- Select domain

2.3.1.4 Mesh setting

- In **modal builder** window > component 1 click **mesh 1**
- In **setting** window for mesh choose physics controlled Mesh
- From **element size list** select between **fine** to **extra coarser**
- Click on **build all** button

2.3.1.5 Study Setting

- In **modal builder** window under **study 1** click **mode analysis.**
- In the setting window for mode, analysis locates the **study setting** window.
- In the **search for mode around a** text field type refractive index of the core.
- In the **search for frequency around** text field type frequency.
- On the **home,** toolbar clicks **compute.**

2.3.1.6 Post processing

- In modal builder window under result click 1D plot group.
- Under 1D plot group select line graph.
- Plot line graph between wavelength and n_{eff}.
- Extract spreadsheet from comsol to excel.

CHAPTER 3

LITERATURE SURVEY

Md Asiful Islam and M Shah Alam proposed a structure of spiral PCF. This PCF can be used to compensate the dispersion properties and used for supercontinuum generation. The structure contains the air holes in silica material. there is N circular air hole in each arm and diameter of each air hole is increased progressively. The angular displacement of each arm is θ than by previous one. the proposed structure contains an elliptical air hole at the center of air core This design is simulated by comsol Multiphysics which is based on full vector finite element method. The design of PCF shows the dispersion of -293.5 and -393 ps /nm km. another exceptional feature of this design is their high birefringence of 0.0278.

Agrawal, A., Kejalakshmy, N., Rahman, B.M.A. and Grattan, K.T.V. (2009) [2] the proposed spiral PCF fiber design in the SF57 is presented with high nonlinearity with low and flattened dispersion. The design of PCF is inspired by nature. Each arm of PCF contains air holes with constant radius r and angular displacement θ. A full vector finite element method is used to simulate the design. ES-PCF design in SF57 has been presented that have high nonlinearity of 2150/W.km at 1550nm and also the PCF optimized for low dispersion of 0.8 Ps/nm.km. it combines the advantage of better dispersion control with the smaller effective area and high nonlinearity.

M. Samiul Habib, M. Selim Habib, M. Imran Hasan, S.M.A Razzak (2013) [3], this paper presents a soft glass spiral photonic crystal fiber for tune two zero dispersion wavelength in the visible and near infrared region. The design contains six circular rings and eight spiral arm, each air hole of the first ring is the starting point of a spiral arm. The distance of second air ole in the spiral arm from the center is $r_{b1}=r_{b0}+0.8(2\times r_a)$ with an angular shift $\theta_1=\frac{360}{2\times N}$ where N is the number of spiral arms. To produce high birefringence, an artificial defect is introduced in the core region. The designed fiber has two ZDW at 700nm and 1050nm with very large nonlinearity of 7326/W. Km at 700nm and 3919/W. Km at 1050nm. The designed PCF offer birefringence of 0.1 at 1.8μm.

S. Revathi*, Srinivasa Inabathini, Ram Sandeep (2015) [4] This paper present a soft glass spiral photonic crystal fiber with a circular air hole for achieving high birefringence, large nonlinearity, and large negative dispersion. For achieving high birefringence, the defect is introduced in the core region. The structure is designed using the comsol 3.5 it is based on finite element method, an accurate numerical method used to find the solution of boundary problems. The structure contains 8 spiral arms and each arm contains five circular air hole. An elliptical air hole introduced in the center of core with semi major axis a and semi minor axis b. this fiber can be used as polarization maintaining fiber which has more control on polarization. This fiber optimized for high birefringence of 2.96×10^{-2} at 1.55μm and high nonlinearity of 5828/W.Km.this fiber give negative dispersion -1546.6ps/nm.km at 850 nm.

S. Revathi*, Srinivasa Inabathini and Rizwan Ali Saifudeen (2014) [5] the proposed structure is designed with elliptical air hole using comsol. The structure is designed with chalcogenide glass. This structure is optimized for different ellipticity ratio of the air hole. The structure contains seven spiral arms and each arm contains five elliptical air holes. The angular displacement between two adjacent elliptical air hole is $\frac{180}{N}$ where N is the number of air holes in a ring. The effect of ellipticity ratio on the various property of fiber is observed. The advantage of spiral structure is low effective area and high nonlinearity. By obtaining result from simulation, we get high birefringence of order 10^{-2} which is larger than conventional PCF. Fiber offers high birefringence of 0.0256 at 1.55μm and gets negative dispersion of -1136.69 at .85μm. We can use this fiber in the nonlinear application.

Varshali Sharma, Ritu Sharma (2016) [6] the proposed design of PCF with elliptical and circular air hole is analysed for high birefringence and large flattened dispersion. There are five rings, inner three rings have elliptical air hole and outer two rings have circular air holes. These layouts are designed and analysed and also compare with layout having only circular air holes arrangement. From the analysis, we observed flattened dispersion over a large range from 1.2 to 1. 8μm.the proposed design also give high birefringence value which can be used in various sensing application.

Philip St.J. Russell (2006) [7] Photonic crystal fiber with a periodic transverse microstructure have been in practical since 1996. It is now possible to manufacture PCF of a scale 10 nm on a scale of 1um scale, which allows exceptional control on optical properties like dispersion, effective area, birefringence and nonlinearity of optical fiber. The novel idea for developing PCFs was the creation of a new design dielectric waveguide, one that guides light by means of a two-dimensional (2-D) PBG. the idea was to trap the light in two dimensional PCF by using air holes array.

Theis P. Hansen, Jes Broeng, Stig E. B. Libori, Erik Knudsen, Anders Bjarklev, Jacob Riis Jensen, and Harald Simonsen (2001) [9], photonic crystal fiber offers new possibilities of highly birefringence fiber due to large index difference between core and cladding region compared to conventional fiber. The proposed design consists triangular lattice of air holes with a pitch of 4.5μm. the core is made by removing two air holes. The fiber was found to exhibit the highest birefringence of 6.9 $\times 10^{-4}$ at frequency 1.05μm. by optimizing the design of PCF, we get high birefringence at 1.55μm for pitch ratio 1.7μm.

Md. Ibadul Islam, Kawsar Ahmed, Sayed Asaduzzaman, Bikash Kumar Paul a, Touhid Bhuiyan, Shuvo Sen, Md. Shadidul Islam, Sawrab Chowdhury (2017) [10], proposed structure consists air holes that are arranged in a hexagonal design of pitch ʌ. The refractive index of the silica regions is 1.4445. The holes are characterized by the area and ellipticity ratio $\frac{a}{b}$, where a and b are the diameter of the major and minor axes, respectively. Geometry of PCF is simulated for different ellipticity ratio and hole area is less than 0. 4μm.it has been observed from the result that on the holes area. whereas for larger holes and ellipticities, the core itself has an elongated elliptical shape. for small hole area and small ellipticity, birefringence depends only on the ellipticity and not on area.

Jianfei Liao, Junqiang Sun, Mingdi Du, and Yi Qin (2014) [11], the structure consists spiral photonic crystal fiber that is used as a sensor. This design can be used to sense the colorless gas and air pollution by metering gas condensate elements. The proposed structure simulated by finite element method. Design consist of a cluster of circular air holes in core region which are formed into porous shape and cladding is formed in a spiral shape. The proposed structure gives high sensitivity and high birefringence for the wavelength range of 1μm to 1.8μm. we get high birefringence of 7.23×10^{-3} at 1.33μm. so proposed spiral PCF ensure major change in colorless and toxic gas detection.

Jianfei Liao, Tianye Huang, Zuzhou Xiong, Fangguang Kuang, Yingmao Xie (2017) [12] proposed design has been analysed for large flattened dispersion and high nonlinearity coefficient. Design consist slotted core region surrounded by the three rings of air hole in the spiral lattice. The optical properties of this fiber designed has been analysed for the wavelength range from 1.4 to 1.7 μm. Simulation results show that the nonlinear coefficients as high as 224.36 $W^{-1}m^{-1}$ and 226.39$W^{-1}m^{-1}$ respectively. Chromatic dispersion (−5.64,2.62) for wavelength range 1.4 to 1.7 μm.

Md. Ibadul Islam1, Maksuda Khatun1, Shuvo sen1, Kawsar Ahmed1 and Sayed Asaduzzaman (2016) [13] author proposed a design of spiral photonic crystal fiber having an elliptical slot in core region for purpose of controlling dispersion and birefringence property of PCF. Elliptical slot in the core region is made of SF57 (soft glass). fiber cladding consists of spiral lattice on fused silica having refractive index 1.45. the diameter of air hole in each arm is increase respectively. Here SF57 is used for two regions 1) SF57 has high nonlinearity.2) it enhances the confinement of light in high index SF57 area.in addition of this SF57 also alter the chromatic dispersion and destroy the symmetry of fiber and increase birefringence.by examining the design, the result shows birefringence of 0.0341 at 1.55 μm.dispersion at 1.55 is -491.16ps/nm-km.

Jianfei Liao Yingmao Xie Xinghua Wang Dongbo Li Tianye Huang(2017) [14], the proposed design of spiral PCF has been used in gas sensing application. Inner core region consists hexagonal lattice and shape of air holes is elliptical. Outer cladding region having spiral lattice. In fiber design, there is 10 spiral arms and each arm has 9 circular air holes. It has been observed from a simulation that relative sensitivity is 42.27% and due to the presence of hexagonal lattice in the core region, we observe high birefringence of order (0.01727) at 1.33μm wavelength range.

Arti Agrawal, Y. O. Azabi and B. M. A. Rahman (2013) [15] the proposed structure contains slotted silicon PCF with ultra-high birefringence, nonlinearity, and ultrahigh flattened dispersion. Cladding consists of a triangular lattice of air holes of diameter D and pitch ʌ.in addition of this a design consists elliptical silicon nichrome rod, is situated in the center of the core that breaks the symmetry of design and increases birefringence of fiber. Simulation result shows that by introducing silicon nichrome rod birefringence of order 0.0736 at 1.55µm is achieved. Low dispersion of .49ps/nm-km is achieved at 180nm.The designed PCF can be used as power efficient optical application.

Ritu Sharma, Vijay Janyani, S. K. Bhatnagar (2011) [16], index core two-dimensional photonic crystal fiber has been proposed in this paper modal analysis is done by FDTD for TE and TM mode. The PCF consist three rings of elliptical air and compare with circular air hole design.by observing the result of simulating designs we analyse that elliptical air hole design gives lower dispersion as compared to circular air hole design.

Rui Hao, Guifang Sun (2015) [17], An elliptical spiral soft glass PCF has been designed and analysed for high birefringence. The geometry is inspired by nature, such as galaxies, distribution of sunflower, shells of snails etc. PCF consist 12 circular air hole and spiral lattice having same ellipticity ratio from the first ring to the last ring. Due to the compactness of design light confinement in PCF is tight than conventional fiber. By examined the simulation result, for wavelength range 1000-1800nm, designed PCF offer birefringence up to 0.05554.

CHAPTER 4

NUMERICAL ANALYSIS OF SPIRAL PCF

4.1 Introduction

In this chapter, two dimensional spiral PCF has been designed using Comsol 5.1. Comsol 5.1 is based on finite element method. [1-5] The Design contains five rings of circular air holes in the spiral . Three configurations of spiral PCF have been analysed for different optical properties such as effective refractive index, dispersion, effective area etc. In these three configurations, the diameter of air hole is changed and all another parameter like pitch etc. is kept constant. Approaching from circular air hole spiral PCF to elliptical air hole spiral PCF, air filling fraction is kept same and the results compared for each design. [20-21]

4.2 Design Parameter of Circular spiral PCF

NAME	VALUE	DISCRIPTION
d	1,0.8,0.8[µm]	Diameter of air hole
r_0	2[µm]	Radius of first air hole
r_1	3.8[µm]	Radius of second air hole
r_2	5.6[µm]	Radius of third air hole
r_3	7.4[µm]	Radius of fourth air hole
r_4	9.2[µm]	Radius of fifth air hole
W	1.55[µm]	wavelength
f	C_const/w	frequency
n_{core}	1.45	Refractive index
$n_{air\ hole}$	1	Refractive index

4.3Geometry of Circular air hole spiral PCF

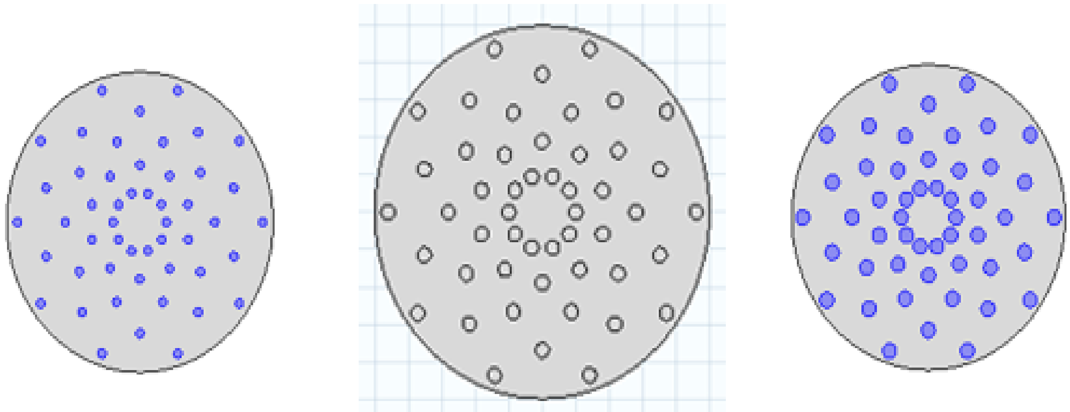

Figure 4.1 Snap shot of Circular air hole spiral PCF with (a) d=0.6[μm] (b)d=0.8[μm] and (c)d=1[μm]

4.4 Snapshot of mode profile

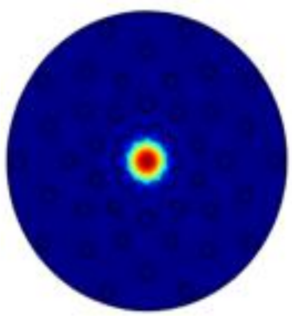

Fig:4.2 (a) d=1[μm]

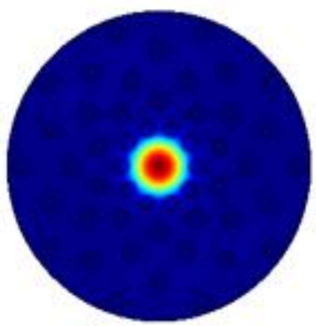

Fig:4.2 (b) d=0.8[μm]

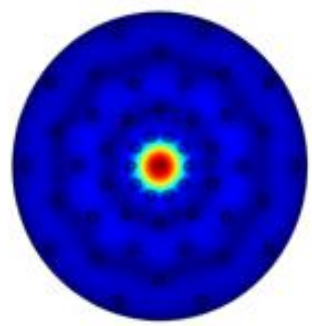

Fig:4.2 (c) d=0.6[μm]

Mode profile of Spiral PCF is shown at 1.55 μm wavelength for the fundamental mode. Color variation (red for maximum, blue for minimum power) for power is shown. From this figure, it is shown that maximum light is passed through the core, not in the cladding.

4.5 Effective mode index

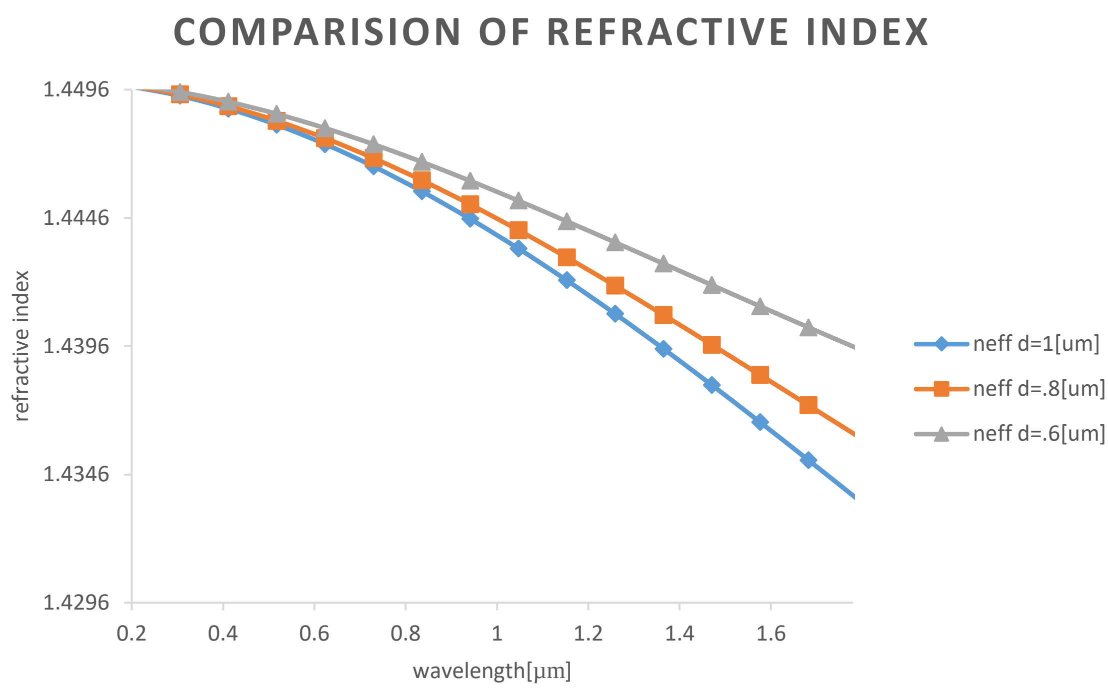

Figure 4.3 refractive index vs wavelength plot for d=1, 0.8, 0.6[µm]

Fig 4.3 shows the variation of effective index with wavelength for different circular air hole spiral PCF. It can be analysed that the slope of Effective refractive index increases with a diameter of air holes. Relation between n_{eff} and wavelength is given as

$$\beta = \frac{2\pi}{\lambda} \times n_{eff}$$

From above formula, there is reciprocal relation between n_{eff} and wavelength and it is verified from the Fig 4.3.

4.6 Dispersion profile

Total dispersion is the variation of group velocity with variation in wavelength. Dispersion of PCF is highly effected by the size of air holes and the air hole arrangement in geometry. Another parameter that can alter dispersion profile is a number of spiral arm and size of the core. From Fig 4.4, it can be analysed that dispersion is minimum for diameter 0.6µm and maximum for diameter 1µm.Total dispersion (chromatic dispersion) made of two forms of component (1) waveguide dispersion (2) material dispersion [28]

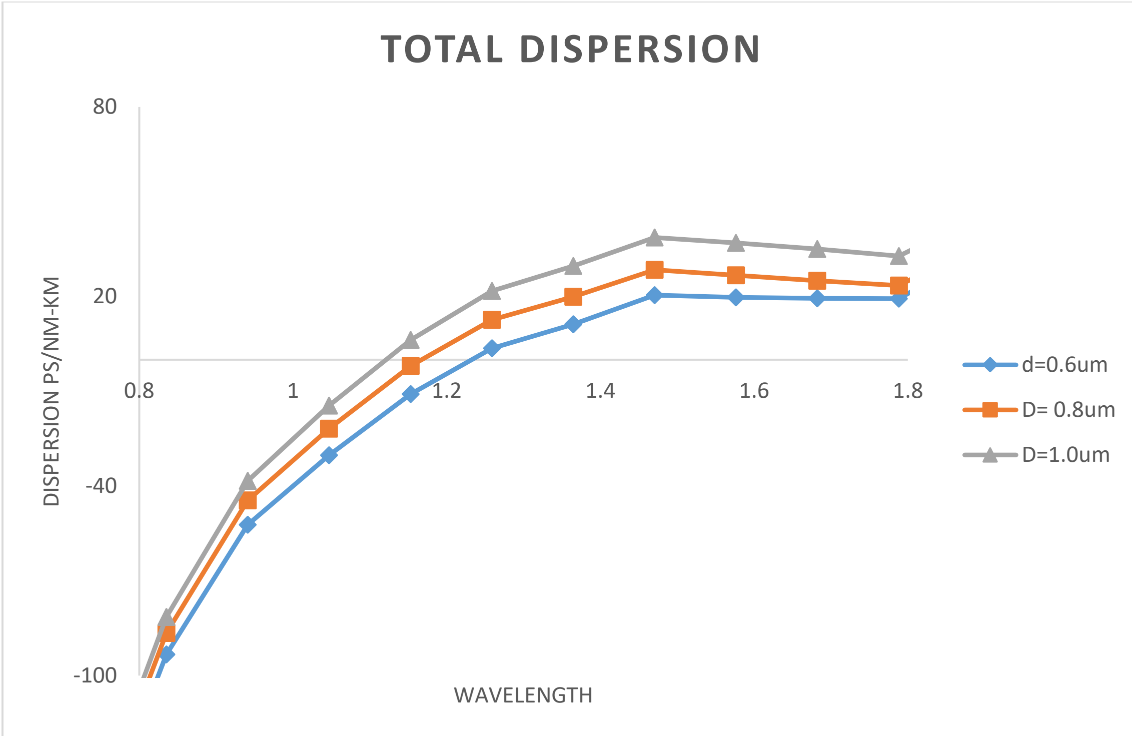

Fig 4.4 Plot of waveguide dispersion (ps/nm-km) v/s wavelength for d=1[µm],0.8 [µm].0.6 [µm].

4.7 Effective Area

In Figure 4.5, the effect of diameter of air hole on the effective area is analysed. Effective area linearly increases with wavelength**.** The effective area of conventional PCF is high over a spiral photonic crystal fiber. This less effective area is an advantage over conventional PCF. Due to the less effective area, this fiber can be used in the nonlinear application. It can be observed from Fig 4.5 that as we increase the diameter of the air hole effective area get reduced and at diameter 1µm we get low effective area than others. [11]

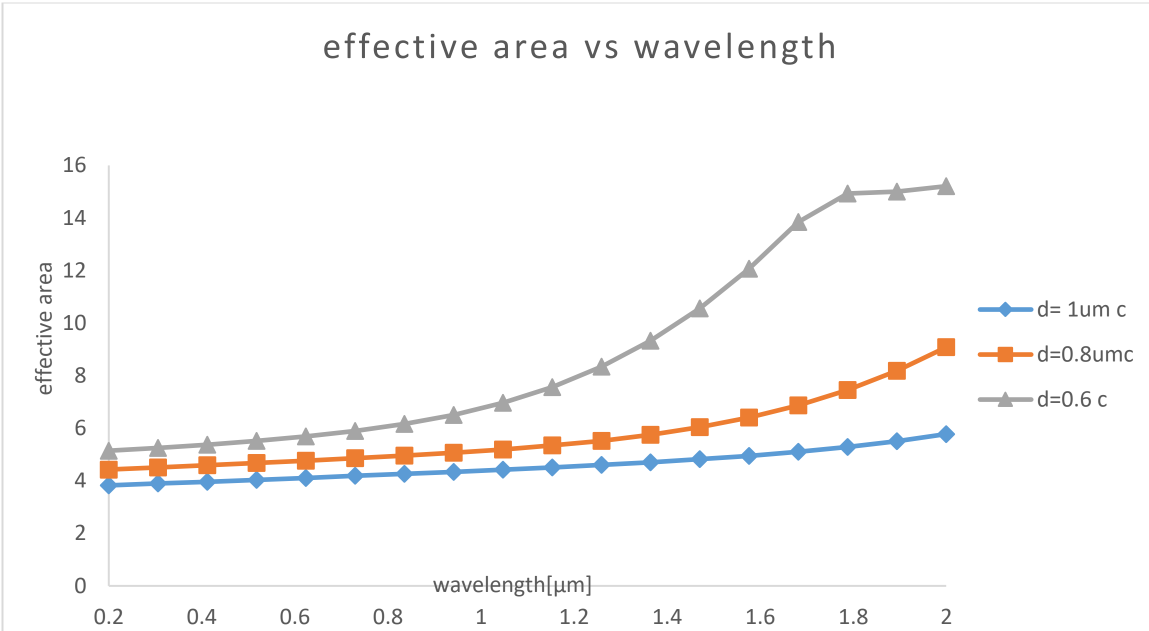

Fig:4.5 Plot of Effective Area vs wavelength for d=1[µm],0.8[µm],0.6[µm].

4.8 Design Parameters of Elliptical Air hole spiral PCF

NAME	VALUE	DISCRIPTION
d	1[µm]	Diameter of air hole
r_0	2[µm]	Radius of first air hole
r_1	3.8[µm]	Radius of second air hole
r_2	5.6[µm]	Radius of third air hole
r_3	7.4[µm]	Radius of fourth air hole
r_4	9.2[µm]	Radius of fifth air hole
w	1.55[µm]	Wavelength
f	C_const/w	Frequency
n_{core}	1.45	Refractive index of core
$n_{air\ hole}$	1	Refractive index of air hole in cladding
a	.55[μm]	Major axis diameter of elliptical air hole
b	.45[µm]	Minor axis diameter of elliptical air hole

4.9 Geometry of elliptical air hole spiral PCF

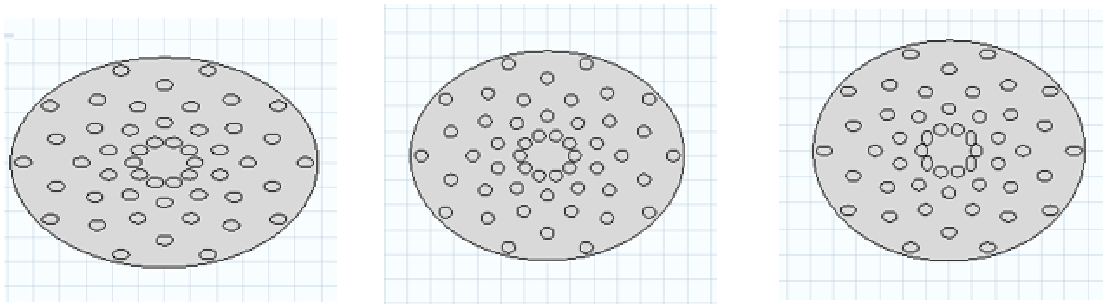

Figure 4.6 snap shot of elliptical air hole spiral PCF a: major axis b: minor axis of ellipse

Fig 4.6(a) a=.0.57[μm], b=0.43[μm] Fig 4.6(b) with different ellipticity Fig 4.6(c) a=0.62[μm],b=0.40

4.10 Snapshot of mode profile

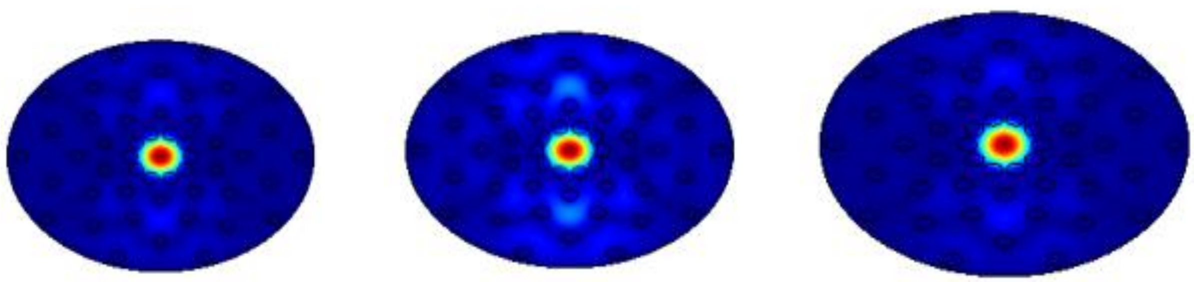

Figure 4.7 Snap shot of mode profile for different Elliptical air hole spiral PCF

Fig 4.7(a) a=0.57[μm],b=0.43[μm] Fig 4.7(b) with different ellipticity Fig 4.7(c) a=0.62[μm],b=0.40

In given figure, red color shows the maximum intensity of light and blue color shows the minimum intensity of light. From mode profile, we can examine that most of the light is confined in core region due to refractive index variation. Confinement in PCF is high than conventional fiber. This is the advantage of PCF over conventional fiber.[24]

4.11 Refractive index vs wavelength

The wavelength is varied from 0.2μm to 2μm for the simulation. n_{eff} is calculated by simulating the design. The variation in effective refractive index v/s wavelength is shown in Fig 4.8. It can be examined from the graph that effective refractive index decreases as the wavelength is increased. From the graph, it observed that the slope of effective refractive index increases with ellipticity ratio.

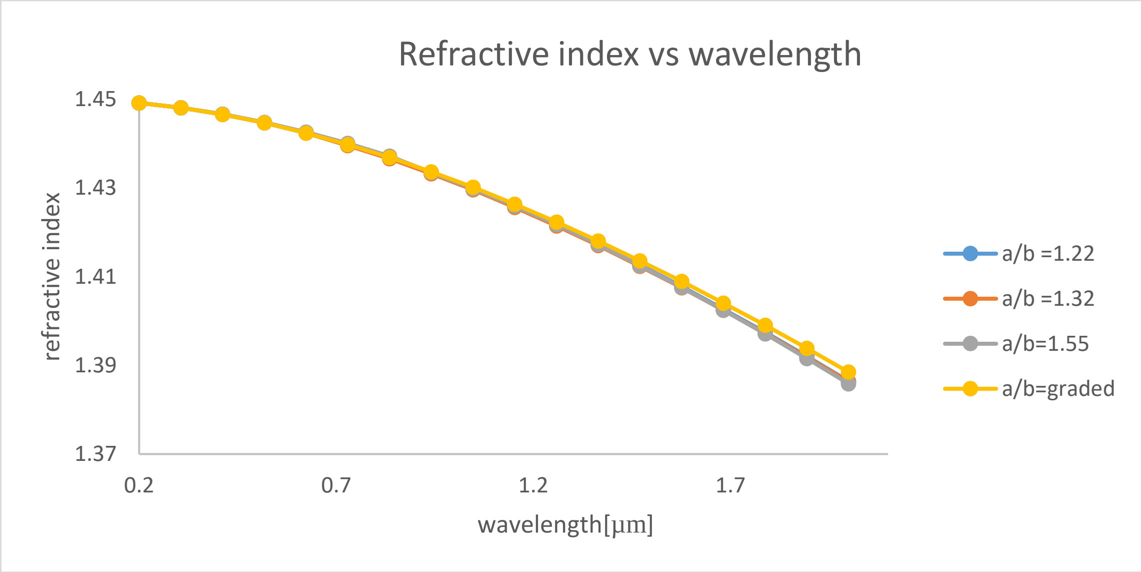

Figure 4.8(a) Plot of Effective refractive index v/s wavelength for ellipticity ratio 1.22,1.32,1.55.

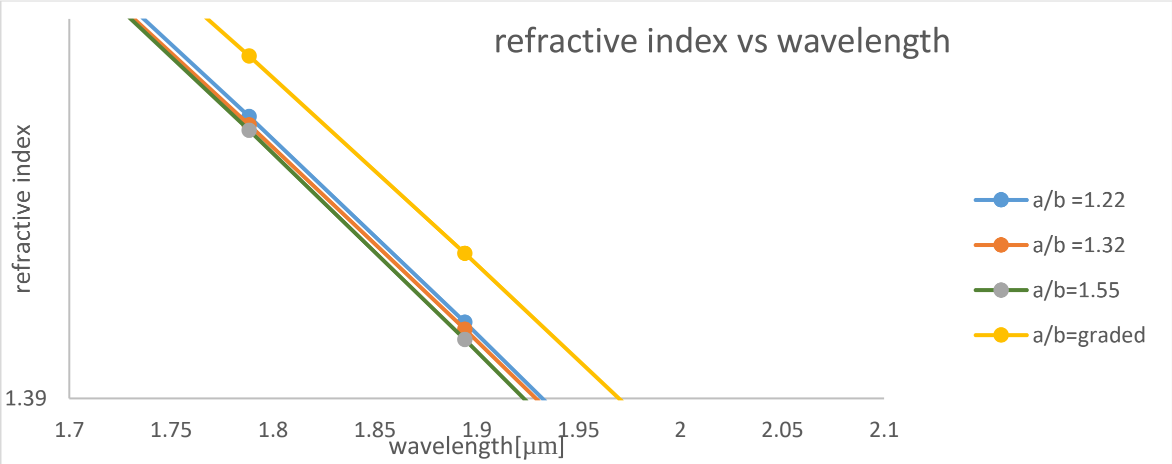

Fig 4.8(b) zoom view of refractive index vs wavelength plot

4.12 Dispersion vs wavelength

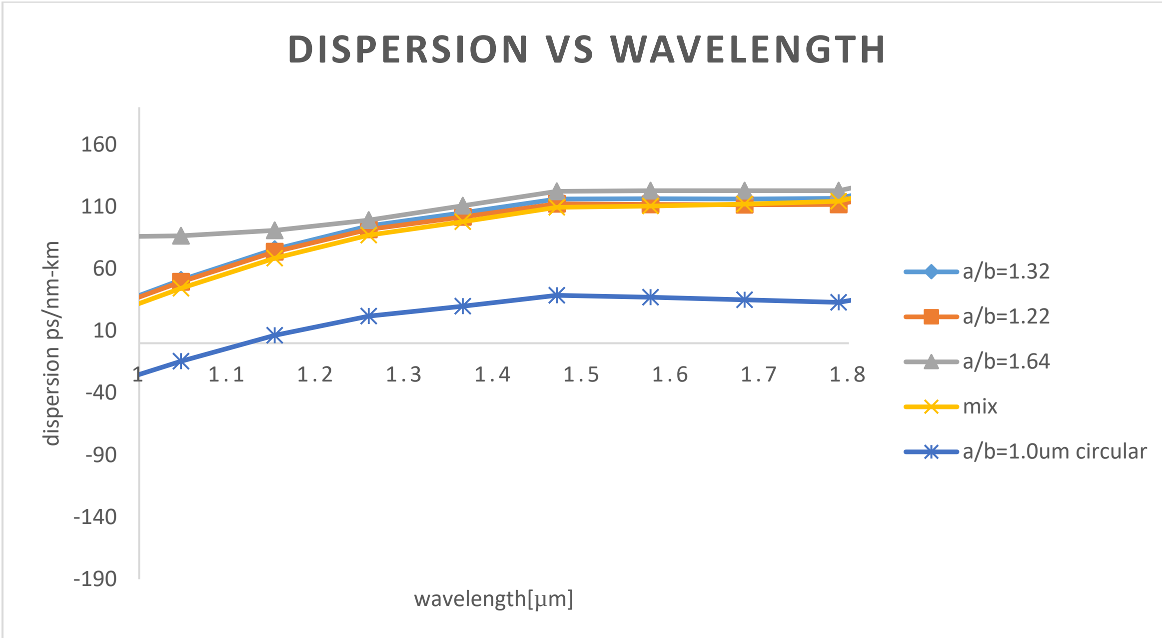

Fig 4.9(a) Plot of Total dispersion v/s wavelength for ellipticity ratio 1,1.22,1.32,1.64

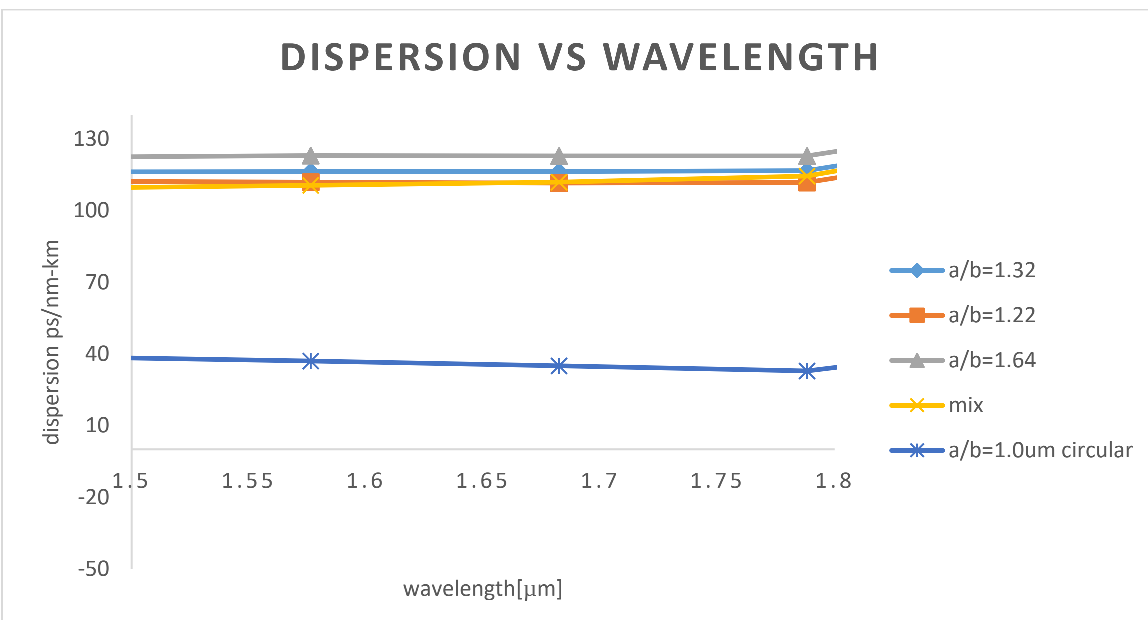

Fig 4.9(b) Plot showing Flat range of dispersion v/s wavelength

It can be analysed that dispersion is highly affected by the size of air hole so if the air filling fraction is increased or size of air hole is increased the dispersion also changes.

From Fig 4.8 and Fig 4.9, it can be analysed that for ellipticity ratio 1.64 we get the highest dispersion and for graded size air hole we get minimum distortion.So if ellipticity ratio from the first ring to the last ring is increased or decreased the magnitude of dispersion is highly affected. A minimum magnitude of dispersion is obtained for ellipticity ratio 1.22. From figure 4.9(b) it can be examined that nearly flat dispersion is obtained from 1.5µm to 1. 68µm wavelength range. An important fact that can be observed from the Fig 4.9 is that when the geometry is changed from circular to elliptical air holes, the magnitude of dispersion gets increased but birefringence increases. [21]

4.13 Birefringence

Birefringence is the difference between the two orthogonal directions. Modal birefringence is defined as [12]

$$\text{Birefringence} = [n_{\text{eff}}(\text{X mode}) - n_{\text{eff}}(\text{Y mode})]$$

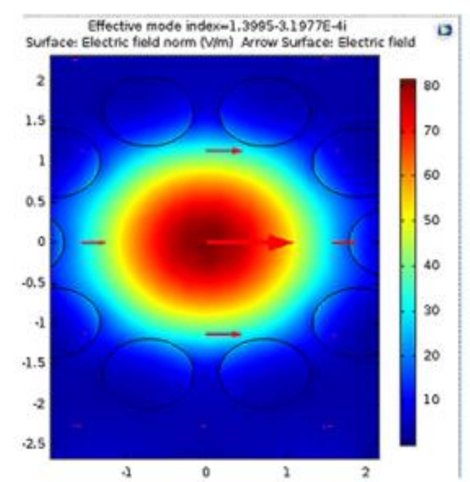

Fig 4.10(a) snap shot of X polarization

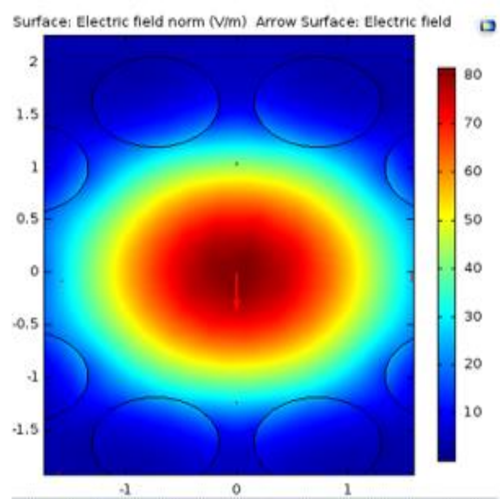

Fig 4.10(b) snap shot of Y polarization

Fig 4.10 (a) snap shot of X polarization mode

Fig 4.10 (b) snap shot of Y polarization mode

4.14 Birefringence v/s Ellipticity ratio

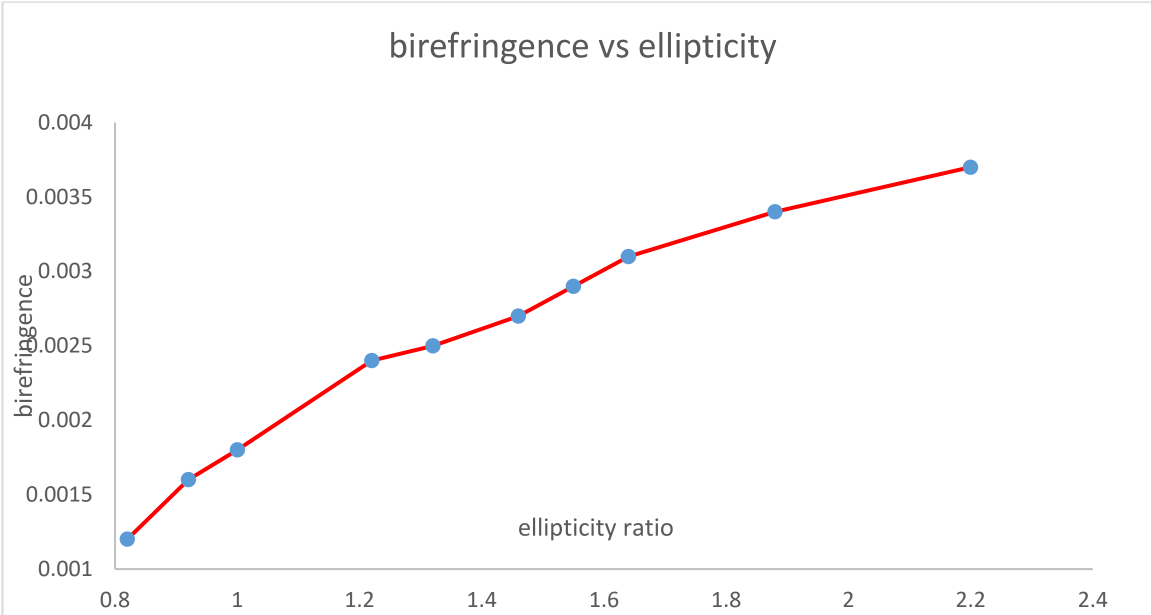

Fig 4.11 Plot of ellipticity ratio vs wavelength

The effect of ellipticity ratio on wavelength is shown in Fig 4.11. It can see from the graph that birefringence varies with ellipticity ratio. In the plot, the ellipticity range is varied from 0.8 to 2.4 and for ellipticity ratio 2.2, we get the highest value of birefringence.

4.15 Birefringence v/s Wavelength

The proposed PCF consists of an elliptical-Spiral arrangement of the air hole. In comparison to conventional PCF structure supporting different properties, the compact design of elliptical air hole spiral PCF achieves large birefringence. From Figure 4.12, it can be seen that birefringence increases linearly with frequency [26]. We get high birefringence for ellipticity ratio 1.64 for wavelength range 1.50 to 1.80µm, designed PCF offered high birefringence up to 0.004.

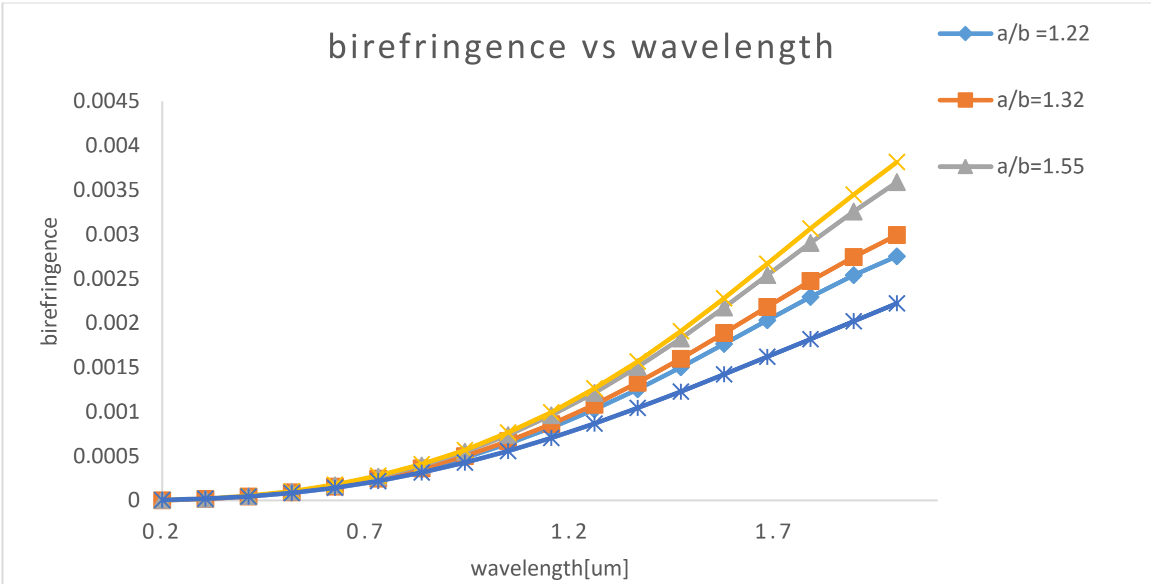

Fig 4.12 Plot of Birefringence v/s wavelength for different ellipticity ratio

4.16 Effective area v/s wavelength plot

From the plot shown in Fig 4.13, the effect of ellipticity ratio on the effective area can be examined. It is observed that effective area of elliptical air hole spiral PCF linearly increases with wavelength. The effective area of elliptical air hole spiral PCF is considerably small than conventional fiber. This property of PCF can be used in various nonlinearity application such as supercontinuum generation, four waves mixing etc. It can be observed from the plot that at ellipticity ratio 1.55, the effective area is lowest as compared others.

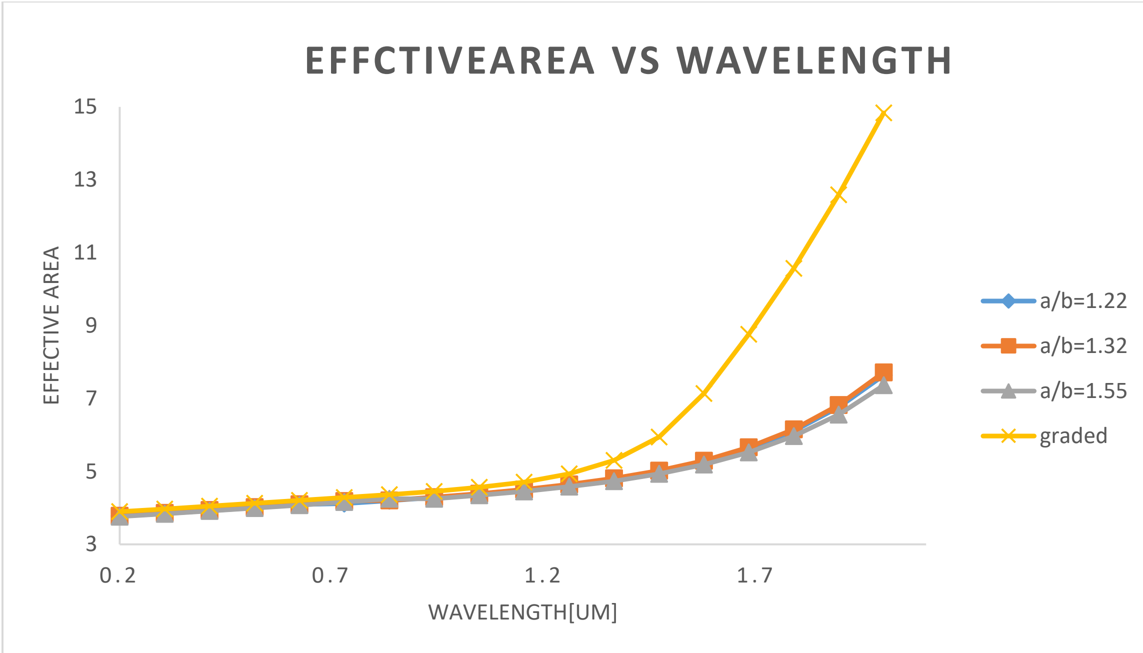

Fig 4.13(a) Effective area v/s wavelength plot

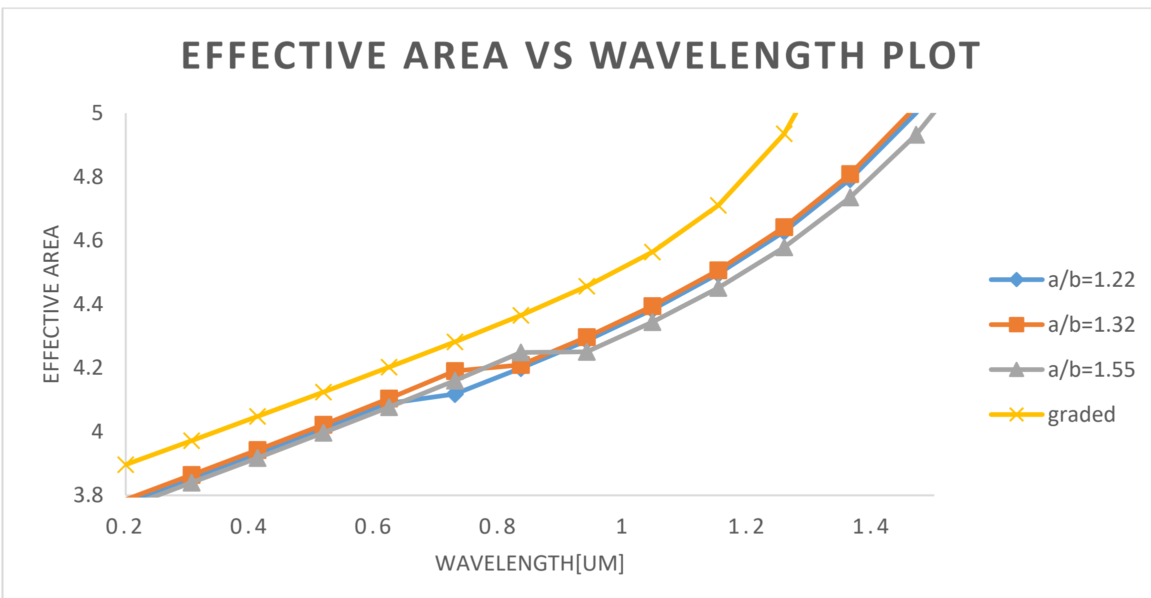

Fig 4.13 (b) zoom view of Effective area v/s wavelength p

CHAPTER 5

COMPARATIVE STUDY AND CONCLUSION

5.1 Introduction

This chapter deals with the comparative analysis of different characterstics of spiral photonic crystal fiber like effective mode index, waveguide dispersion and chromatic dispersion by varying wavelength for different diameter of air hole spiral photonic crystal fiber.[15]

5.2 Comparison of Effective mode index

Fig 4.19 shows the comparative study of effective mode index. In Fig 4.19 it can be seen that as the wavelength is increased the value of n_{eff} decreases. Fig 4.19 shows that the slope of refractive index v/s wavelength plot is maximum for elliptical air hole spiral PCF as compared with circular air hole PCF.

Table 5.1 Wavelength v/s effective refractive index

wavelength	a/b =1.22	a/b =1.32	a/b=1.55	a/b=graded	neff d=1[um]	neff d=.8[um]	neff d=.6[um]
0.2	1.449166853	1.449151	1.449173039	1.449151355	1.449721812	1.449743592	1.449784087
0.305882353	1.448092071	1.448057	1.448105572	1.448056659	1.449360212	1.449412177	1.449506576
0.411764706	1.446612718	1.44655	1.446635343	1.446550049	1.448860308	1.448956318	1.449127117
0.517647059	1.444752092	1.444656	1.444785287	1.444656022	1.448229799	1.448384668	1.448654858
0.623529412	1.442532128	1.442398	1.442577074	1.442397615	1.447476559	1.447706235	1.448099731
0.729411765	1.439734601	1.439578	1.440031218	1.439796464	1.446608729	1.446930514	1.447472466
0.835294118	1.436747866	1.43656	1.437167239	1.436872939	1.445634794	1.446067536	1.446784355
0.941176471	1.433437125	1.43322	1.433453364	1.433646334	1.444563643	1.445127821	1.446046878
1.047058824	1.429820031	1.429578	1.429821449	1.4301351	1.443404583	1.444122218	1.44527127
1.152941176	1.425914275	1.425652	1.42589325	1.426357078	1.442167287	1.44306169	1.444468127
1.258823529	1.421737785	1.421462	1.421685639	1.422329697	1.4408617	1.441957056	1.443647091
1.364705882	1.417308825	1.417026	1.41721593	1.41807006	1.439497899	1.440818747	1.442816623
1.470588235	1.412645929	1.412365	1.412501872	1.413594847	1.438085938	1.439656573	1.441983883
1.576470588	1.40776757	1.407497	1.407561426	1.408919975	1.436635675	1.438479534	1.441154705

1.682352941	1.402691513	1.402442	1.402412262	1.404059973	1.435156604	1.437295687	1.440333644
1.788235294	1.397433823	1.397214	1.397070941	1.399027094	1.433657705	1.436112051	1.439524076
1.894117647	1.392007662	1.391827	1.391551818	1.393830249	1.432147303	1.434934579	1.438728337

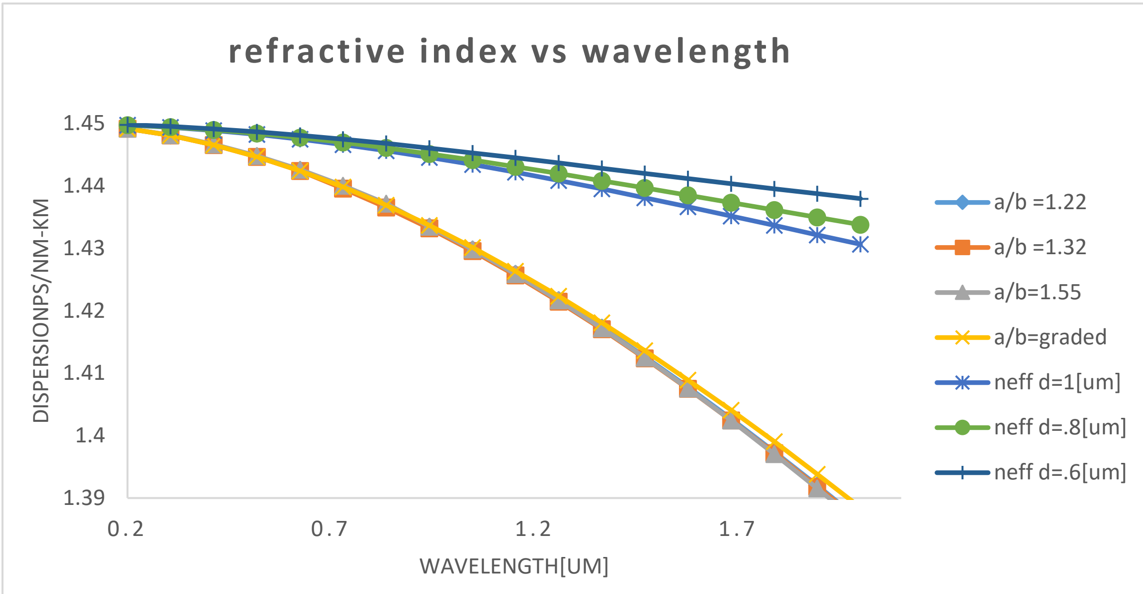

Fig 5.1(a) comparision of n_{eff} v/s wavelength for diameter =1µm,0.8µm,0.6µm

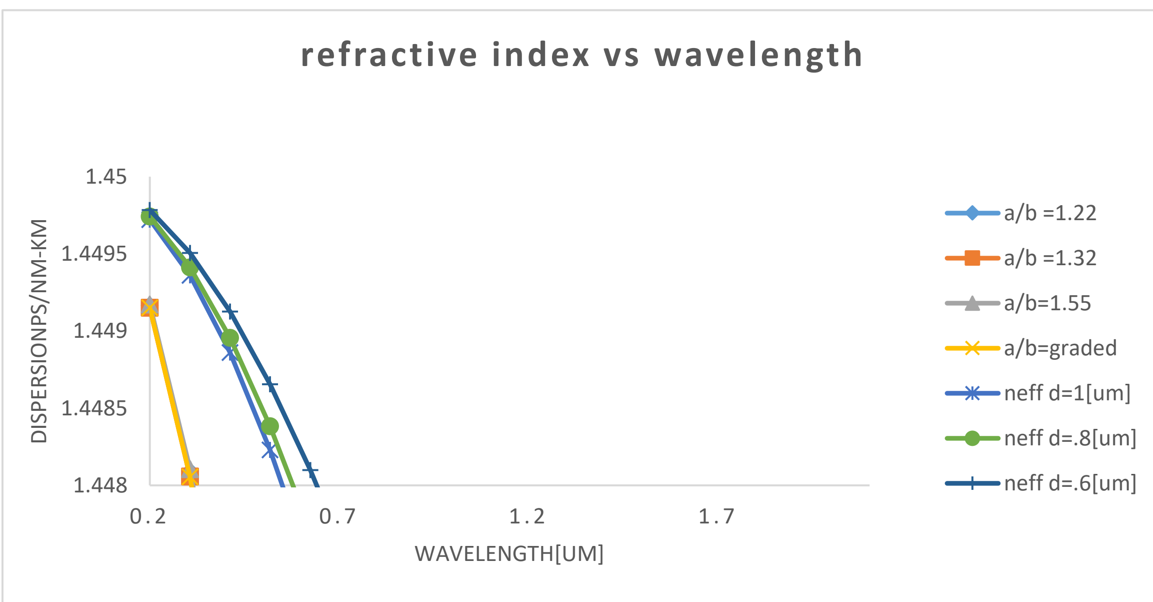

Fig 5.1(b) Zoom View of Fig 5.1(a)

5.3 comparision of waveguide dispersion

Fig 5.20 shows a variation of dispersion with wavelength and it can be seen from the graph that as we increase the diameter of airhole dispersion also increases.

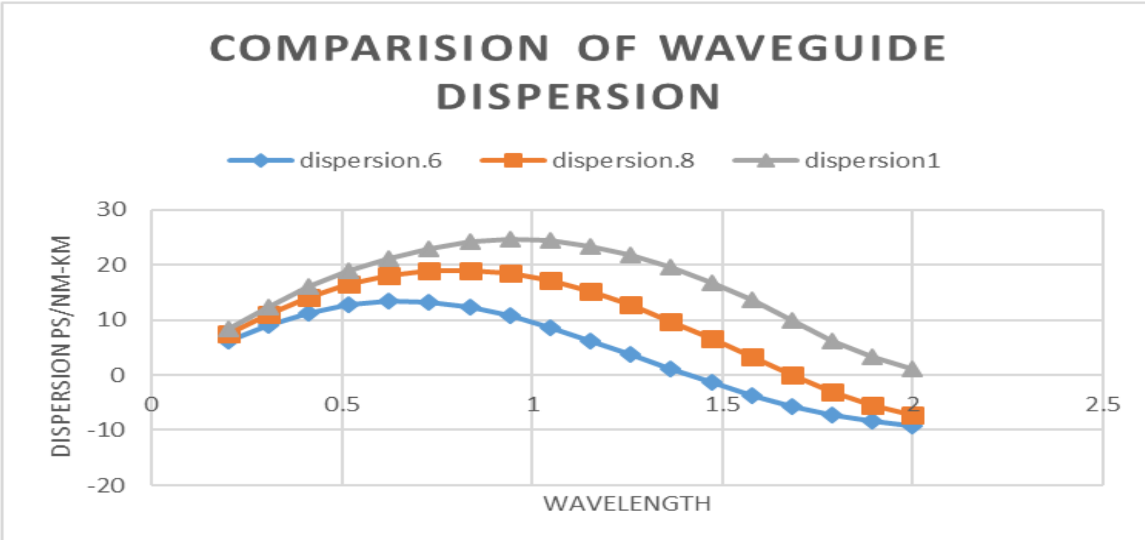

Fig 5.2 waveguide dispersion v/s wavelength for dimeter = 1μm,0.8μm,0.6μm

5.4 comparision of chromatic dispersion(total dispersion)

Table 5.2 Wavelength v/s total dispersion

wavelength	a/b=1.32	a/b=1.22	a/b=1.64	mix	a/b=1.0um circular	d=0.6um	D= 0.8um
0.517647059	- 631.8940409	- 631.8957836	-641.136751	-640.304876	- 677.5611786	- 683.7168533	-680.024165
0.623529412	- 245.4728624	- 246.3333746	-261.64019	-260.833925	- 303.2061562	- 311.0864995	-306.422742
0.729411765	- 104.0996341	- 104.1374419	-104.299298	-103.525587	- 150.5085352	-160.312355	-154.600807
0.835294118	- 34.54773613	- 34.51025927	16.39738005	-30.2269825	- 81.43242087	- 93.27491991	-86.5129079
0.941176471	22.76285561	21.73327127	85.41220659	16.72897307	- 38.38854081	- 52.24782281	-44.5331464
1.047058824	50.93237015	49.38628283	86.46978143	44.17308078	- 14.57959505	- 30.26835016	-21.8043405
1.152941176	75.63847525	73.52690224	90.89383425	68.36791401	6.258813238	- 10.90495025	-1.98725523
1.258823529	94.46920131	91.75597403	99.21576505	86.96833067	21.79047736	3.65205423	12.66207736

1.364705882	105.0723451	101.7400514	110.5827549	97.69374364	29.70546452	11.20029635	19.90978681
1.470588235	116.1491334	112.2145752	122.3159461	109.3133502	38.64923401	20.44435016	28.46475035
1.576470588	116.3013997	111.8417734	122.8905755	110.4779158	36.99938551	19.76981603	26.74891725
1.682352941	116.2271908	111.4052306	122.8489322	111.9023659	35.01027064	19.3916755	25.03795682
1.788235294	116.6914955	111.7601394	122.8176309	114.3325155	32.80046206	19.35024654	23.44774087
1.894117647	133.2507909	128.3315139	138.7569288	132.6238378	45.5178704	33.83913783	36.69932799

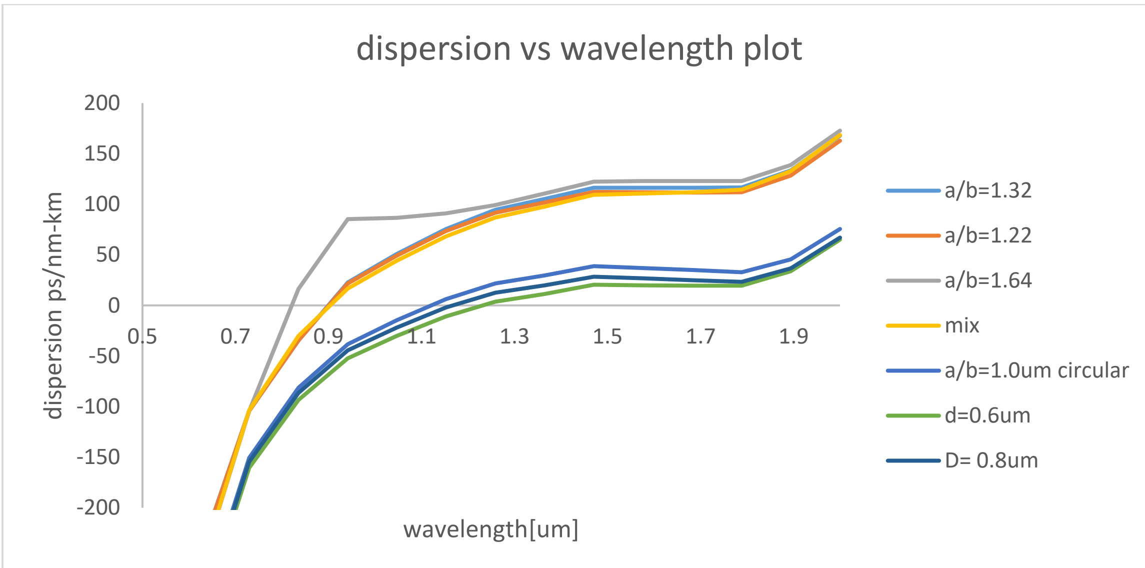

Fig 5.3 comparision of chromatic dispersion v/s wavelength

Chromatic dispersion is a combination of two type of dispersion 1) waveguide dispersion 2) material disersion. Dispersion in PCF is highly effected by the size of air holes and arrangement of air hole in cladding region. The dispersion propery can be altered by changing the geometry of PCF. Fig 5.3 shows the variation of dispersion with wavelength, it can be observed from the Fig 5.3 that the magnitude of dispersion is minimum for circular air hole spiral PCF and higher for eliptical air hole spiral PCF. At 1.55μm, the minimum dispersion obtained for 0.6μm circular air hole.By comparing the result of circular air hole spiral PCF for diameter 1μm and elliptical air hole spiral PCF for same air filling fraction, we get lower dispersion for circular air hole spiral PCF.

5.5 Comparison of zero dispersion wavelength

Table 5.3 Zero dispersion wavelength

Circular air hole	Zero dispersion wavelength	Elliptical air hole	Zero dispersion wavelength
Diameter =1.0 [µm]	1.12[µm]	Ellipticity ratio=1.22	0.901[µm]
Diameter =0.8 [µm]	1.18[µm]	Ellipticity ratio=1.32	0.896[µm]
Diameter =0.6 [µm]	1.24[µm]	Ellipticity ratio=1.62	0.835[µm]
		Ellipticity ratio=graded	0.903[µm]

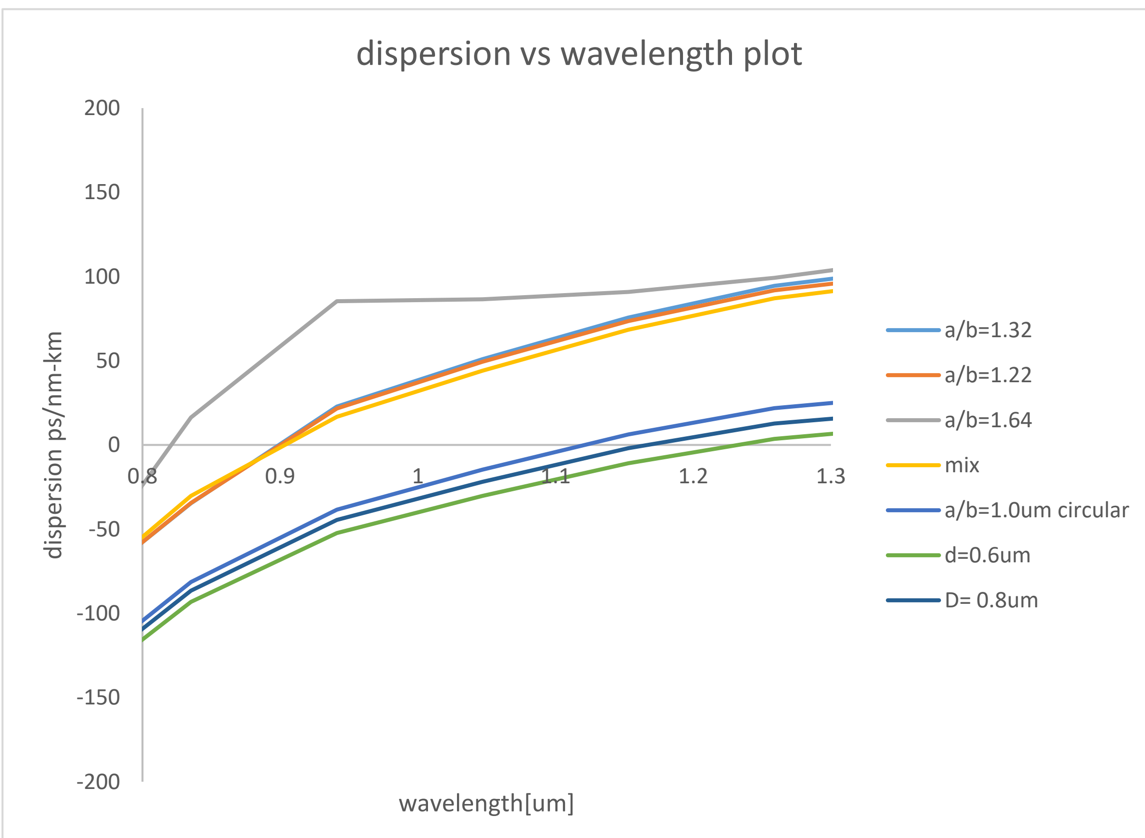

Fig 5.4(a) zero dispersion wavelength at diameter = 1µm,0.8µm,0.6µm

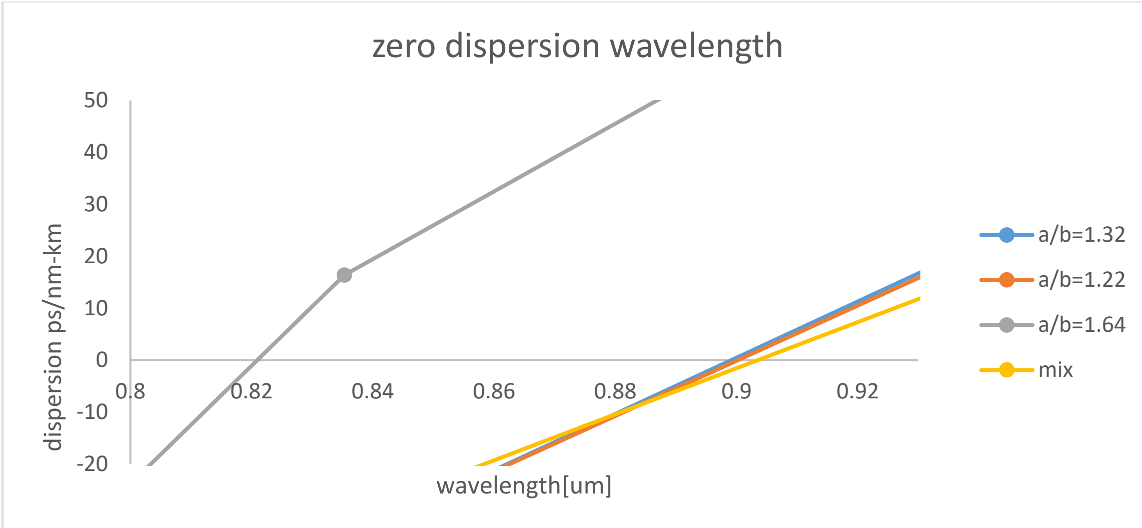

Fig 5.4(b) zoom view of above graph

the zero-dispersion wavelength is the wavelength at which waveguide dispersion and material dispersion and cancel one another. it can be seen from fig 5.4(b) that as reduce the diameter of air hole zero dispersion wavelength shift toward right hand side. By analyzing the result of both designs, it observes that as change the geometry of air holes from circular to elliptical, zero dispersion wavelength get shifted to the lower side of wavelength. [23]

5.6 Comparison of effective area

Table 5.4 Wavelength v/s effective area

w[µm]	a/b=1.22	a/b=1.32	a/b=1.55	graded	d= 1um c	d=0.8um c	d=0.6 c
0.2	3.772131186	3.786415948	3.76221508	3.896396857	3.823071697	4.426735403	5.143228341
0.305882353	3.849690648	3.864293064	3.839919906	3.971831001	3.892767746	4.506450938	5.253455655
0.411764706	3.927900397	3.942710503	3.917756542	4.047917293	3.963409882	4.588071714	5.37541498
0.517647059	4.007346111	4.022148574	3.996381016	4.124576639	4.035180071	4.672394294	5.515343806

0.623529412	4.089229882	4.103893848	4.076630939	4.202359198	4.108553734	4.760437539	5.68245269
0.729411765	4.118498296	4.190001386	4.159832827	4.282067549	4.18377514	4.853597558	5.890022937
0.835294118	4.198970615	4.20942438	4.249063148	4.365328268	4.261146999	4.954023671	6.156144673
0.941176471	4.286266404	4.296538583	4.250328471	4.456159114	4.341103581	5.065053793	6.504054728
1.047058824	4.383503932	4.394087191	4.344036914	4.564281211	4.424287177	5.191684424	6.96196707
1.152941176	4.495354449	4.506904522	4.451578296	4.710695973	4.51168719	5.341034793	7.562255223
1.258823529	4.628532812	4.641889572	4.579201431	4.935023101	4.60482817	5.522750946	8.339836175
1.364705882	4.792460576	4.808718265	4.735596964	5.305759001	4.706002609	5.749290284	9.329664759
1.470588235	5.00025413	5.020882095	4.932772544	5.94694723	4.818541391	6.036030659	10.56341686
1.576470588	5.270173552	5.297142956	5.187249215	7.136820457	4.94710728	6.401163022	12.06575651
1.682352941	5.627588888	5.663443122	5.521634868	8.759497803	5.097987091	6.865345171	13.85088964
1.788235294	6.107423164	6.155222861	5.966564693	10.57457026	5.279347959	7.451074732	14.92622588
1.894117647	6.756828862	6.819849249	6.562803146	12.58651604	5.501416427	8.181756249	14.99871432

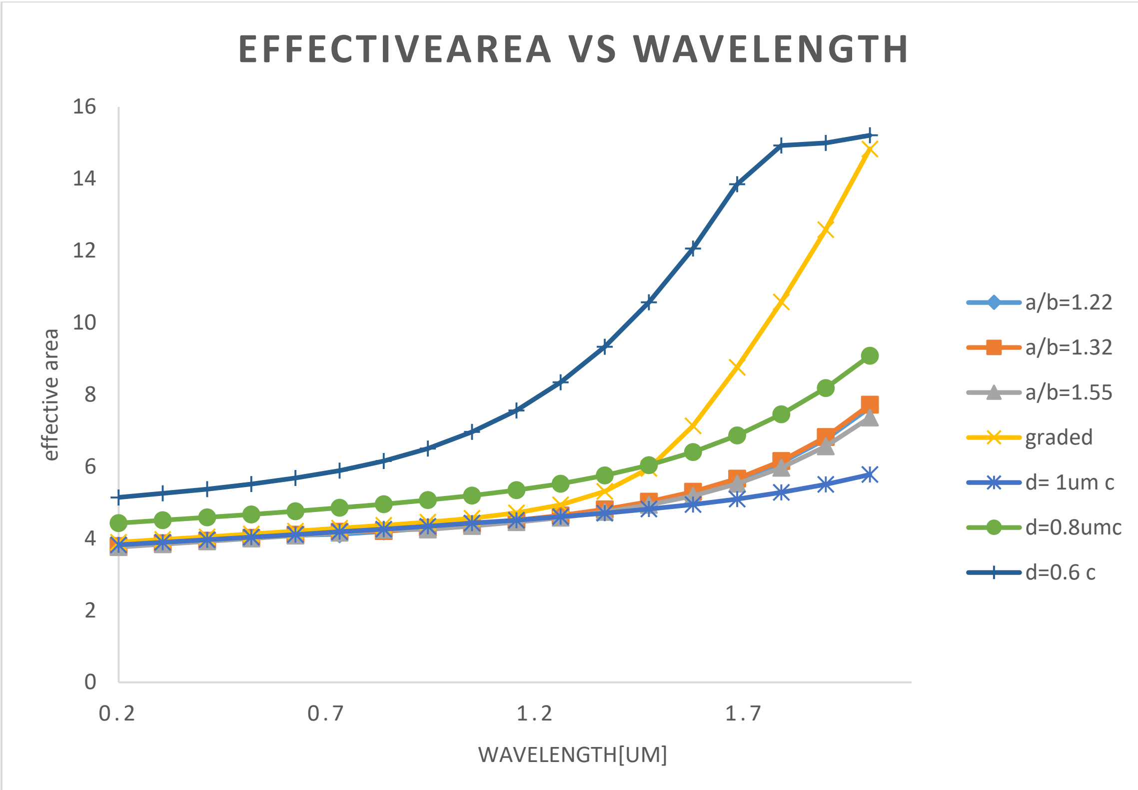

Figure 5.5 comparison of Effective area vs wavelength plot

In Fig 5.5, the effect of diameter of air hole and geometry of air hole on the effective area is examined. The effective area of PCF is much smaller than conventional PCF. By analyzing the result of PCF, it is observed that elliptical air hole PCF offers high effective area than circular air hole PCF. For circular air hole PCF of diameter 1µm, a minimum effective area is obtained.

5.7 Birefringence vs Wavelength

. High birefringence fiber can be used as a sensor. To increase the birefringence, elliptical air holes are introduced in PCF or the symmetry of PCF is broken. It can be seen from Fig 5.6 that birefringence varies with ellipticity ratio. Because if, there is a change in ellipticity ratio air filling fraction get changed. It can be seen from the graph that for circular air hole minimum birefringence of the order 10^{-3} is observed and as the ellipticity ratio is increased, the magnitude of birefringence for PCF also increases.

Table 5.5 Wavelength v/s birefringence

Wavelength	a/b =1.22	a/b=1.32	a/b=1.55	a/b=1.64	graded ellip holes	circular air hole
0.2	1.74847E-06	1.50167E-06	2.80366E-06	3.14214E-06	4.19246E-06	4.19467E-06
0.305882353	1.48852E-05	1.46567E-05	1.77249E-05	1.85311E-05	1.78522E-05	1.78587E-05
0.411764706	4.26633E-05	4.29268E-05	4.84759E-05	5.0027E-05	4.39874E-05	4.39995E-05
0.517647059	8.78263E-05	8.92817E-05	9.85487E-05	0.00010136	8.50137E-05	8.50318E-05
0.623529412	0.000152641	0.000156227	0.000171126	0.000175951	0.000142772	0.000142797
0.729411765	0.00023896	0.000245888	0.000269052	0.000276875	0.000218491	0.000218521
0.835294118	0.000348186	0.000359985	0.000394811	0.000406856	0.000312774	0.000312807
0.941176471	0.000481257	0.000499825	0.000550549	0.000568325	0.000425615	0.000425648
1.047058824	0.000638642	0.000666297	0.000738086	0.000763449	0.000556416	0.000556448
1.152941176	0.000820319	0.000859838	0.00095887	0.000994067	0.000704013	0.000704039
1.258823529	0.001025688	0.001080311	0.001213811	0.001261502	0.000866706	0.000866651
1.364705882	0.001253352	0.001326715	0.001502907	0.001566158	0.001042292	0.001041817
1.470588235	0.001500671	0.001596573	0.001824443	0.001906677	0.001228134	0.001226181
1.5764705	0.0017629	0.0018847	0.0021733	0.0022782	0.0014213	0.0014151

88	22	75	81	2	25	78
1.6823529 41	0.0020319 75	0.0021818 62	0.0025389 63	0.0026698 45	0.0016190 21	0.0016024 97
1.7882352 94	0.0022953 31	0.0024735 5	0.0029046 53	0.0030644 66	0.0018189 35	0.0017793 89
1.8941176 47	0.0025385 98	0.0027456 21	0.0032560 59	0.0034475 62	0.0020198 56	0.0019346 94

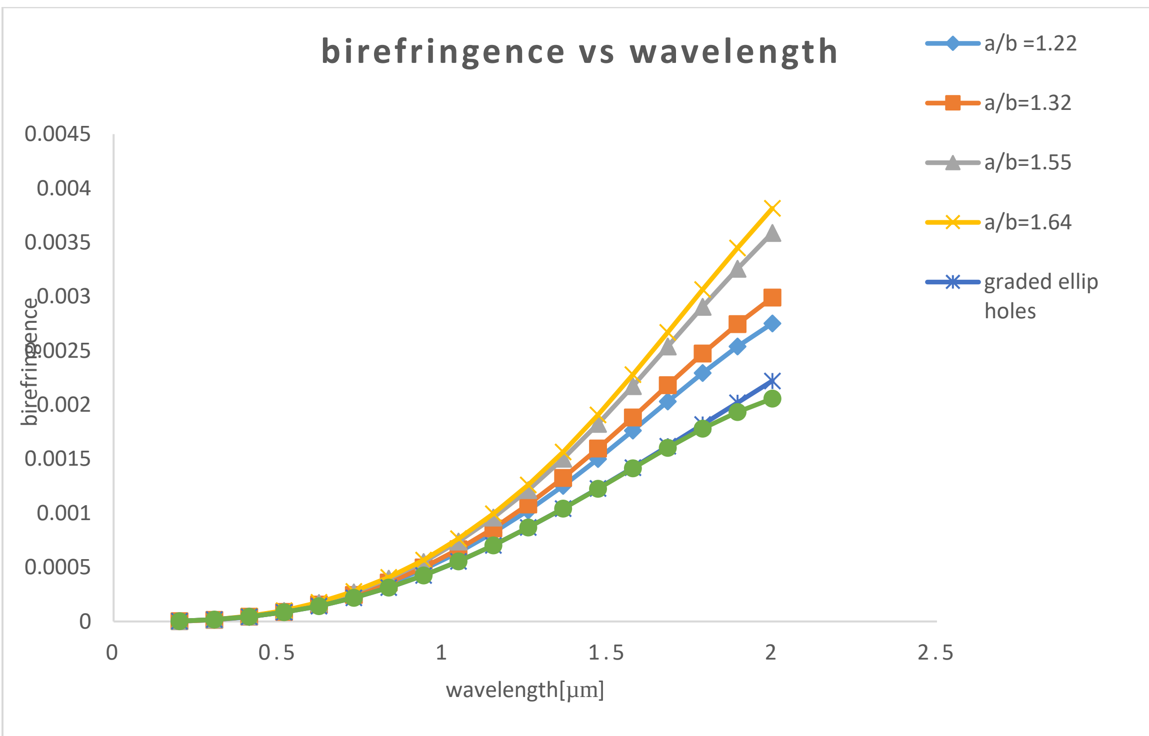

Fig 5.6 birefringence v/s frequency plot for different ellipticity ratio

Conclusion and discussion

Proposed two-dimensional photonic crystal fiber has been designed and analysed for high birefringence and flattened dispersion. For analyzing the proposed design Finite Element Method has been used. The following fundamental characteristics of PCFs have been found out. They are shown in tabular format.

Our finding

1.Power confinement of spiral PCF for different diameter in circular spiral PCF
2.Effective mode index variation with wavelength for different diameter in circular spiral PCF
3.Material dispersion for diffused silica at refractive index 1.45 in circular spiral PCF
4.Wavefuide dispersion for circular hole PCF at different diameter by varying wavelength
5.Chromatic dispersion for circular hole PCF at different diameter by varying wavelength
6.Zero dispersion wavelength at different diameter for circular spiral PCF
7.New structure of elliptical hole spiral PCF keeping all parameter similar
8.Effective refractive index variation v/s wavelength for elliptical hole spiral PCF
9.Chromatic dispersion vs wavelength for elliptical hole spiral PCF
10. Birefringence vs ellipticity ratio for elliptical hole spiral PCF
11. Birefringence vs wavelength plot for elliptical hole spiral PCF
12. Effective area vs wavelength plot for elliptical hole spiral PCF
13. Comparative study of different diameter circular air hole spiral photonic crystal fiber and different ellipticity ratio spiral PCF

Here It, found out properties of different diameter of air hole for doped silica spiral photonic crystal fiber. In this report, different spiral photonic crystal fiber has been examined. By optimizing the geometry of PCF, we get almost flat dispersion in the range of 1.45[um] to 1.70[um].The numerically simulated result shows that a significantly lower dispersion occurs at a diameter of 0.6 μm. a circular spiral PCF has been designed in which we increase the diameter of air hole and analyzed that as reduce the diameter of air hole dispersion also decreases and It also get the zero-dispersion wavelength shift toward right hand side as we reduce the diameter of the air hole. the designed structure also has lower dispersion than octagonal photonic crystal fiber. Due to lower dispersion, the fiber has its prominence in dispersion flatter device application. For further improvement of the result of PCF, move from spiral circular hole to elliptical air hole spiral PCF. Due to the compactness of design, PCF offers high nonlinearity, birefringence, and low effective area. From simulation result, it observes that if increase ellipticity ratio from 1 to 1.64, dispersion will also increase.it can be examined from the result that birefringence of order 0.003 at 1.80μm and 0.002 at 1.55μm is observed and Birefringence also increase with ellipticity ratio and at ellipticity ratio 1.64, birefringence of order 0.003 is observed. It observed that effective area increases with wavelength and get lower effective area for ellipticity ratio 1.55.but if compare circular air hole PCF and elliptical air hole PCF, circular air hole PCF offer lower effective area.

Future work

Present Research work on photonic crystal fibers is based on different spiral PCF. By changing the geometry of spiral PCF and air holes ellipticity ratio, the range of flattened dispersion will be increased to significant label and birefringence will be improved. Dispersion engineering is possible in PCFs in the range unachievable for classical fibers (flat dispersion in the large range, zero-dispersion, and anomalous dispersion in the visible range).

REFERENCES

[1] Md. Asiful Islam and M. Shah Alam (2012)" Design of a Polarization-Maintaining Equiangular Spiral Photonic Crystal Fiber for Residual Dispersion Compensation Over E+S+C+L+U Wavelength Bands" IEEE photonics technology letters, vol. 24, no. 11.

[2] Agrawal, A., Kejalakshmy, N., Rahman, B.M.A. and Grattan, K.T.V. (2009) 'Soft glass Equiangular spiral Photonic crystal fiber for Supercontinuum generation', IEEE Photonics Technology Letters, 21(22), pp. 1722–1724. doi: 10.1109/lpt.2009.2032523

[3] M. Samiul Habib, M. Selim Habib, M. Imran Hasan, S.M.A Razzak (2013) "Highly nonlinear polarization maintaining two zero dispersion spiral photonic crystal fiber using artificial defects" Elsevier optical fiber technology 19, 539-542.

[4] S. Revathi*, Srinivasa Inabathini, Ram Sandeep (2015) "Soft glass spiral photonic crystal fiber for large nonlinearity and high birefringence" Optica Applicata, vol. xlv, no. 1, 2015 doi: 10.5277/oa150102

[5] S. Revathi*, Srinivasa Inabathini and Rizwan Ali Saifudeen (2014) "Highly nonlinear and Birefringence spiral photonic crystal fiber" Hindawi. Advances in Optoelectronics.

[6] Varshali Sharma, Ritu Sharma (2016) "Design of Hybrid photonic crystal fiber with elliptical and circular air holes analysed for large flattened dispersion and high birefringence" SPIE "Journal of nanophotonics" doi: 10.1117/I.JNP.10.026016

[7] Philip St.J. Russell "Photonic-Crystal Fibers" (2006) IEEE journal of lightwave technology, vol. 24, no. 12

[8] Richard Soref, Life Fellow "The Past, Present, and Future of Silicon Photonics" (2006) IEEE journal of selected topics in quantum electronics, vol. 12, no. 6.

[9] Theis P. Hansen, Jes Broeng, Stig E. B. Libori, Erik Knudsen, Anders Bjarklev, Jacob Riis Jensen, and Harald Simonsen (2001) “Highly Birefringent Index-Guiding Photonic Crystal Fibers” IEEE photonics technology letters, vol. 13, no. 6.

[10] Md. Ibadul Islam a, Kawsar Ahmed a, Sayed Asaduzzaman a,b, Bikash Kumar Paul a, Touhid Bhuiyan b, Shuvo Sen a, Md. Shadidul Islam a, Sawrab Chowdhury (2017) “Design of single mode spiral photonic crystal fiber for gas sensing applications” Elsevier Sensing and Bio-Sensing Research.

[11] Jianfei Liao, Junqiang Sun, Mingdi Du, and Yi Qin (2014)” Highly Nonlinear Dispersion-Flattened Slotted Spiral Photonic Crystal Fibers” IEEE photonics technology letters, vol. 26, no. 4.

[12] Jianfei Liao, Tianye Huang, Zuzhou Xiong, Fangguang Kuang, Yingmao Xie (2017) “Design and analysis of an ultrahigh birefringent nonlinear spiral photonic crystal fiber with large negative flattened dispersion” Elsevier optic 135.

[13] Md. Ibadul Islam1, Maksuda Khatun1, Shuvo sen1, Kawsar Ahmed1 and Sayed Asaduzzaman (2016) “Spiral Photonic Crystal Fiber for Gas Sensing Application” 9th International Conference onElectrical and Computer Engineering 20-22 December 2016, Dhaka, Bangladesh.

[14] Arti Agrawal, Y. O. Azabi and B. M. A. Rahman (2013) “Stacking the Equiangular Spiral Photonics Technology Letters,25(3),pp.291-294 doi:10.1109/LPT.2012.2236309

[15] Ritu Sharma, Vijay Janyani, S. K. Bhatnagar (2011)"Low chromatic dispersion and highbirefringence investigated in elliptical air hole photonic crystal fiber", **Journal of Modern Optics** Volume:59 / 205-212 / 2011

[16] Rui Hao, Guifang Sun (2015) “Design of photonic crystal fiber with large negative dispersion and high nonlinearity” Optic 126,3353-3356

[17] Yashar E. Monfared, A.R. Maleki Javan, A.R. Monajati Kashani (2013) "Confinement loss in hexagonal lattice photonic crystal fibers" optik international journal for light and electron optics

[18] J. C. Knight, J. Arriaga, T. A. Birks (2000) "Anomalous Dispersion in Photonic Crystal fiber" IEEE photonics technology letters, vol. 12, no.7

[19] Jianfei Liao, Junqiang Sun, Mingdi Du, and Yi Qin (2014) "Highly Nonlinear Dispersion-Flattened Slotted Spiral Photonic Crystal Fibers" IEEE photonics technology letters, vol. 26, no. 4.

[20] Jamshid Heiadarialamdarloo, Carvalho MI, Ricardo Nunes Nogueira and Antonio Luis Jesus Teixeira(2016) "Highly nonlinear, dispersion flattened equiangular spiral photonic crystal fiber in telecommunication window" journal of laser optics and photonics doi:10.4172/2469-410X.1000

[21] Ritu Sharma, Vijay Janyani, S. K. Bhatnagar,"Improved Single Mode Property in Elliptical Air Hole Photonic Crystal Fiber", **Journal of Modern Optics** Volume:58 / 604-610 / 2011.

[22] Sumaiya Kabir, Mosst Tasnim Binte Shawkat, Muhammad Abdul Goffar Khan, S.M.A Razzak (2015) "Bending Insensitive Dispersion Flattened Modified Equiangular Spiral Photonic Crystal Fiber(MES-PCF)"IEEE international WIE Conference on Electrical and Computer Engineering.

[23]Japatosh Mondal Mohammad Shaifur Rahman (2015)"Design of Highly BirefringentDispersion Compensating Spiral Photonic Crystal Fiber" IEEE 2nd Int'l Conf on Electrical Engineering and Information & Communication Technology (ICEEICT).

[24] Boyao Li, Mingqin Li, Lu Peng, Guiyao Zhou, Zhiyun Hou, Changming Xia (2017) "Research on Dual-Wavelength Single Polarizing Filter Based on Photonic Crystal Fiber" IEEE Photonic Journal.

[25] Chengcheng Gui and Jian Wang (2012) "Elliptical–Spiral Photonic Crystal Fibers With Wideband High Birefringence, Large Nonlinearity, and Low Dispersion" IEEE Photonic Journal.Volume 4, number 6

[26] Tianye Huang, Jianfei Liao, Songnian Fu, M. Tang, P. Shum, Deming Liu (2014) "Slot Spiral Silicon Photonic Crystal Fiber With Property of Both High Birefringence and High Nonlinearity" IEEE Photonics Journal, volume 6 number 3

[27] Mahmud, R. R., Razzak, S. A., Hasan, M. I., & Hasanuzzaman, G. K. M. (2015)."Ultra-flattened high negative chromatic dispersion over O+ E+ S+ C+ L+ U bands of a microstructured optical fiber". Optical Engineering, 54(9), 097105-097105.

[28] Mondal, J., & Rahman, M. S. (2015, May). The design of highly birefringent dispersion compensating spiral photonic crystal fiber. In Electrical Engineering and Information Communication Technology (ICEEICT), 2015 International Conference on (pp. 1-4). IEEE.

[29] Geerthana, S., Raja, A. S., & Sundar, D. S. (2015). Design and optimization of photonic crystal fiber with improved optical characteristics. Journal of Nonlinear Optical Physics & Materials, 24(04), 1550051.

[30] Liao, J., Huang, T., Xiong, Z., Kuang, F., & Xie, Y. (2017). Design and analysis of an ultrahigh birefringent nonlinear spiral photonic crystal fiber with large negative flattened dispersion. Optik-International Journal for Light and Electron Optics,135,4249.

[31] Amin, M. N., & Faisal, M. (2016). Highly nonlinear polarization-maintaining photonic crystal fiber with nanoscale GaP strips. Applied optics, 55(35), 10030-10037.

[32] Chowdhury, S., & Kushary, S. (2017, February). The design of a nearly zero ultra-flattened dispersion shifted fiber with high birefringence and high non-linearity. In Electrical, Computer and Communication Engineering (ECCE), International Conference on (pp. 106-108). IEEE

List of Publications

Conference Paper

[1] Julie Devi, Amritveer Kaur, Ritu Sharma, Varshali Sharma, Santosh Chaudhary (2017) "Design and Analysis of Spiral Photonic Crystal Fiber giving Ultra Flattened Dispersion for C+L+U Band" *International Conference on Optical & Wireless Technologies (OWT2017)* March 18-19, Jaipur

[2] Amritveer Kaur, Julie Devi, Ritu Sharma, Varshali Sharma, Santosh Chaudhary (2017) "Design of Octagonal and Decagonal lattice Photonic Crystal Fiber for achieving Ultra Low flattened dispersion" *International Conference on Optical & Wireless Technologies (OWT2017)* March 18-19, Jaipur

Thesis

by Julie Devi

CHAPTER – 1

INTRODUCTION

1.1 Introduction

Since the introduction of conventional step index fibers, optical fibers have evolved into many forms in the 70s and later single material fiber where effective cladding structures determined the propagation of light. The principle objective was the transportation of light from one point to another whether by step index confinement or by band-gap confinement such as in Bragg fiber. We can use optical fiber in many applications like transporting high speed data, bio sensors Etc. the optical fiber can also use in Gas sensing application, strain or pressure measurement in bridges and high-power amplifier. Photonic Crystal Fibers (PCF) is a variant of the micro structured fibers with greater control of guiding properties. Such a vital Photonic Crystal fiber have large application area in nonlinear devices and high power optical fiber amplifier.

1.2History of PCF

Optical fibers were discovered in the 1970s and are now the backbone of opticalcommunication systems due to a large amount of information they can handle. Particularly designed optical fibers are also used for many optical applications, including sensors, medicine, illumination and much more. Standard step-index optical fibers guide light through total internal reflection, which occurs only if the core has a larger refractive index than the outer cladding. The optical signal propagates in the core is completely reflected at the interface core/cladding and is, therefore guided in the core. First fiber is fabricated by Russell consist hexagonal lattice in silica fiber. These novel periodic structures were called photonic crystals. Only light with certain wave vectors can propagate in the structure If a defect or periodic structure is introduced in the is in the structure, the wavelengths forbidden in the periodic structure are now allowed to “stay” in the defect as the photonic crystal running along the air hole prevents them from “escaping”. The refractive index is not required to be higher than that of the periodic material. By using this idea light can be trapped inside a hollow core (defect). Therefore, light can even be guided in the air.[8]

1.3 Theory of PCF

In the last decade, photonic crystal fibers have been under rigorous study and due to the development of PCF and unique application, attracted huge research interest. PCF is a fiber which contains its different optical properties from particularly varying the design and arrangement of air holes in fiber which run through the length of the fiber, not from different glass composition. The simplest type of PCF has triangular lattice. Photonic crystal fiber is categorized into two types of mechanism 1) Photonic band Gap 2) Total Internal reflection

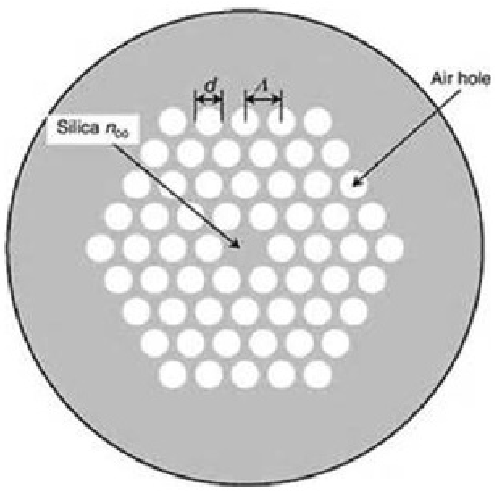

Fig 2.1 geometry of hexagonal PCF

1.3.1 Advantage of Photonic Crystal Fiber

- Better light confinement than conventional fibers
- Low dispersion
- Very low attenuation (holey fiber)
- More flexible than conventional fibers
- Many core fiber

1.3.2 Basics equations

Propagation of light in PCFs is described by Maxwell's equations. For no free charge or current, the following equations become applicable

$$\nabla . D = 0 \qquad \text{(a)}$$

$$\nabla \times H = \frac{\partial D}{\partial t}$$

$$\nabla . B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad (2.1)$$

$$\varepsilon(\mathrm{r},\omega) = \varepsilon(\mathrm{r}) \in R$$

$$\mathrm{D(r)} = \varepsilon(r) \times \varepsilon o \times E(r)$$

$$\mathrm{B} = \mu o \times H \qquad (2.2)$$

Inserting equation b into a

$$\nabla . \varepsilon(r) \times \epsilon o \times E(r,t) = 0$$

$$\nabla \times H(r,t) = \varepsilon(r) \times \varepsilon o \times \frac{\partial E(r,t)}{\partial t}$$

$$\nabla . \mu o . H(r,t) = 0 \qquad (2.3)$$

$$\nabla \times E(r,t) = -\mu o . \frac{\partial H(r,t)}{\partial t}$$

Since Maxwell's equations are linear we can separate out the time dependence by expanding into

a set of harmonic modes

$$H(r,t) = H(r) . e^{j\omega t}$$

$$E(r,t) = E(r) . e^{j\omega t}$$

To obtain coupled equations we need the following ones

$$\nabla.\varepsilon(r).E(r) = 0 \qquad (2.4)$$

$$\nabla \times H(r,t) = j\omega\varepsilon(r)\varepsilon o E(r)$$

$$\nabla.H(r) = 0$$

$$\nabla \times E(r) = j\omega.\mu o.H(r) \qquad (2.5)$$

1.4 Guiding mechanism in PCF

1.4.1 Total internal reflection

In solid core PCF light, is comes from high refractive index core to lower refractive index cladding. Light is kept in the core by total internal reflection in photonic crystal fiber. In PCF, When the angle of incident is greater is greater than the critical angle, total internal reflection takes place in solid core fiber.

1.4.2 Photonic bandgap in photonic crystal fiber defects is created by introducing air hole in fiber and the photonic band gap is created.in this case light guidance mechanism is like electron conduction mechanism in solid-state physics. Photonic band gap structure offer opportunity to design new optical property in existing fiber. Due to the presence of air hole, light is confined in the core region and these modes guided along the defect through the fiber.

1.5 Properties of PCF

1.5.1 Confinement loss

The losses in PCFs occur for many reasons, such as Rayleigh scattering loss, intrinsic material absorption loss, macro and micro binding loss, and so on. Fabrication related losses can be reduced by carefully optimizing the fabrication process. The Periodic arrangement of air holes in PCF causes a decrease in optical confinement, is called Confinement loss. PCF is made by single material and so guided mode is leaky. The region of loss is that the refractive index of the core is same the refractive index of the cladding. Confinement loss depends on the structure and arrangement of air holes in PCF. We can alter the value of loss by changes the geometry of fiber. For analyzing the confinement loss, PML layer is applied to PCF. With the help of PML layer, we find the value of the imaginary refractive index and find the confinement loss.

$$\text{Confinement loss} = 8.686 \times 10^6 \times \text{ko} \times \text{im}(n_{\text{eff}}) \qquad (\text{dB/m})$$

1.5.2 Normalized frequency

The V parameter (normalized frequency) is commonly used in the design of conventional SIFs and is given by

$$V = \frac{2\pi a}{\lambda} \times \sqrt{n_{co}^2 - n_{cl}^2}$$

To finding the V parameter for PCF, its different nature is considered. V parameter of PCF given as

$$V_{\text{PCF}} = \frac{2\pi a}{w} \times \sqrt{n_{FM}^2(w) - n_{FSM}^2(w)}$$

Where $n_{FM}(w)$ is wavelength dependent refractive index of fundamental mode and $n_{FSM}^2(w)$ is fundamental space filling factor. For single mode fiber V_{PCF} should be equal to π.

1.5.3 Effective modal area

The effective mode area A_{eff}, is computed using transverse electric or magnetic field vector of the whole cross-sectional area of the fiber. The effective area of the of the fiber core A_{eff} is defined as [2]

$$A_{eff} = \frac{(\iint |E_t|^2 dxdy)^2}{\iint |E_t|^4 dxdy}$$

Or

$$A_{eff} = \frac{(\iint |H_t|^2 dxdy)^2}{\iint |H_t|^4 dxdy}$$

where E_t and H_t is the transverse electric field vector and magnetic field vector respectively and the integration is done through the whole cross-sectional area of the fiber.

1.5.4 Chromatic dispersion

Effective refractive index of mode profile depends on wavelength. Relation between wavelength and refractive index is given by equation below

$$v=\frac{c}{n}$$

All optical source used for optical transmission emit light, in the band of spectral width $\Delta\lambda$, distributed around λ.so individual frequency component experienced different velocity so different frequency component travel with different speed and pulse get dispersed. The speed at which light travel through fiber rely on its wavelength and design of fiber thus some wavelength of band of which the pulse is embraced may be delayed compared with other, leading to pulse spreading with time after traversing a significant length of fiber called chromatic(Total) dispersion. Total dispersion is the sum of two form of dispersion (1) material dispersion (2) waveguide dispersion. The chromatic dispersion D of a PCF is calculated from given formula [18-20]

$$D = -\frac{\lambda}{c} \times \frac{d^2_{neff}}{d\lambda^2}$$

where c is the velocity of light in a vacuum n_{eff} is effective refractive index of PCF.

1.5.4.1 Material dispersion

The material refractive index depends on the value of wavelength. Material dispersion is calculated by a sellmeier equation which gives the relation between refractive index and wavelength. Usual form of equation is given as [22]

$$n^2(w)= 1+\frac{B_1 w^2}{w^2-C_1}+\frac{B_2 w^2}{w^2-C_2}+\frac{B_3 w^2}{w^2-C_3}$$

where n is refractive index of material and w is operating wavelength. Coefficient $B_{1,2,3}$ and $C_{1,2,3}$ is experimentally examine. The coefficient of the sellmeier equation is different for different material.

1.5.4.2 Waveguide dispersion

Waveguide dispersion depends on the fiber refractive index profile. Waveguide dispersion is significant for the fiber having small effective area. Altering the refractive index profile will alter the waveguide dispersion.

$$D = \frac{\lambda}{c}\frac{d^2 n}{d\lambda^2}$$

1.5.5 Modal birefringence

Effective index profile sometimes depends on the polarization and propagation direction of optical signal. So the refractive index of the two fundamental modes (x and y mode) will not be same. Birefringence is the difference of effective refractive index between these two-fundamental modes. Birefringence can be calculated using the equation [9]

$$\text{Birefringence} = [n_{eff}(X\text{ mode}) - n_{eff}(Y\text{ mode})]$$

1.5.6 Non-linearity

The nonlinear effect in optical fiber occurs due to intensity dependence of refractive index in medium or different scattering phenomenon. Nonlinearity is a most important phenomenon in optical fiber communication and used in various applications such as four-wave mixing, Supercontinuum generation and self-phase modulation. Nonlinearity depends on the type of material and design of fiber. Nonlinearity is calculated with the help of nonlinear coefficient that is different to different materials. [12]

$$\gamma = \frac{2\pi}{\lambda} \times \frac{n_2}{A_{eff}}$$

where n_2 is nonlinear coefficient

1.6 Applications of PCF

1.6.1 Dispersion compensation Fiber

DCF is a simple and developed technology used in optical communication system. Commercially available DCF can compensate the dispersion of all transmission fiber even for high bit rate and long distance. The newest development in DCF reduced losses and length of optical fiber. This fiber can also be used as dispersion shifted fiber. [33]

1.6.2 Polarization maintaining PCF

Optical fiber always shows some amount of birefringence even if PCF has a circular design because in fabrication process there is always some stress or pressure which breaks the symmetry of fiber because of this polarization of light propagating in the fiber regularly changes in an uncontrolled manner. To remove this problem PMF is used. PMF has a high value of birefringence, the polarization of light launched into the fiber is aligned with one of the birefringence axes and polarization is maintained even if the fiber is bent. Due to strong birefringence, the propagation constant of two polarization modes is different so the relative phase of such copropagating modes rapidly drift away so any disturbance in giber does not affect large enough on polarization direction. [32]

1.6.3 Hollow core fiber

Hollow core fibers light is guided by using a photonic bandgap structure in place of a traditional total internal reflection. Since most of the optical power propagates through the core region, not cladding region, these fibers are particularly unaffected by nonlinear optical effects. Hollow core fibers can offer other advantages like extremely low loss bends, extreme dispersion values and the ability to modify the core material properties by exchange air for some other gas and HC-PCF can be used as microcell.

1.6.4 Fiber laser amplifier

Fiber amplifiers are one of the key components of modern telecommunication. Also, fiber lasers are starting to be more and more important in medicine, spectroscopy, and industry. Compared to conventional solid-state lasers, the great advantage of fiber lasers is their outstanding heat dissipation capability. The fiber laser is insusceptible to thermal lensing and all other temperature properties. The one most important advantage of fiber laser amplifier than a conventional laser is the quality of stream of light which is close to the diffraction limit.

CHAPTER 2

ANALYSIS METHOD

2.1 Methodology

In general, three methods are utilized to analyze the structure and the properties of photonic crystal fibers. They are

- Effective refractive Index Approach
- Basis-Function Expansion Approach
- Numerical Approach

2.1.1 Effective Index approach

The first approach developed for PCFs was the effective index approach based on a very simple scalar model using an effective cladding index. In this approach propagation of light is through slab like PCF is commonly describe in terms of refractive indices , we can replace 3D structure by an effective 2D refractive index profile .first, an effective index for the periodically repeated hole-in-silica structure is evaluated and then the microstructured cladding region is replaced by a uniform medium with a properly chosen effective index, resulting in an equivalent step index fiber (SIF) consisting of a core and a cladding region. Using this simple model and the well-established fiber theory, we can obtain a qualitative information about PCFs with perfect hexagonal symmetry. The core is pure silica, but the effective cladding index is determined by using the propagation constant of the lowest-order fundamental mode propagating in the periodically repeated hole-in-silica structure without any defects. The propagating modes in such an infinite cladding material are called space filling modes, the propagation constants of which are strongly dependent on the operating wavelength λ. The propagation constants of the space-filling modes are usually calculated by solving an approximate scalar-wave equation within a unit cell centered on one of the air holes. By reflection symmetry, the Neumann condition is enforced on each cell edge, namely, the normal derivative of the cladding mode field to the edge must be zero.

2.1.2 Basic Function Expansion approach

Although the effective index approach can provide good qualitative information about PCFs, this approach is unable to accurately predict modal properties such as dispersion or birefringence. These quantities depend critically on PCF geometries. An early full-vector model for PCFs has been based on a modal decomposition technique using various basis functions such as sinusoidal functions, Hermite–Gaussian functions and cylindrical functions. The PWE has been effectively applied not only to index guiding PCFs but also to PBGFs. PWE involves defining the supercell over a restricted region and using periodic boundary conditions to extend the structure spatially, and therefore, the applicability to PCFs that do not need to be periodic is somewhat restricted. An alternative approach is a localized-function method (LFM). As the guided modes in PCFs are localized in the defect core region, their modal fields are well described using localized Hermite–Gaussian functions. The LFM takes advantage of mode localization, and thus, a modest number of functions are required to accurately model the guided modes, resulting in less computational efforts, compared with the PWE.

2.1.3 Numerical approach

Although the basis-function expansion approach can accurately predict the modal properties such as dispersion and birefringence, it is difficult to apply it to more complicated fibers with noncircular air holes and/or longitudinally varying structures. Recently, published models utilize other direct numerical analysis techniques such as BPM, FDM, FDTD, BEM, and FEM. In the FEM, instead of solving the wave equation, the corresponding functional to which a variational method is applied is set up, where the fiber cross section is divided into the so-called elements, an equivalent discretized model for each element is constructed, and then all the element contributions to the whole fiber cross section are assembled.

2.2 Full Vectored Finite Element Method

- A finite element optical mode solver is the most popular method to thoroughly analyze photonic crystal fibers. The finite element method is a numerical approximation process used for the solution of boundary and initial value problems for differential equations
- The FEM produces approximate solutions by writing them as linear combinations of simple basis functions and test functions equal to the basic functions and introducing these into the variational formulation of the problem
- The final FEM equations that must be solved are systems of linear algebraic equations
- COMSOL is modern software embedding the FEM with a cleverly designed user interface designed to increase the applicability and ease of use of mathematical modeling methods

There is different matched layer condition in finite element method.

2.2.1 Perfect Magnetic conductor: - This boundary condition can be expressed as

$$n.D = 0$$

$$n \times H = 0$$

According to this condition, tangential components of H and normal components of D is continuous across any interface

2.2.2 Perfect Electric conductor This boundary condition can be expressed as

$$n.B = 0$$

$$n \times E = 0$$

Here, n is the unit normal vector to the boundary. According to this condition, tangential components of E and normal components of B is continuous across any interface.

2.3 Comsol Multiphysics

COMSOL MULTIPHYSICS software is used to check different properties of PCF. COMSOL software (5.1) is used for the numerical answers & graphs of different parameters of spiral PCF and the results are reported in this thesis.

2.3.1 Design of PCF using COMSOL

- Open software COMSOL 5.1. A window named **Model Wizard** will be opened
- Then following steps are followed: **optics Module>Wave optics>Electromagnetic, frequency domain Waves>Mode analysis**
- The software is opened with working window.

To design the structure of a PCF first set it at appropriate modal analysis, then draw the structure of PCF and give input for geometrical properties, initialize mesh and then solve the structure. The procedure for this work is given bellow

2.3.1.1Setting appropriate parameter and study

- We Select Physics in the Physics menu to open the Application Mode Properties dialog box**.**
- We select the correct study using **Add study** dialog box
- We select the appropriate parameter for our geometry and define all the parameter in setting window of the parameter.

2.3.1.2 Geometry Modeling

- On geometry, toolbar click **primitive** and choose circle
- In **setting window** of circle locate size and shape
- We start by drawing a circle with the radius and the center at desired values with right click in geometry icon.
- In geometry tool bar click **transforms** and select **rotate.**
- Click the build all object button.

2.3.1.3 Material setting

- After making the geometry of PCF we add material in our geometry.
- First, click on **material toolbar** and select blank material and write the refractive index of material in material setting window
- Select domain

2.3.1.4 Mesh setting

- In **modal builder** window > component 1 click **mesh 1**
- In **setting** window for mesh choose physics controlled Mesh
- From **element size list** select between **fine** to **extra coarser**
- Click on **build all** button

2.3.1.5 Study Setting

- In **modal builder** window under **study 1** click **mode analysis.**
- In the setting window for mode, analysis locates the **study setting** window.
- In the **search for mode around a** text field type refractive index of the core.
- In the **search for frequency around** text field type frequency.
- On the **home,** toolbar clicks **compute.**

2.3.1.6 Post processing

- In modal builder window under result click 1D plot group.
- Under 1D plot group select line graph.
- Plot line graph between wavelength and n_{eff}.
- Extract spreadsheet from comsol to excel.

CHAPTER 3

LITERATURE SURVEY

Md Asiful Islam and M Shah Alam proposed a structure of spiral PCF. This PCF can be used to compensate the dispersion properties and used for supercontinuum generation. The structure contains the air holes in silica material. there is N circular air hole in each arm and diameter of each air hole is increased progressively. The angular displacement of each arm is θ than by previous one. the proposed structure contains an elliptical air hole at the center of air core This design is simulated by comsol Multiphysics which is based on full vector finite element method. The design of PCF shows the dispersion of -293.5 and -393 ps /nm km. another exceptional feature of this design is their high birefringence of 0.0278.

Agrawal, A., Kejalakshmy, N., Rahman, B.M.A. and Grattan, K.T.V. (2009) [2] the proposed spiral PCF fiber design in the SF57 is presented with high nonlinearity with low and flattened dispersion. The design of PCF is inspired by nature. Each arm of PCF contains air holes with constant radius r and angular displacement θ. A full vector finite element method is used to simulate the design. ES-PCF design in SF57 has been presented that have high nonlinearity of 2150/W.km at 1550nm and also the PCF optimized for low dispersion of 0.8 Ps/nm.km. it combines the advantage of better dispersion control with the smaller effective area and high nonlinearity.

M. Samiul Habib, M. Selim Habib, M. Imran Hasan, S.M.A Razzak (2013) [3], this paper presents a soft glass spiral photonic crystal fiber for tune two zero dispersion wavelength in the visible and near infrared region. The design contains six circular rings and eight spiral arm, each air hole of the first ring is the starting point of a spiral arm. The distance of second air ole in the spiral arm from the center is $r_{b1}=r_{b0}+0.8(2\times r_a)$ with an angular shift $\theta_1=\frac{360}{2\times N}$ where N is the number of spiral arms. To produce high birefringence, an artificial defect is introduced in the core region. The designed fiber has two ZDW at 700nm and 1050nm with very large nonlinearity of 7326/W. Km at 700nm and 3919/W. Km at 1050nm. The designed PCF offer birefringence of 0.1 at 1.8μm.

S. Revathi*, Srinivasa Inabathini, Ram Sandeep (2015) [4] This paper present a soft glass spiral photonic crystal fiber with a circular air hole for achieving high birefringence, large nonlinearity, and large negative dispersion. For achieving high birefringence, the defect is introduced in the core region. The structure is designed using the comsol 3.5 it is based on finite element method, an accurate numerical method used to find the solution of boundary problems. The structure contains 8 spiral arms and each arm contains five circular air hole. An elliptical air hole introduced in the center of core with semi major axis a and semi minor axis b. this fiber can be used as polarization maintaining fiber which has more control on polarization. This fiber optimized for high birefringence of 2.96×10^{-2} at 1.55μm and high nonlinearity of 5828/W.Km.this fiber give negative dispersion -1546.6ps/nm.km at 850 nm.

S. Revathi*, Srinivasa Inabathini and Rizwan Ali Saifudeen (2014) [5] the proposed structure is designed with elliptical air hole using comsol. The structure is designed with chalcogenide glass. This structure is optimized for different ellipticity ratio of the air hole. The structure contains seven spiral arms and each arm contains five elliptical air holes. The angular displacement between two adjacent elliptical air hole is $\frac{180}{N}$ where N is the number of air holes in a ring. The effect of ellipticity ratio on the various property of fiber is observed. The advantage of spiral structure is low effective area and high nonlinearity. By obtaining result from simulation, we get high birefringence of order 10^{-2} which is larger than conventional PCF. Fiber offers high birefringence of 0.0256 at 1.55μm and gets negative dispersion of -1136.69 at .85μm. We can use this fiber in the nonlinear application.

Varshali Sharma, Ritu Sharma (2016) [6] the proposed design of PCF with elliptical and circular air hole is analysed for high birefringence and large flattened dispersion. There are five rings, inner three rings have elliptical air hole and outer two rings have circular air holes. These layouts are designed and analysed and also compare with layout having only circular air holes arrangement. From the analysis, we observed flattened dispersion over a large range from 1.2 to 1. 8μm.the proposed design also give high birefringence value which can be used in various sensing application.

Philip St.J. Russell (2006) [7] Photonic crystal fiber with a periodic transverse microstructure have been in practical since 1996. It is now possible to manufacture PCF of a scale 10 nm on a scale of 1um scale, which allows exceptional control on optical properties like dispersion, effective area, birefringence and nonlinearity of optical fiber. The novel idea for developing PCFs was the creation of a new design dielectric waveguide, one that guides light by means of a two-dimensional (2-D) PBG. the idea was to trap the light in two dimensional PCF by using air holes array.

Theis P. Hansen, Jes Broeng, Stig E. B. Libori, Erik Knudsen, Anders Bjarklev, Jacob Riis Jensen, and Harald Simonsen (2001) [9], photonic crystal fiber offers new possibilities of highly birefringence fiber due to large index difference between core and cladding region compared to conventional fiber. The proposed design consists triangular lattice of air holes with a pitch of 4.5µm. the core is made by removing two air holes. The fiber was found to exhibit the highest birefringence of 6.9×10^{-4} at frequency 1.05µm. by optimizing the design of PCF, we get high birefringence at 1.55µm for pitch ratio 1.7µm.

Md. Ibadul Islam, Kawsar Ahmed, Sayed Asaduzzaman, Bikash Kumar Paul a, Touhid Bhuiyan, Shuvo Sen, Md. Shadidul Islam, Sawrab Chowdhury (2017) [10], proposed structure consists air holes that are arranged in a hexagonal design of pitch Λ. The refractive index of the silica regions is 1.4445. The holes are characterized by the area and ellipticity ratio $\frac{a}{b}$, where a and b are the diameter of the major and minor axes, respectively. Geometry of PCF is simulated for different ellipticity ratio and hole area is less than 0. 4µm.it has been observed from the result that on the holes area. whereas for larger holes and ellipticities, the core itself has an elongated elliptical shape. for small hole area and small ellipticity, birefringence depends only on the ellipticity and not on area.

Jianfei Liao, Junqiang Sun, Mingdi Du, and Yi Qin (2014) [11], the structure consists spiral photonic crystal fiber that is used as a sensor. This design can be used to sense the colorless gas and air pollution by metering gas condensate elements. The proposed structure simulated by finite element method. Design consist of a cluster of circular air holes in core region which are formed into porous shape and cladding is formed in a spiral shape. The proposed structure gives high sensitivity and high birefringence for the wavelength range of 1μm to 1.8μm. we get high birefringence of 7.23×10^{-3} at 1.33μm. so proposed spiral PCF ensure major change in colorless and toxic gas detection.

Jianfei Liao, Tianye Huang, Zuzhou Xiong, Fangguang Kuang, Yingmao Xie (2017) [12] proposed design has been analysed for large flattened dispersion and high nonlinearity coefficient. Design consist slotted core region surrounded by the three rings of air hole in the spiral lattice. The optical properties of this fiber designed has been analysed for the wavelength range from 1.4 to 1.7 μm. Simulation results show that the nonlinear coefficients as high as 224.36 $W^{-1}m^{-1}$ and 226.39$W^{-1}m^{-1}$ respectively. Chromatic dispersion (−5.64,2.62) for wavelength range 1.4 to 1.7 μm.

Md. Ibadul Islam1, Maksuda Khatun1, Shuvo sen1, Kawsar Ahmed1 and Sayed Asaduzzaman (2016) [13] author proposed a design of spiral photonic crystal fiber having an elliptical slot in core region for purpose of controlling dispersion and birefringence property of PCF. Elliptical slot in the core region is made of SF57 (soft glass). fiber cladding consists of spiral lattice on fused silica having refractive index 1.45. the diameter of air hole in each arm is increase respectively. Here SF57 is used for two regions 1) SF57 has high nonlinearity.2) it enhances the confinement of light in high index SF57 area.in addition of this SF57 also alter the chromatic dispersion and destroy the symmetry of fiber and increase birefringence.by examining the design, the result shows birefringence of 0.0341 at 1.55 μm.dispersion at 1.55 is -491.16ps/nm-km.

Jianfei Liao Yingmao Xie Xinghua Wang Dongbo Li Tianye Huang(2017) [14], the proposed design of spiral PCF has been used in gas sensing application. Inner core region consists hexagonal lattice and shape of air holes is elliptical. Outer cladding region having spiral lattice. In fiber design, there is 10 spiral arms and each arm has 9 circular air holes. It has been observed from a simulation that relative sensitivity is 42.27% and due to the presence of hexagonal lattice in the core region, we observe high birefringence of order (0.01727) at 1.33μm wavelength range.

Arti Agrawal, Y. O. Azabi and B. M. A. Rahman (2013) [15] the proposed structure contains slotted silicon PCF with ultra-high birefringence, nonlinearity, and ultrahigh flattened dispersion. Cladding consists of a triangular lattice of air holes of diameter D and pitch Λ.in addition of this a design consists elliptical silicon nichrome rod, is situated in the center of the core that breaks the symmetry of design and increases birefringence of fiber. Simulation result shows that by introducing silicon nichrome rod birefringence of order 0.0736 at 1.55µm is achieved. Low dispersion of .49ps/nm-km is achieved at 180nm.The designed PCF can be used as power efficient optical application.

Ritu Sharma, Vijay Janyani, S. K. Bhatnagar (2011) [16], index core two-dimensional photonic crystal fiber has been proposed in this paper modal analysis is done by FDTD for TE and TM mode. The PCF consist three rings of elliptical air and compare with circular air hole design.by observing the result of simulating designs we analyse that elliptical air hole design gives lower dispersion as compared to circular air hole design.

Rui Hao, Guifang Sun (2015) [17], An elliptical spiral soft glass PCF has been designed and analysed for high birefringence. The geometry is inspired by nature, such as galaxies, distribution of sunflower, shells of snails etc. PCF consist 12 circular air hole and spiral lattice having same ellipticity ratio from the first ring to the last ring. Due to the compactness of design light confinement in PCF is tight than conventional fiber. By examined the simulation result, for wavelength range 1000-1800nm, designed PCF offer birefringence up to 0.05554.

CHAPTER 4

NUMERICAL ANALYSIS OF SPIRAL PCF

4.1 Introduction

In this chapter, two dimensional spiral PCF has been designed using Comsol 5.1. Comsol 5.1 is based on finite element method. [1-5] The Design contains of five rings of circular air holes in the spiral lattice. Three configurations of spiral PCF have been analysed for different optical properties such as effective refractive index, dispersion, effective area etc. In these three configurations, the diameter of air hole is changed and all another parameter like pitch etc. is kept constant. Approaching from circular air hole spiral PCF to elliptical air hole spiral PCF air filling fraction is kept same and the results are compared. [20-21]

4.2 Design Parameter of Circular spiral PCF

NAME	VALUE	DISCRIPTION
d	1,0.8,0.8[μm]	Diameter of air hole
r_0	2[μm]	Radius of first air hole
r_1	3.8[μm]	Radius of second air hole
r_2	5.6[μm]	Radius of third air hole
r_3	7.4[μm]	Radius of fourth air hole
r_4	9.2[μm]	Radius of fifth air hole
W	1.55[μm]	wavelength
f	C_const/w	frequency
n_{core}	1.45	Refractive index
$n_{air\ hole}$	1	Refractive index

4.3Geometry of Circular air hole spiral PCF

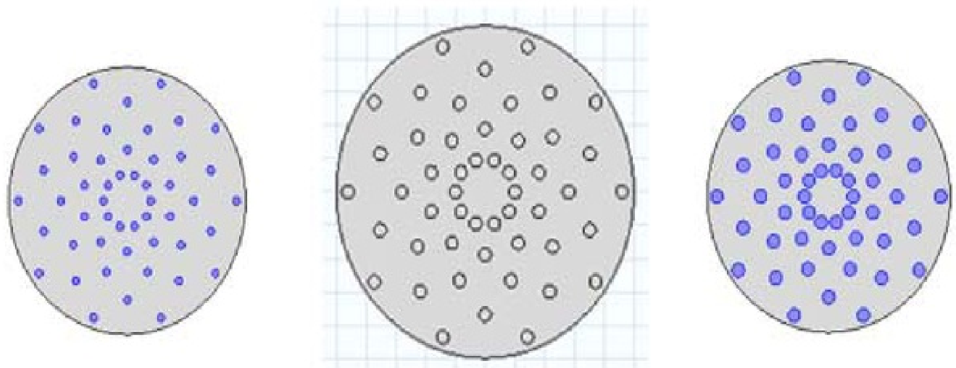

Figure 4.1 Snap shot of Circular air hole spiral PCF with (a) d=0.6[μm] (b)d=0.8[μm] and (c)d=1[μm]

4.4 Snapshot of mode profile

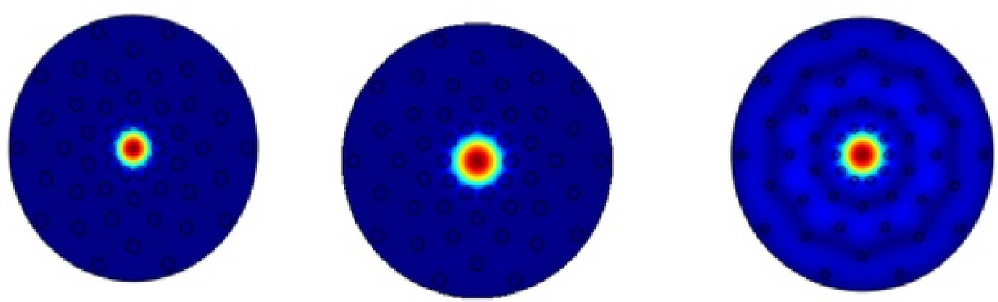

Fig:4.2 (a) d=1[μm] Fig:4.2 (b) d=0.8[μm] Fig:4.2 (c) d=0.6[μm]

Mode profile of Spiral PCF is shown at 1.55 μm wavelength for the fundamental mode. Color variation (red for maximum, blue for minimum power) for power is shown. From this figure, it is shown that maximum light is passed through the core, not in the cladding.

4.5 Effective mode index

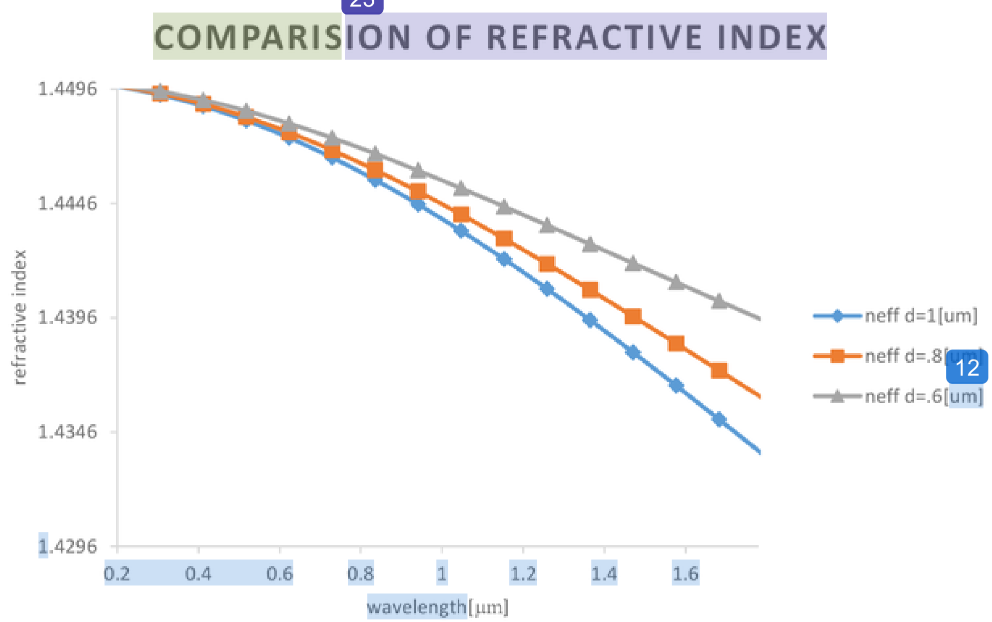

Figure 4.3 refractive index vs wavelength plot for d=1, 0.8, 0.6[µm]

Fig 4.3 shows the variation of effective index with wavelength for different circular air hole spiral PCF. It can be analysed that the slope of Effective refractive index increases with a diameter of air holes. Relation between n_{eff} and wavelength is given as

$$\beta = \frac{2\pi}{\lambda} \times n_{eff}$$

From above formula, there is reciprocal relation between n_{eff} and wavelength and it is verified from the Fig 4.3.

4.6 Dispersion profile

Total dispersion is the variation of group velocity with variation in wavelength. Dispersion of PCF is highly effected by the size of air holes and the air hole arrangement in geometry. Another parameter that can alter dispersion profile is a number of spiral arm and size of the core. From Fig 4.4, it can be analysed that dispersion is minimum for diameter 0.6µm and maximum for diameter 1µm.Total dispersion (chromatic dispersion) made of two form of component (1) waveguide dispersion (2) material dispersion [28]

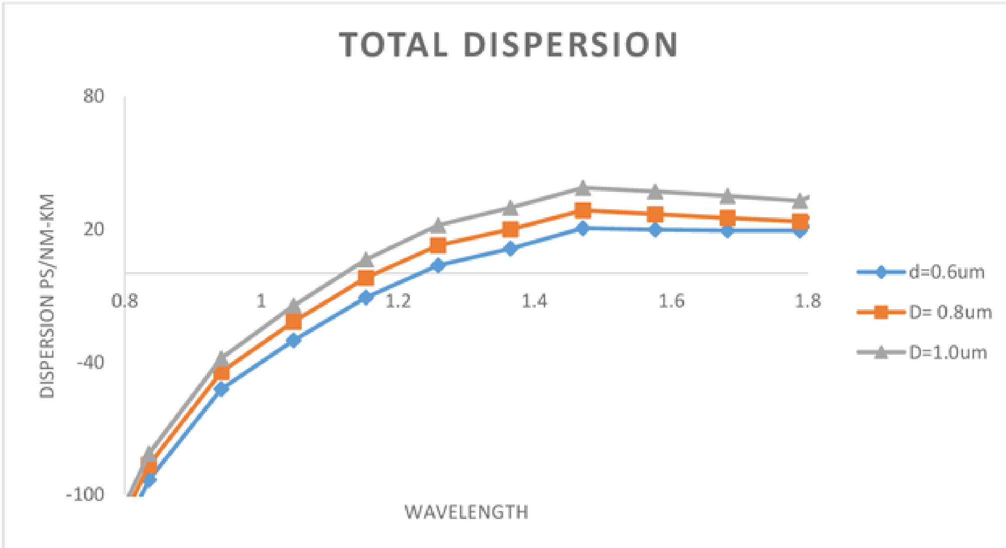

Fig 4.4 Plot of waveguide dispersion (ps/nm-km) v/s wavelength for d=1[µm],0.8 [µm].0.6 [µm].

4.7 Effective Area

In Figure 4.5, the effect of diameter of air hole on the effective area is analysed. Effective area linearly increases with wavelength. The effective area of conventional PCF is high over a spiral photonic crystal fiber. This less effective area is an advantage over conventional PCF. Due to the less effective area, this fiber can be used in the nonlinear application. It can be observed from Fig 4.5 that as we increase the diameter of the air hole effective area get reduced and at diameter 1µm we get low effective area than others. [11]

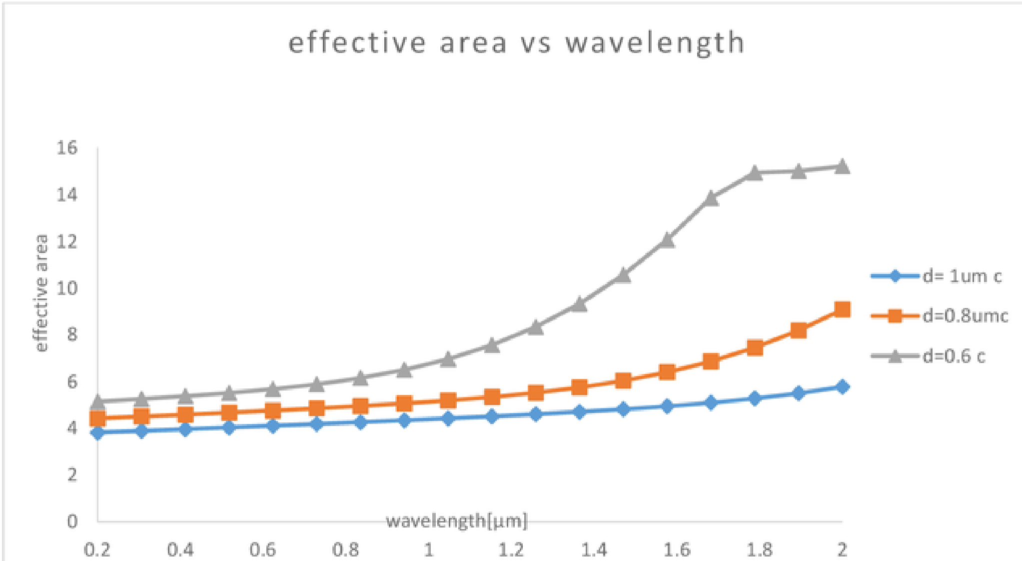

Fig:4.5 Plot of Effective Area vs wavelength for d=1[µm],0.8[µm],0.6[µm].

4.8 Design Parameters of Elliptical Air hole spiral PCF

NAME	VALUE	DISCRIPTION
d	1[µm]	Diameter of air hole
r_0	2[µm]	Radius of first air hole
r_1	3.8[µm]	Radius of second air hole
r_2	5.6[µm]	Radius of third air hole
r_3	7.4[µm]	Radius of fourth air hole
r_4	9.2[µm]	Radius of fifth air hole
w	1.55[µm]	Wavelength
f	C const/w	Frequency
n_{core}	1.45	Refractive index of core
$n_{air\ hole}$	1	Refractive index of air hole in cladding
a	.55[μm]	Major axis diameter of elliptical air hole
b	.45[µm]	Minor axis diameter of elliptical air hole

4.9 Geometry of elliptical air hole spiral PCF

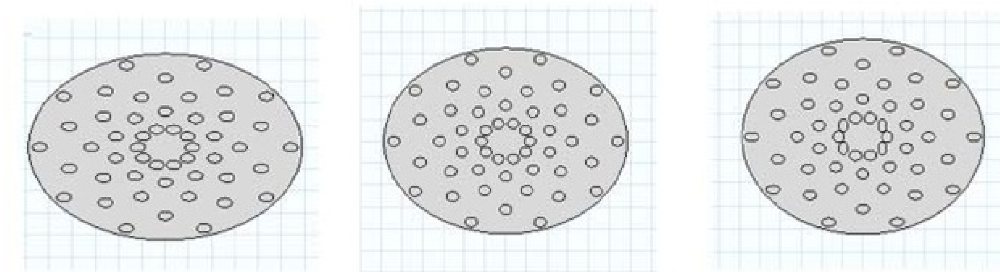

Figure 4.6 snap shot of elliptical air hole spiral PCF a: major axis b: minor axis of ellipse

Fig 4.6(a) a=.0.57[μm], b=0.43[μm] Fig 4.6(b) with different ellipticity Fig 4.6(c) a=0.62[μm],b=0.40

4.10 Snapshot of mode profile

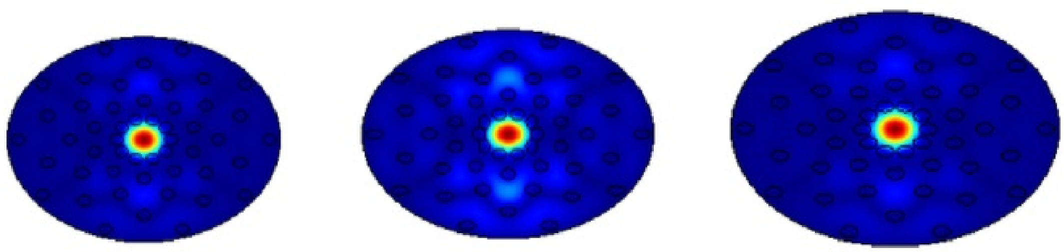

Figure 4.7 Snap shot of mode profile for different Elliptical air hole spiral PCF

Fig 4.7(a) a=0.57[μm],b=0.43[μm] Fig 4.7(b) with different ellipticity Fig 4.7(c) a=0.62[μm],b=0.40

In given figure, red color shows the maximum intensity of light and blue color shows the minimum intensity of light. From mode profile, we can examine that most of the light is confined in core region due to refractive index variation. Confinement in PCF is high than conventional fiber. This is the advantage of PCF over conventional fiber.[24]

4.11 Refractive index vs wavelength

The wavelength is varied from 0.2μm to 2µm for the simulation. n_{eff} is calculated by simulating the design. The variation in effective refractive index v/s wavelength is shown in Fig 4.8. It can be examined from the graph that effective refractive index decreases as the wavelength is increased. From the graph, it observed that the slope of effective refractive index increases with ellipticity ratio.

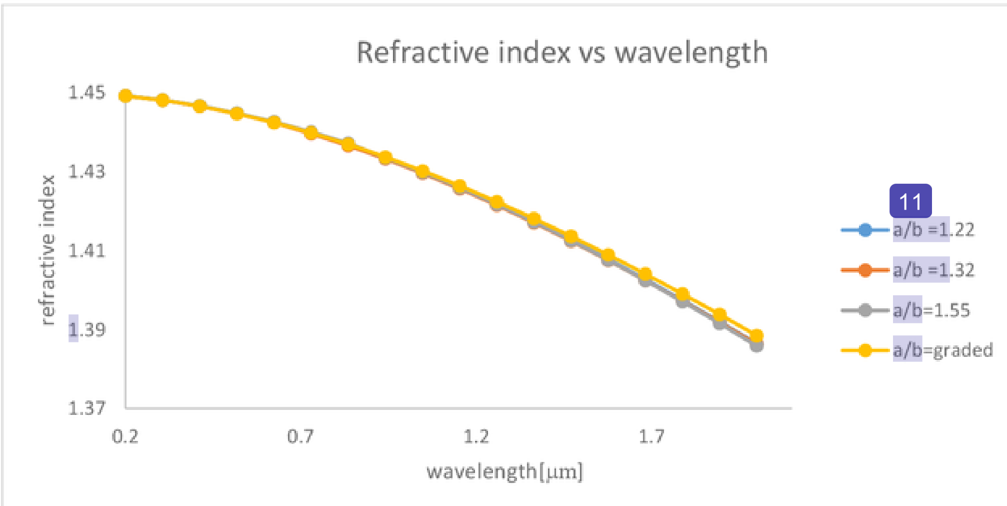

Figure 4.8(a) Plot of Effective refractive index v/s wavelength for ellipticity ratio 1.22,1.32,1.55.

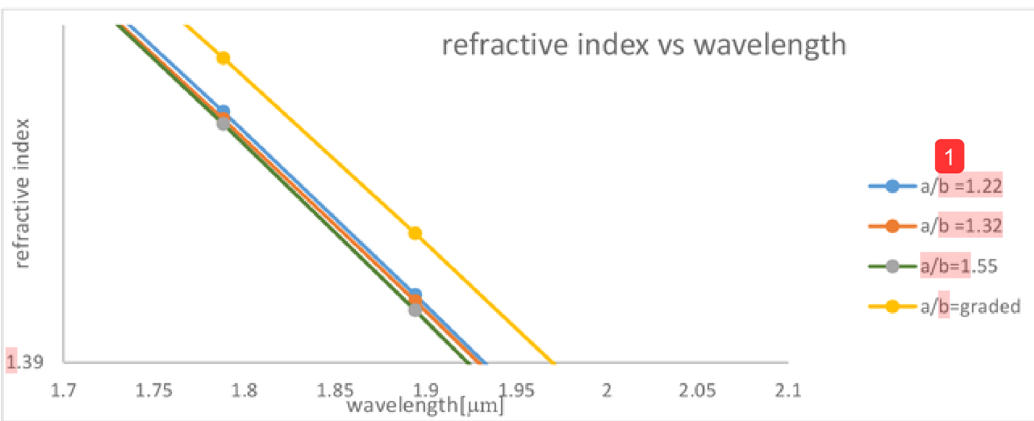

Fig 4.8(b) zoom view of refractive index vs wavelength plot

4.12 Dispersion vs wavelength

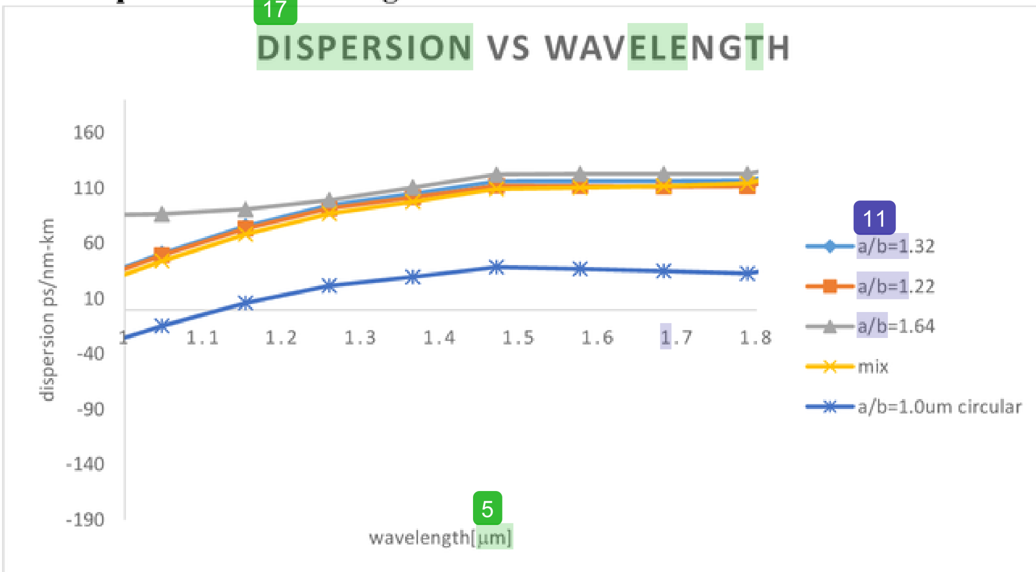

Fig 4.9(a) Plot of Total dispersion v/s wavelength for ellipticity ratio 1,1.22,1.32,1.64

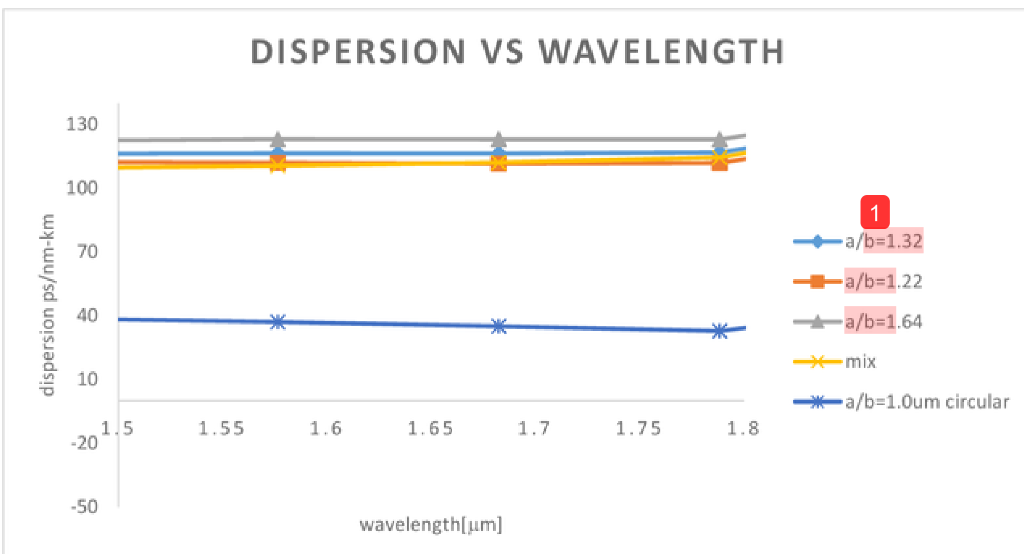

Fig 4.9(b) Plot showing Flat range of dispersion v/s wavelength

It can be analysed that dispersion is highly affected by the size of air hole so if the air filling fraction is increased or size of air hole is increased the dispersion also changes.

From Fig 4.8 and Fig 4.9, it can be analysed that for ellipticity ratio 1.64 we get the highest dispersion and for graded size air hole we get minimum distortion.So if ellipticity ratio from the first ring to the last ring is increased or decreased the magnitude of dispersion is highly affected. A minimum magnitude of dispersion is obtained for ellipticity ratio 1.22. From figure 4.9(b) it can be examined that nearly flat dispersion is pbtained from 1.5μm to 1. 68μm wavelength range. An important fact that can be observed from the Fig 4.9 is that when the geometry is changed from circular to elliptical air holes, the magnitude of dispersion gets increased but birefringence also increases.[21]

4.13 Birefringence

Birefringence is the difference between the two orthogonal directions. Modal birefringence is defined as [12]

$$\text{Birefringence} = [n_{eff}(X\ \text{mode}) - n_{eff}(Y\ \text{mode})]$$

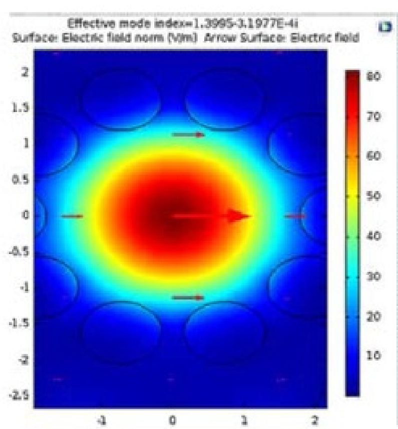

Fig 4.10(a) snap shot of X polarization

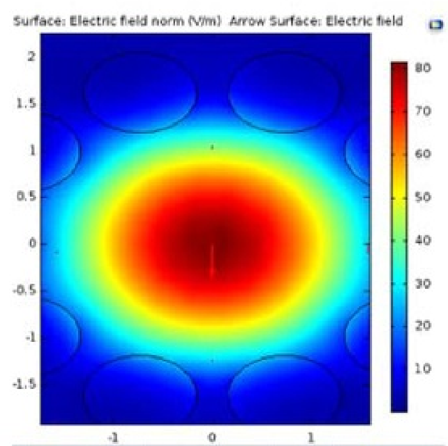

Fig 4.10(b) snap shot of Y polarization

Fig 4.10 (a) snap shot of X polarization mode

Fig 4.10 (b) snap shot of Y polarization mode

4.14 Birefringence v/s Ellipticity ratio

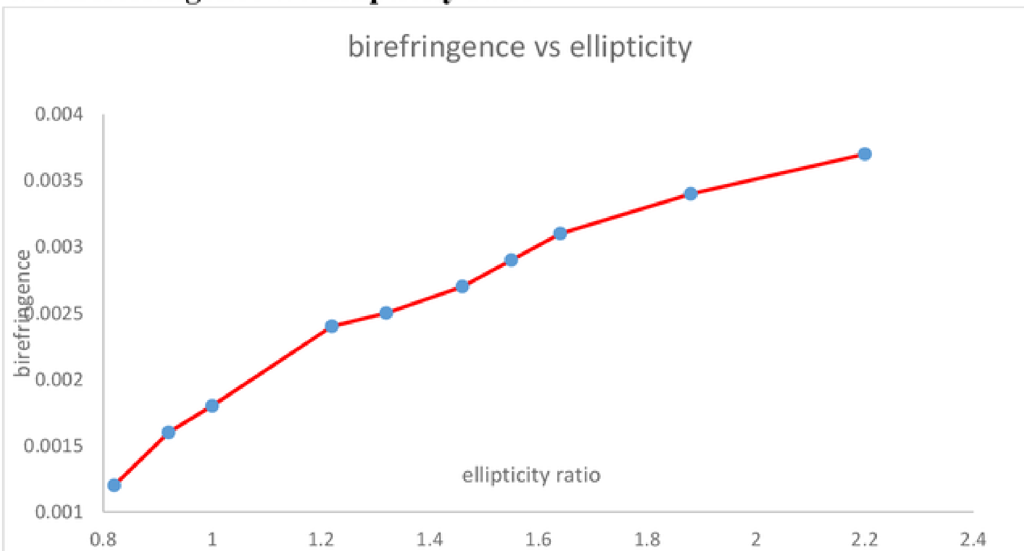

Fig 4.11 Plot of ellipticity ratio vs wavelength

The effect of ellipticity ratio on wavelength is shown in Fig 4.11. It can see from the graph that birefringence varies with ellipticity ratio. In the plot, the ellipticity range is varied from 0.8 to 2.4 and for ellipticity ratio 2.2, we get the highest value of birefringence.

4.15 Birefringence v/s Wavelength

The proposed PCF consists of an elliptical-Spiral arrangement of the air hole. In comparison to conventional PCF structure supporting different properties, the compact design of elliptical air hole spiral PCF achieves large birefringence. From Figure 4.12, it can be seen that birefringence increases linearly with frequency [26]. We get high birefringence for ellipticity ratio 1.64 for wavelength range 1.50 to 1.80µm, designed PCF offered high birefringence up to 0.004.

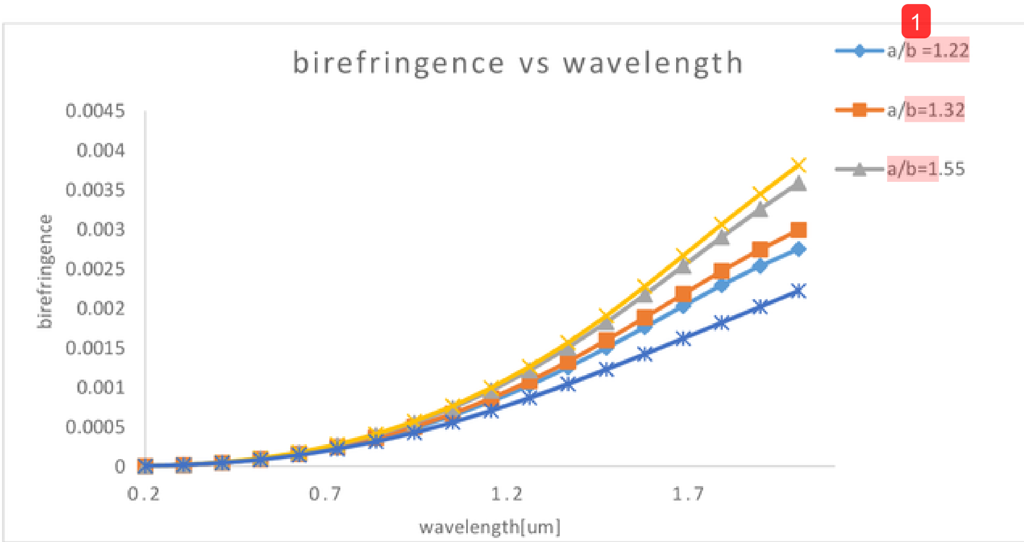

Fig 4.12 Plot of Birefringence v/s wavelength for different ellipticity ratio

.

4.16 Effective area v/s wavelength plot

From the plot shown in Fig 4.13, the effect of ellipticity ratio on the effective area can be examined. It is observed that effective area of elliptical air hole spiral PCF linearly increases with wavelength. The effective area of elliptical air hole spiral PCF is considerably small than conventional fiber. This property of PCF can be used in various nonlinearity application such as supercontinuum generation, four waves mixing etc. It can be observed from the plot that at ellipticity ratio 1.55, the effective area is lowest as compared others.

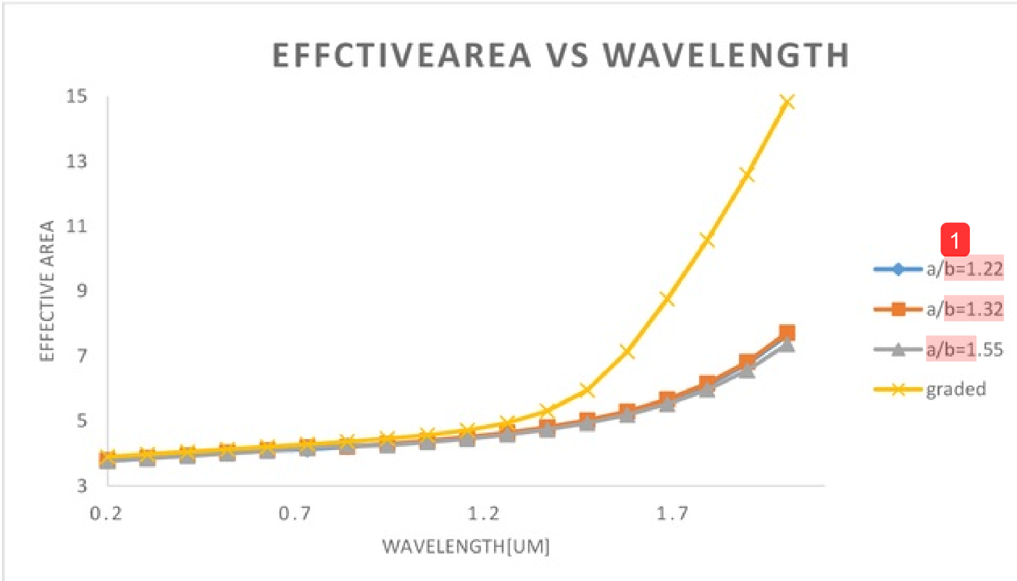

Fig 4.13(a) Effective area v/s wavelength plot

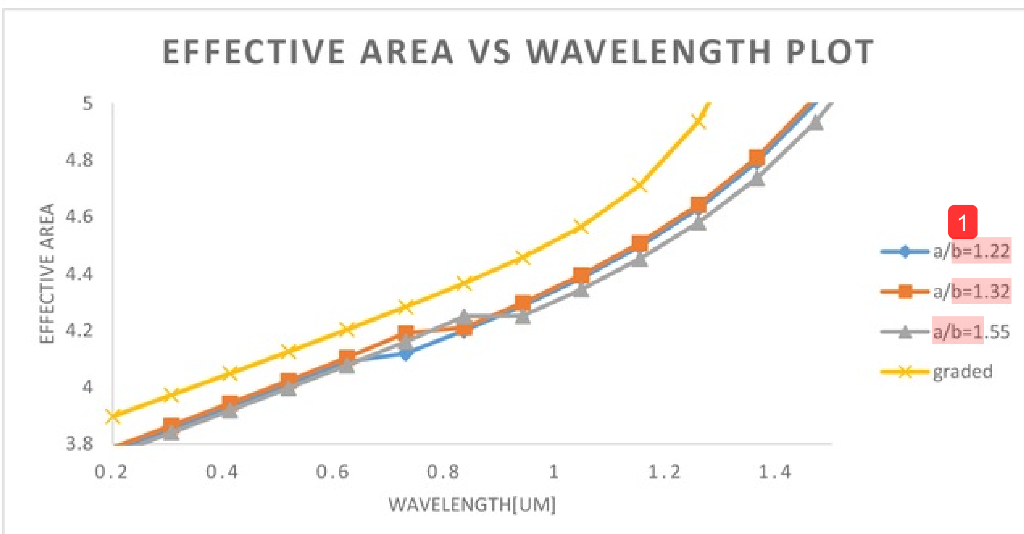

Fig 4.13 (b) zoom view of Effective area v/s wavelength p

CHAPTER 5

COMPARATIVE STUDY AND CONCLUSION

5.1 Introduction

This chapter deals with the comparative analysis of different characterstics of spiral photonic crystal fiber like effective mode index, waveguide dispersion and chromatic dispersion by varying wavelength for different diameter of air hole spiral photonic crystal fiber.[15]

5.2 Comparison of Effective mode index

Fig 4.19 shows the comparative study of effective mode index. In Fig 4.19 it can be seen that as the wavelength is increased the value of n_{eff} decreases. Fig 4.19 shows that the slope of refractive index v/s wavelength plot is maximum for elliptical air hole spiral PCF as compared with circular air hole PCF.

Table 5.1 Wavelength v/s effective refractive index

wavelength	a/b =1.22	a/b =1.32	a/b=1.55	a/b=graded	neff d=1[um]	neff d=.8[um]	neff d=.6[um]
0.2	1.449166853	1.449151	1.449173039	1.449151355	1.449721812	1.449743592	1.449784087
0.305882353	1.448092071	1.448057	1.448105572	1.448056659	1.449360212	1.449412177	1.449506576
0.411764706	1.446612718	1.44655	1.446635343	1.446550049	1.448860308	1.448956318	1.449127117
0.517647059	1.444752092	1.444656	1.444785287	1.444656022	1.448229799	1.448384668	1.448654858
0.623529412	1.442532128	1.442398	1.442577074	1.442397615	1.447476559	1.447706235	1.448099731
0.729411765	1.439734601	1.439578	1.440031218	1.439796464	1.446608729	1.446930514	1.447472466
0.835294118	1.436747866	1.43656	1.437167239	1.436872939	1.445634794	1.446067536	1.446784355
0.941176471	1.433437125	1.43322	1.433453364	1.433646334	1.444563643	1.445127821	1.446046878
1.047058824	1.429820031	1.429578	1.429821449	1.4301351	1.443404583	1.444122218	1.44527127
1.152941176	1.425914275	1.425652	1.42589325	1.426357078	1.442167287	1.44306169	1.444468127
1.258823529	1.421737785	1.421462	1.421685639	1.422329697	1.4408617	1.441957056	1.443647091
1.364705882	1.417308825	1.417026	1.41721593	1.41807006	1.439497899	1.440818747	1.442816623
1.470588235	1.412645929	1.412365	1.412501872	1.413594847	1.438085938	1.439656573	1.441983883
1.576470588	1.40776757	1.407497	1.407561426	1.408919975	1.436635675	1.438479534	1.441154705

1.682352941	1.402691513	1.402442	1.402412262	1.404059973	1.435156604	1.437295687	1.440333644
1.788235294	1.397433823	1.397214	1.397070941	1.399027094	1.433657705	1.436112051	1.439524076
1.894117647	1.392007662	1.391827	1.391551818	1.393830249	1.432147303	1.434934579	1.438728337

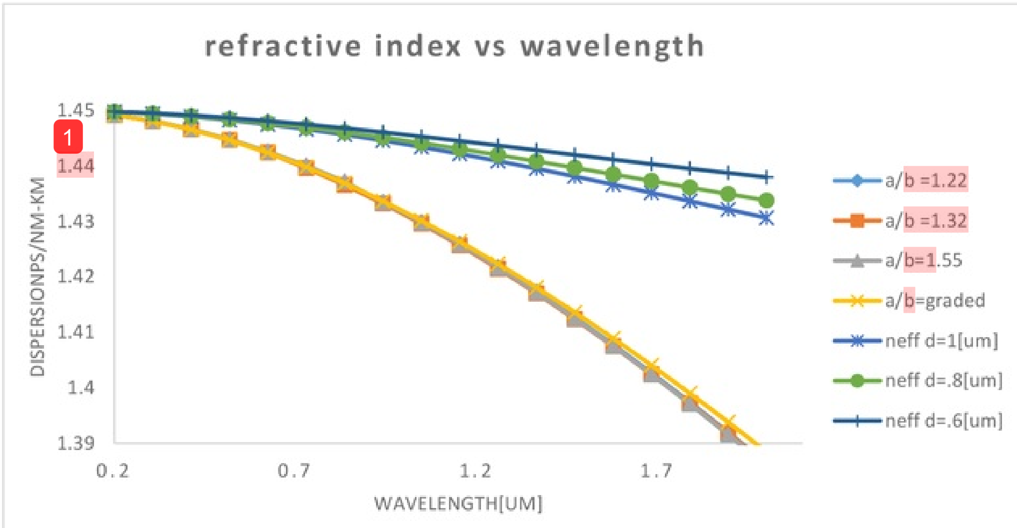

Fig 5.1(a) comparision of n_{eff} v/s wavelength for diameter =1μm,0.8μm,0.6μm

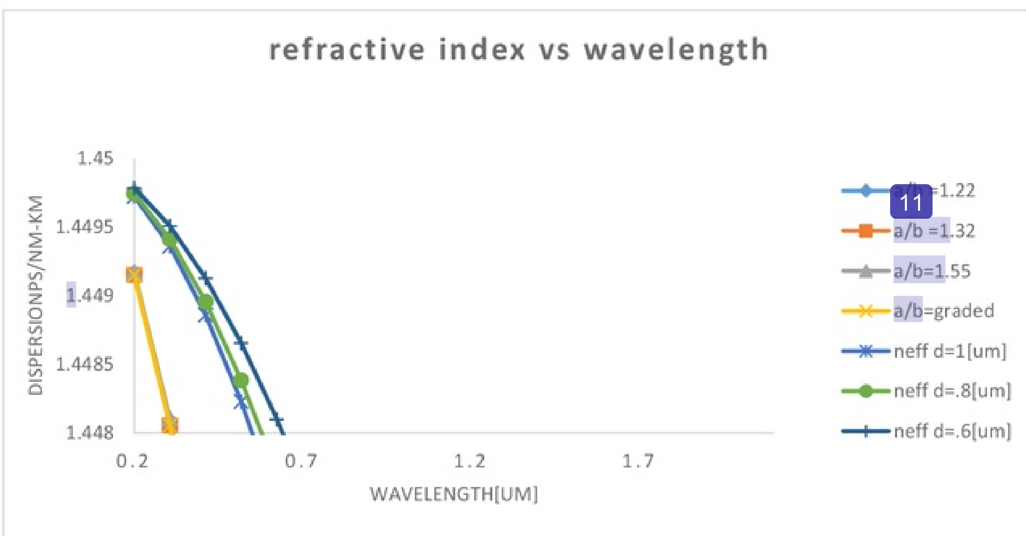

Fig 5.1(b) Zoom View of Fig 5.1(a)

5.3 comparision of waveguide dispersion

Fig 5.20 shows a variation of dispersion with wavelength and it can be seen from the graph that as we increase the diameter of airhole dispersion also increases.

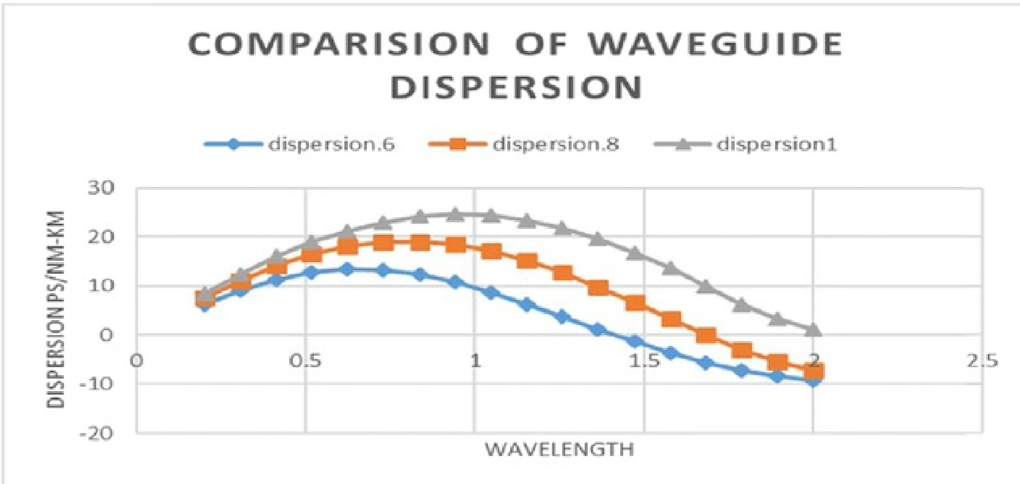

Fig 5.2 waveguide dispersion v/s wavelength for dimeter = 1µm,0.8µm,0.6µm

5.4 comparision of chromatic dispersion(total dispersion)

Table 5.2 Wavelength v/s total dispersion

wavelength	a/b=1.32	a/b=1.22	a/b=1.64	mix	a/b=1.0um circular	d=0.6um	D= 0.8um
0.517647059	-631.8940409	-631.8957836	-641.136751	-640.304876	-677.5611786	-683.7168533	-680.024165
0.623529412	-245.4728624	-246.3333746	-261.64019	-260.833925	-303.2061562	-311.0864995	-306.422742
0.729411765	-104.0996341	-104.1374419	-104.299298	-103.525587	-150.5085352	-160.312355	-154.600807
0.835294118	-34.54773613	-34.51025927	16.39738005	-30.2269825	-81.43242087	-93.27491991	-86.5129079
0.941176471	22.76285561	21.73327127	85.41220659	16.72897307	-38.38854081	-52.24782281	-44.5331464
1.047058824	50.93237015	49.38628283	86.46978143	44.17308078	-14.57959505	-30.26835016	-21.8043405
1.152941176	75.63847525	73.52690224	90.89383425	68.36791401	6.258813238	-10.90495025	-1.98725523
1.258823529	94.46920131	91.75597403	99.21576505	86.96833067	21.79047736	3.65205423	12.66207736

1.364705882	105.0723451	101.7400514	110.5827549	97.69374364	29.70546452	11.20029635	19.90978681
1.470588235	116.1491334	112.2145752	122.3159461	109.3133502	38.64923401	20.44435016	28.46475035
1.576470588	116.3013997	111.8417734	122.8905755	110.4779158	36.99938551	19.76981603	26.74891725
1.682352941	116.2271908	111.4052306	122.8489322	111.9023659	35.01027064	19.3916755	25.03795682
1.788235294	116.6914955	111.7601394	122.8176309	114.3325155	32.80046206	19.35024654	23.44774087
1.894117647	133.2507909	128.3315139	138.7569288	132.6238378	45.5178704	33.83913783	36.69932799

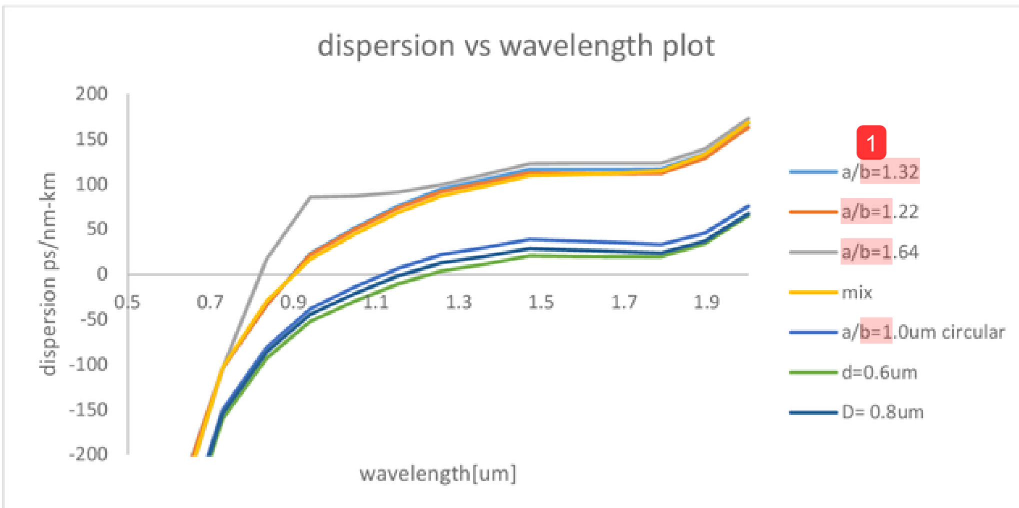

Fig 5.3 comparision of chromatic dispersion v/s wavelength

Chromatic dispersion is a combination of two type of dispersion 1) waveguide dispersion 2) material disersion. Dispersion in PCF is highly effected by the size of air holes and arrangement of air hole in cladding region. The dispersion propery can be altered by changing the geometry of PCF. Fig 5.3 shows the variation of dispersion with wavelength, it can be observed from the Fig 5.3 that the magnitude of dispersion is minimum for circular air hole spiral PCF and higher for eliptical air hole spiral PCF. At 1.55µm, the minimum dispersion obtained for 0.6µm circular air hole.By comparing the result of circular air hole spiral PCF for diameter 1µm and elliptical air hole spiral PCF for same air filling fraction, we get lower dispersion for circular air hole spiral PCF.

5.5 Comparison of zero dispersion wavelength

Table 5.3 Zero dispersion wavelength

Circular air hole	Zero dispersion wavelength	Elliptical air hole	Zero dispersion wavelength
Diameter=1.0 [µm]	1.12[µm]	Ellipticity ratio=1.22	0.901[µm]
Diameter=0.8 [µm]	1.18[µm]	Ellipticity ratio=1.32	0.896[µm]
Diameter=0.6 [µm]	1.24[µm]	Ellipticity ratio=1.62	0.835[µm]
		Ellipticity ratio=graded	0.903[µm]

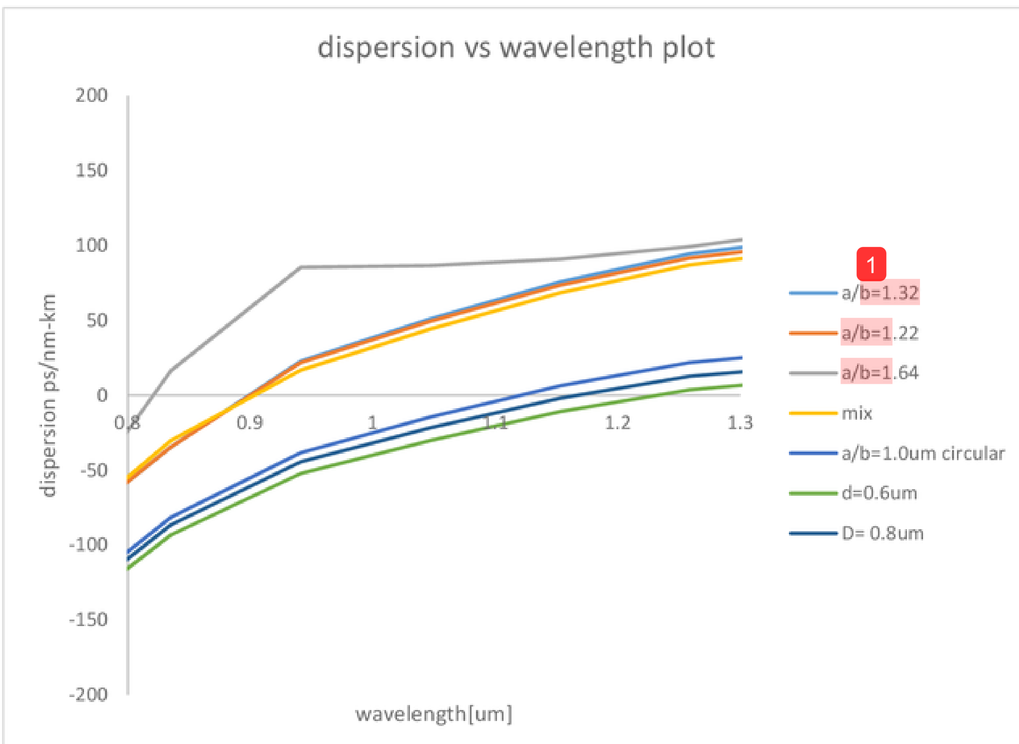

Fig 5.4(a) zero dispersion wavelength at diameter = 1µm,0.8µm,0.6µm

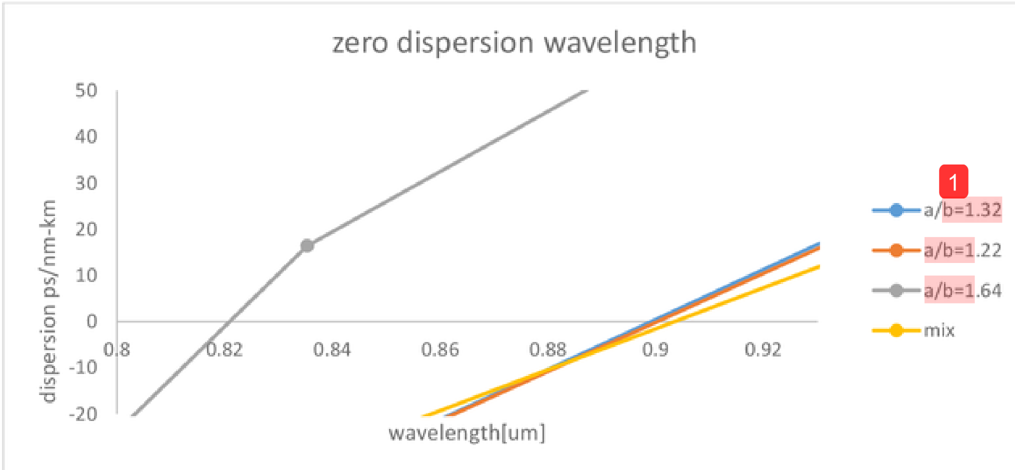

Fig 5.4(b) zoom view of above graph

the zero-dispersion wavelength is the wavelength at which waveguide dispersion and material dispersion and cancel one another. In fig 5.4(a) it can be seen that as we reduce the diameter of air hole zero dispersion wavelength shift toward right hand side. By analyzing the result of both designs, it observe that as we change the geometry of air holes from circular to elliptical, zero dispersion wavelength get shifted to the lower side of wavelength. [23]

5.6 Comparison of effective area

Table 5.3 Wavelength v/s effective area

w[µm]	a/b=1.22	a/b=1.32	a/b=1.55	graded	d= 1um c	d=0.8um c	d=0.6 c
0.2	3.772131186	3.786415948	3.76221508	3.896396857	3.823071697	4.426735403	5.143228341
0.305882353	3.849690648	3.864293064	3.839919906	3.971831001	3.892767746	4.506450938	5.253455655
0.411764706	3.927900397	3.942710503	3.917756542	4.047917293	3.963409882	4.588071714	5.37541498
0.517647059	4.007346111	4.022148574	3.996381016	4.124576639	4.035180071	4.672394294	5.515343806

0.623529412	4.089229882	4.103893848	4.076630939	4.202359198	4.108553734	4.760437539	5.68245269
0.729411765	4.118498296	4.190001386	4.159832827	4.282067549	4.18377514	4.853597558	5.890022937
0.835294118	4.198970615	4.20942438	4.249063148	4.365328268	4.261146999	4.954023671	6.156144673
0.941176471	4.286266404	4.296538583	4.250328471	4.456159114	4.341103581	5.065053793	6.504054728
1.047058824	4.383503932	4.394087191	4.344036914	4.564281211	4.424287177	5.191684424	6.96196707
1.152941176	4.495354449	4.506904522	4.451578296	4.710695973	4.51168719	5.341034793	7.562255223
1.258823529	4.628532812	4.641889572	4.579201431	4.935023101	4.60482817	5.522750946	8.339836175
1.364705882	4.792460576	4.808718265	4.735596964	5.305759001	4.706002609	5.749290284	9.329664759
1.470588235	5.00025413	5.020882095	4.932772544	5.94694723	4.818541391	6.036030659	10.56341686
1.576470588	5.270173552	5.297142956	5.187249215	7.136820457	4.94710728	6.401163022	12.06575651
1.682352941	5.627588888	5.663443122	5.521634868	8.759497803	5.097987091	6.865345171	13.85088964
1.788235294	6.107423164	6.155222861	5.966564693	10.57457026	5.279347959	7.451074732	14.92622588
1.894117647	6.756828862	6.819849249	6.562803146	12.58651604	5.501416427	8.181756249	14.99871432

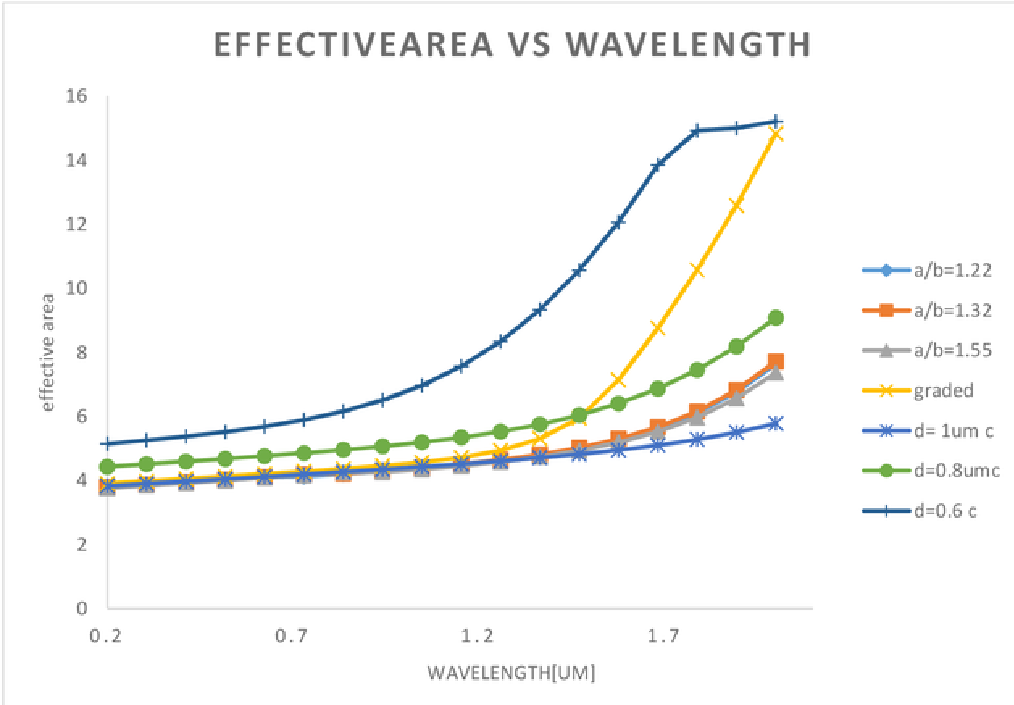

Figure 5.5 comparison of Effective area vs wavelength plot

In Fig 5.5, the effect of diameter of air hole and geometry of air hole on the effective area is examined. The effective area of PCF is much smaller than conventional PCF. By analyzing the result of PCF, it is observed that elliptical air hole PCF offers high effective area than circular air hole PCF. For circular air hole PCF of diameter 1µm, a minimum effective area is obtained.

5.7 Birefringence vs Wavelength

. High birefringence fiber can be used as a sensor. To increase the birefringence, elliptical air holes are introduced in PCF or the symmetry of PCF is broken. It can be seen from Fig 5.6 that birefringence varies with ellipticity ratio. Because if, there is a change in ellipticity ratio air filling fraction get changed. It can be seen from the graph that for circular air hole minimum birefringence of the order $10^{-3 \text{ is observed}}$ and as the ellipticity ratio is increased, the magnitude of birefringence for PCF also increases.

Table 5.4 Wavelength v/s birefringence

Wavelength	a/b =1.22	a/b=1.32	a/b=1.55	a/b=1.64	graded ellip holes	circular air hole
0.2	1.74847E-06	1.50167E-06	2.80366E-06	3.14214E-06	4.19246E-06	4.19467E-06
0.305882353	1.48852E-05	1.46567E-05	1.77249E-05	1.85311E-05	1.78522E-05	1.78587E-05
0.411764706	4.26633E-05	4.29268E-05	4.84759E-05	5.0027E-05	4.39874E-05	4.39995E-05
0.517647059	8.78263E-05	8.92817E-05	9.85487E-05	0.00010136	8.50137E-05	8.50318E-05
0.623529412	0.000152641	0.000156227	0.000171126	0.000175951	0.000142772	0.000142797
0.729411765	0.00023896	0.000245888	0.000269052	0.000276875	0.000218491	0.000218521
0.835294118	0.000348186	0.000359985	0.000394811	0.000406856	0.000312774	0.000312807
0.941176471	0.000481257	0.000499825	0.000550549	0.000568325	0.000425615	0.000425648
1.047058824	0.000638642	0.000666297	0.000738086	0.000763449	0.000556416	0.000556448
1.152941176	0.000820319	0.000859838	0.00095887	0.000994067	0.000704013	0.000704039
1.258823529	0.001025688	0.001080311	0.001213811	0.001261502	0.000866706	0.000866651
1.364705882	0.001253352	0.001326715	0.001502907	0.001566158	0.001042292	0.001041817
1.470588235	0.001500671	0.001596573	0.001824443	0.001906677	0.001228134	0.001226181
1.5764705	0.0017629	0.0018847	0.0021733	0.0022782	0.0014213	0.0014151

88	22	75	81	2	25	78
1.6823529 41	0.0020319 75	0.0021818 62	0.0025389 63	0.0026698 45	0.0016190 21	0.0016024 97
1.7882352 94	0.0022953 31	0.0024735 5	0.0029046 53	0.0030644 66	0.0018189 35	0.0017793 89
1.8941176 47	0.0025385 98	0.0027456 21	0.0032560 59	0.0034475 62	0.0020198 56	0.0019346 94

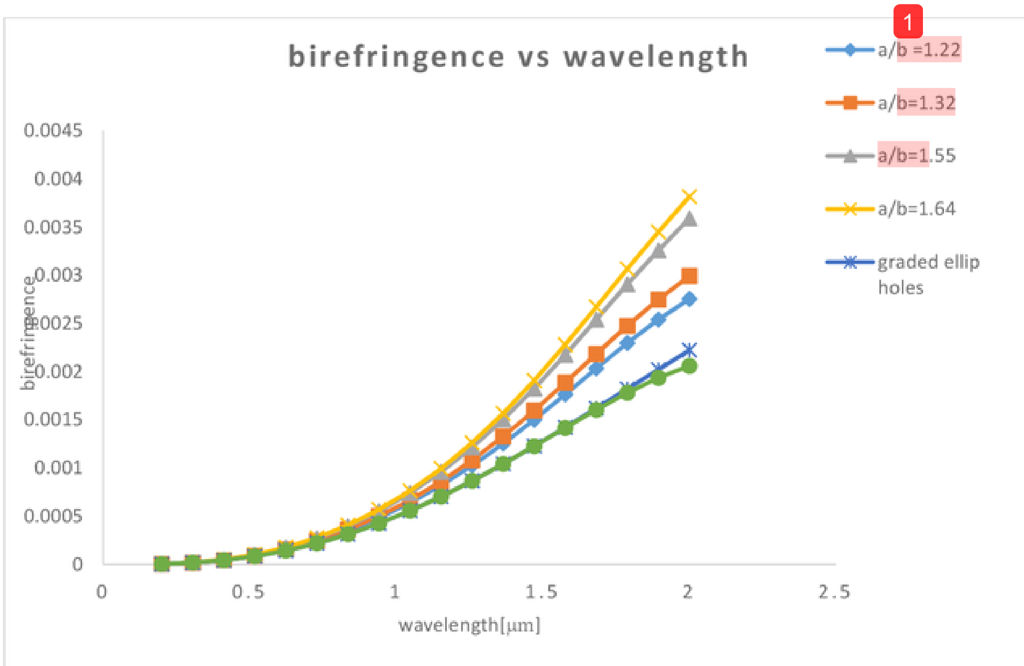

Fig 5.6 birefringence v/s frequency plot for different ellipticity ratio

Conclusion and discussion

Proposed two-dimensional photonic crystal fiber has been designed and analysed for high birefringence and flattened dispersion. For analyzing the proposed design Finite Element Method has been used.The following fundamental characteristics of PCFs have been found out. They are shown in tabular format.

Our finding

1.power confinement of spiral PCF for different diameter in circular spiral PCF
2.effective mode index variation with wavelength for different diameter in circular spiral PCF
3.material dispersion for diffused silica at refractive index 1.45 in circular spiral PCF
4.wavefuide dispersion for circular hole PCF at different diameter by varying wavelength
5.chromatic dispersion for circular hole PCF at different diameter by varying wavelength
6.zero dispersion wavelength at different diameter for circular spiral PCF
7.new structure of elliptical hole spiral PCF keeping all parameter similar
8.effective refractive index variation v/s wavelength for elliptical hole spiral PCF
9.Chromatic dispersion vs wavelength for elliptical hole spiral PCF
10.birefringence vs ellipticity ratio for elliptical hole spiral PCF
11.birefringence vs wavelength plot for elliptical hole spiral PCF
12.effective area vs wavelength plot for elliptical hole spiral PCF
13.comparative study of different diameter circular air hole spiral photonic crystal fiber and different ellipticity ratio spiral PCF

Here we have found out properties of different diameter of air hole for doped silica spiral photonic crystal fiber. Finite element method has been used for analyzing the layouts. In this report, different spiral photonic crystal fiber has been examined. By optimizing the geometry of PCF, we get almost flat dispersion in the range of 1.45[um] to 1.70[um]. In this report, the numerically simulated result shows that a significantly lower dispersion occurs at a diameter of 0.6 µm. a circular spiral PCF has been designed in which we increase the diameter of air hole and analyzed that as we reduce the diameter of air hole dispersion also decreases and we also get the zero-dispersion wavelength shift toward right hand side as we reduce the diameter of the air hole. the designed structure also has lower dispersion than octagonal photonic crystal fiber. Due to lower dispersion, the fiber has its prominence in dispersion flatter device application. For further improvement of the result of PCF, we move from spiral circular hole to elliptical air hole spiral PCF. Due to the compactness of design, PCF offers high nonlinearity, birefringence, and low effective area. From simulation result, we observe that if we increase ellipticity ratio from 1 to 1.64, dispersion will also increase.it can be examined from the result that birefringence of order 0.003 at 1.80μm and 0.002 at 1.55μm is observed and Birefringence also increase with ellipticity ratio and at ellipticity ratio 1.64, birefringence of order 0.003 is observed. From figure () is observed that effective area increases with wavelength and we get lower effective area for ellipticity ratio 1.55.but if we compare circular air hole PCF and elliptical air hole PCF, circular air hole PCF offer lower effective area.

Future work

Present Research work on photonic crystal fibers is based on different spiral PCF. By changing the geometry of spiral PCF and air holes ellipticity ratio, the range of flattened dispersion will be increased to significant label and birefringence will be improved. Dispersion engineering is possible in PCFs in the range unachievable for classical fibers (flat dispersion in the large range, zero-dispersion, and anomalous dispersion in the visible range).

REFERENCES

1) Md. Asiful Islam and M. Shah Alam (2012)" Design of a Polarization-Maintaining Equiangular Spiral Photonic Crystal Fiber for Residual Dispersion Compensation Over E+S+C+L+U Wavelength Bands" IEEE photonics technology letters, vol. 24, no. 11.
2) Agrawal, A., Kejalakshmy, N., Rahman, B.M.A. and Grattan, K.T.V. (2009) 'Soft glass Equiangular spiral Photonic crystal fiber for Supercontinuum generation', IEEE Photonics Technology Letters, 21(22), pp. 1722–1724. doi: 10.1109/lpt.2009.2032523
3) M. Samiul Habib, M. Selim Habib, M. Imran Hasan, S.M.A Razzak (2013) "Highly nonlinear polarization maintaining two zero dispersion spiral photonic crystal fiber using artificial defects" Elsevier optical fiber technology 19, 539-542.
4) S. Revathi*, Srinivasa Inabathini, Ram Sandeep (2015) "Soft glass spiral photonic crystal fiber for large nonlinearity and high birefringence" Optica Applicata, vol. xlv, no. 1, 2015 doi: 10.5277/oa150102
5) S. Revathi*, Srinivasa Inabathini and Rizwan Ali Saifudeen (2014) "Highly nonlinear and Birefringence spiral photonic crystal fiber" Hindawi. Advances in Optoelectronics.
6) Varshali Sharma, Ritu Sharma (2016) "Design of Hybrid photonic crystal fiber with elliptical and circular air holes analysed for large flattened dispersion and high birefringence" SPIE "Journal of nanophotonics" doi: 10.1117/I.JNP.10.026016
7) Philip St.J. Russell "Photonic-Crystal Fibers" (2006) IEEE JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 24, NO. 12
8) Richard Soref, Life Fellow "The Past, Present, and Future of Silicon Photonics" (2006) IEEE journal of selected topics in quantum electronics, vol. 12, no. 6.
9) Theis P. Hansen, Jes Broeng, Stig E. B. Libori, Erik Knudsen, Anders Bjarklev, Jacob Riis Jensen, and Harald Simonsen (2001) "Highly Birefringent Index-Guiding Photonic Crystal Fibers" IEEE photonics technology letters, vol. 13, no. 6.
10) Md. Ibadul Islam a, Kawsar Ahmed a, Sayed Asaduzzaman a,b, Bikash Kumar Paul a, Touhid Bhuiyan b, Shuvo Sen a, Md. Shadidul Islam a, Sawrab Chowdhury (2017) "Design of single mode spiral photonic crystal fiber for gas sensing applications" Elsevier Sensing and Bio-Sensing Research.

11) Jianfei Liao, Junqiang Sun, Mingdi Du, and Yi Qin (2014)" Highly Nonlinear Dispersion-Flattened Slotted Spiral Photonic Crystal Fibers" IEEE photonics technology letters, vol. 26, no. 4.

12) Jianfei Liao, Tianye Huang, Zuzhou Xiong, Fangguang Kuang, Yingmao Xie (2017) "Design and analysis of an ultrahigh birefringent nonlinear spiral photonic crystal fiber with large negative flattened dispersion" Elsevier optic 135.

13) Md. Ibadul Islam1, Maksuda Khatun1, Shuvo sen1, Kawsar Ahmed1 and Sayed Asaduzzaman (2016) "Spiral Photonic Crystal Fiber for Gas Sensing Application" 9th International Conference onElectrical and Computer Engineering 20-22 December 2016, Dhaka, Bangladesh.

14) Jianfei Liao Yingmao Xie Xinghua Wang Dongbo Li Tianye Huang(2017) "Ultra-flattened nearly-zero dispersion and ultrahigh nonlinear slot silicon photonic crystal fibers with ultrahigh birefringence" DOI: 10.1016/j.photonics.2017.04.004

15) Arti Agrawal, Y. O. Azabi and B. M. A. Rahman (2013) "Stacking the Equiangular Spiral Photonics Technology Letters,25(3),pp.291-294 doi:10.1109/LPT.2012.2236309

16) Ritu Sharma, Vijay Janyani, S. K. Bhatnagar (2011)"Low chromatic dispersion and highbirefringence investigated in elliptical air hole photonic crystal fiber", **Journal of Modern Optics** Volume:59 / 205-212 / 2011

17) Rui Hao, Guifang Sun (2015) "Design of photonic crystal fiber with large negative dispersion and high nonlinearity" Optic 126,3353-3356

18) Yashar E. Monfared, A.R. Maleki Javan, A.R. Monajati Kashani (2013) "Confinement loss in hexagonal lattice photonic crystal fibers" optik international journal for light and electron optics

19) J. C. Knight, J. Arriaga, T. A. Birks (2000) "Anomalous Dispersion in Photonic Crystal fiber" IEEE photonics technology letters, vol. 12, no.7

20) Jianfei Liao, Junqiang Sun, Mingdi Du, and Yi Qin (2014) "Highly Nonlinear Dispersion-Flattened Slotted Spiral Photonic Crystal Fibers" IEEE photonics technology letters, vol. 26, no. 4.

21) Jamshid Heiadarialamdarloo, Carvalho MI, Ricardo Nunes Nogueira and Antonio Luis Jesus Teixeira(2016) "Highly nonlinear, dispersion flattened equiangular spiral

photonic crystal fiber in telecommunication window" journal of laser optics and photonics doi:10.4172/2469-410X.1000

22) Ritu Sharma, Vijay Janyani, S. K. Bhatnagar,"Improved Single Mode Property in Elliptical Air Hole Photonic Crystal Fiber", **Journal of Modern Optics** Volume:58 / 604-610 / 2011.

23) Sumaiya Kabir, Mosst Tasnim Binte Shawkat, Muhammad Abdul Goffar Khan, S.M.A Razzak (2015) "Bending Insensitive Dispersion Flattened Modified Equiangular Spiral Photonic Crystal Fiber(MES-PCF)"IEEE international WIE Conference on Electrical and Computer Engineering.

24) Japatosh Mondal Mohammad Shaifur Rahman (2015) " Design of Highly BirefringentDispersion Compensating Spiral Photonic Crystal Fiber" IEEE 2nd Int'l Conf on Electrical Engineering and Information & Communication Technology (ICEEICT).

25) Boyao Li, Mingqin Li, Lu Peng, Guiyao Zhou, Zhiyun Hou, Changming Xia(2017) "Research on Dual-Wavelength Single Polarizing Filter Based on Photonic Crystal Fiber" IEEE Photonic Journal.

26) Chengcheng Gui and Jian Wang (2012) "Elliptical–Spiral Photonic Crystal Fibers With Wideband High Birefringence, Large Nonlinearity, and Low Dispersion" IEEE Photonic Journal.

27) Tianye Huang, Jianfei Liao, Songnian Fu, M. Tang, P. Shum, Deming Liu (2014) "Slot Spiral Silicon Photonic Crystal Fiber With Property of Both High Birefringence and High Nonlinearity" IEEE Photonics Journal

28) Mahmud, R. R., Razzak, S. A., Hasan, M. I., & Hasanuzzaman, G. K. M. (2015)."Ultra-flattened high negative chromatic dispersion over O+ E+ S+ C+ L+ U bands of a microstructured optical fiber". Optical Engineering, 54(9), 097105-097105.

29) Mondal, J., & Rahman, M. S. (2015, May). The design of highly birefringent dispersion compensating spiral photonic crystal fiber. In Electrical Engineering and Information Communication Technology (ICEEICT), 2015 International Conference on (pp. 1-4). IEEE.

30) Geerthana, S., Raja, A. S., & Sundar, D. S. (2015). Design and optimization of photonic crystal fiber with improved optical characteristics. Journal of Nonlinear Optical Physics & Materials, 24(04), 1550051.

31) Liao, J., Huang, T., Xiong, Z., Kuang, F., & Xie, Y. (2017). Design and analysis of an ultrahigh birefringent nonlinear spiral photonic crystal fiber with large negative flattened dispersion. Optik-International Journal for Light and Electron Optics, 135, 42-49.

32) Amin, M. N., & Faisal, M. (2016). Highly nonlinear polarization-maintaining photonic crystal fiber with nanoscale GaP strips. *Applied optics*, *55*(35), 10030-10037.

33) Chowdhury, S., & Kushary, S. (2017, February). The design of a nearly zero ultra-flattened dispersion shifted fiber with high birefringence and high non-linearity. In Electrical, Computer and Communication Engineering (ECCE), International Conference on (pp. 106-108). IEEE

Thesis

ORIGINALITY REPORT

%15	%6	%12	%3
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	users.minet.uni-jena.de Internet Source	%1
2	Samiul Habib, M., M. Selim Habib, M. Imran Hasan, and S.M.A. Razzak. "Highly nonlinear polarization maintaining two zero dispersion spiral photonic crystal fiber using artificial defects", Optical Fiber Technology, 2013. Publication	%1
3	M.J. Steel, R.M. Osgood. "Polarization and dispersive properties of elliptical-hole photonic crystal fibers", Journal of Lightwave Technology, 2001 Publication	%1
4	Liao, Jianfei, Junqiang Sun, Mingdi Du, and Yi Qin. "Highly Nonlinear Dispersion-Flattened Slotted Spiral Photonic Crystal Fibers", IEEE Photonics Technology Letters, 2014. Publication	%1
5	Submitted to Malaviya National Institute of Technology Student Paper	%1

6	T.P. Hansen. "Highly birefringent index-guiding photonic crystal fibers", IEEE Photonics Technology Letters, 6/2001 Publication	%1
7	K. Saitoh. "Numerical Modeling of Photonic Crystal Fibers", Journal of Lightwave Technology, 11/2005 Publication	<%1
8	Sharma, Varshali, and Ritu Sharma. "Design of hybrid photonic crystal fiber with elliptical and circular air holes analyzed for large flattened dispersion and high birefringence", Journal of Nanophotonics, 2016. Publication	<%1
9	www.iet.ntnu.no Internet Source	<%1
10	code.ua.pt Internet Source	<%1
11	66.180.169.221 Internet Source	<%1
12	Ritu Sharma. "Improved single mode property in elliptical air hole photonic crystal fiber", Journal of Modern Optics, 03/03/2011 Publication	<%1
13	S. Roy, S. F. Kayser, T. Azmaeen. "Design and	<%1

optimization of a single mode octagonal photonic crystal fiber for high negative dispersion and high nonlinearity", 2016 5th International Conference on Informatics, Electronics and Vision (ICIEV), 2016
Publication

---

14 Islam, Md. Asiful, and M. Shah Alam. "Design of a Polarization-Maintaining Equiangular Spiral Photonic Crystal Fiber for Residual Dispersion Compensation Over $E{+}S{+}C{+}L{+}U$ Wavelength Bands", IEEE Photonics Technology Letters, 2012.
Publication
<%1

---

15 R. Attia. "Modelling microstructured optical fibres", First International Symposium on Control Communications and Signal Processing 2004, 2004
Publication
<%1

---

16 Asiful Islam, Md., and M. Shah Alam. "Equiangular spiral photonic crystal fibers with low bending loss", Optical Engineering, 2013.
Publication
<%1

---

17 www.docstoc.com
Internet Source
<%1

---

18 Agrawal, A., N. Kejalakshmy, B.M.A. Rahman, and K.T.V. Grattan. "Soft Glass Equiangular Spiral Photonic Crystal Fiber for
<%1

Supercontinuum Generation", IEEE Photonics Technology Letters, 2009.
Publication

19	Wang, J.. "Dispersion and polarization properties of elliptical air-hole-containing photonic crystal fibers", Optics and Laser Technology, 200707 Publication	<%1
20	www.if.pwr.wroc.pl Internet Source	<%1
21	Russell, Philip. "Photonic crystal fibers. (Review: applied physics).", Science, Jan 17 2003 Issue Publication	<%1
22	Asaduzzaman, Sayed, Kawsar Ahmed, Touhid Bhuiyan, and Tanjila Farah. "Hybrid photonic crystal fiber in chemical sensing", SpringerPlus, 2016. Publication	<%1
23	www.scilab.in Internet Source	<%1
24	Gui, C., and J. Wang. "Elliptical-Spiral Photonic Crystal Fibers with Wide-Band High Birefringence, Large Nonlinearity and Low Dispersion", IEEE Photonics Journal, 2012. Publication	<%1

25	Md. Ibadul Islam, Maksuda Khatun, Shuvo Sen, Kawsar Ahmed, Sayed Asaduzzaman. "Spiral photonic crystal fiber for gas sensing application", 2016 9th International Conference on Electrical and Computer Engineering (ICECE), 2016 Publication	<%1
26	Kalli, Kyriacos, Alexis Mendez, A. M. Abdelghani, Mohamed Farhat O. Hameed, Maher Abdelrazzak, M. A. Hindy, and S. S. A. Obayya. "Highly nonlinear birefringent tellurite photonic crystal fiber", Micro-structured and Specialty Optical Fibres III, 2014. Publication	<%1
27	Submitted to Thapar University, Patiala Student Paper	<%1
28	umexpert.um.edu.my Internet Source	<%1
29	www.city.ac.uk Internet Source	<%1
30	ira.lib.polyu.edu.hk Internet Source	<%1
31	Submitted to University of Essex Student Paper	<%1
32	Sh. Mohammad nejad. "Design of single mode	<%1

photonic crystal fibers with low-loss and flattened dispersion at 1.55μm wavelength", 2007 International Symposium on High Capacity Optical Networks and Enabling Technologies, 11/2007

Publication

33	Submitted to The Hong Kong Polytechnic University Student Paper	<%1
34	Xuyou Li, Pan Liu, Zhenlong Xu, Zhiyong Zhang. "Design of a pentagonal photonic crystal fiber with high birefringence and large flattened negative dispersion", Applied Optics, 2015 Publication	<%1
35	Yin, Aihan, and Lei Xiong. "Characteristics analysis of large solid-core square-lattice photonic crystal fibers with hybrid cladding", Optical Engineering, 2014. Publication	<%1
36	Cheung, Y K, and K W Chau. "NONLINEAR FINITE ELEMENT ANALYSIS OF REINFORCED CONCRETE FRAME UNDER DIFFERENT LATERAL LOADING PATTERNS", Tall Buildings, 2005. Publication	<%1
37	Jian Tang, Zhigang Zhang, Deng Luo, Ming	

Chen, Hui Chen. "High birefringence terahertz photonic crystal fiber", Optical Engineering, 2013
Publication | <%1

38	Submitted to University of Central Florida Student Paper	<%1
39	Submitted to International Islamic University Malaysia Student Paper	<%1
40	Submitted to VIT University Student Paper	<%1
41	Submitted to City University of Hong Kong Student Paper	<%1
42	www.curtismeyer.com Internet Source	<%1
43	Submitted to Universiti Teknologi MARA Student Paper	<%1
44	Mohamed Hameed, Abdel-Karim Hassan, Ahmed Elqenawy, Salah Obayya. "Modified Trust region Algorithm for Dispersion Optimization of Photonic Crystal Fibers", Journal of Lightwave Technology, 2017 Publication	<%1
45	Islam, M. A., and M. S. Alam. "Design Optimization of Equiangular Spiral Photonic	<%1

Crystal Fiber for Large Negative Flat Dispersion and High Birefringence", Journal of Lightwave Technology, 2012.
Publication

---

46 www.scribd.com <%1
Internet Source

---

47 dspace.cc.tut.fi <%1
Internet Source

---

48 Li, Jianhua. "Highly birefringent photonic crystal fibers with selectively liquid-filled structure in cladding", Optical Engineering, 2011. <%1
Publication

---

49 Makouei, S.. "Study of bending loss and mode field diameter in depressed inner core triple-clad single-mode optical fibers", Optics Communications, 20071201 <%1
Publication

---

50 Wei Chen. "Dispersion-flattened Bragg photonic crystal fiber for large capacity optical communication system", Frontiers of Optoelectronics in China, 06/02/2009 <%1
Publication

---

51 Finlayson, . "Transport Processes in One Dimension", Introduction to Chemical Engineering Computing Finlayson/Chem Eng Computing 2E, 2012. <%1

Publication

52	Johny, Jincy, Sreenesh Shashidharan, and S. K. Sudheer. "Determination of fiber parameters and the effects of dispersion in a Radio over Fiber system", 2012 International Conference on Optical Engineering (ICOE), 2012. Publication	<%1
53	Selim Habib, Md., and Emran Khandker. "Highly birefringent photonic crystal fiber with ultra-flattened negative dispersion over S + C + L + U bands", Applied Optics, 2015. Publication	<%1
54	scholar.lib.vt.edu Internet Source	<%1
55	Dihan, Md. Nuruddin Hasan, Muhammad Nazmul Hossain, M. Shah Alam, and K. M. Mohsin. "Dispersion and birefringence properties of a novel As2Se3 photonic crystal fiber nanowire", 2010 Photonics Global Conference, 2010. Publication	<%1
56	Hameed, Mohamed Farhat O., Salah S.A. Obayya, Moataza Abd el Hamid Hindy, Amr M. Abdelghani, and Maher Abdelrazzak. "Liquid crystal photonic crystal fibre with high non-linearity and birefringence", IET Optoelectronics, 2014.	<%1

Publication

57	Hasan, Md. Imran, R. R. Mahmud, Monir Morshed, and Md. Rabiul Hasan. "Ultra-flattened negative dispersion for residual dispersion compensation using soft glass equiangular spiral photonic crystal fiber", Journal of Modern Optics, 2016. Publication	<%1
58	www.seic.com Internet Source	<%1
59	"Program", 2016 9th International Conference on Electrical and Computer Engineering (ICECE), 2016 Publication	<%1
60	Li, Xuyou, Zhenlong Xu, Weiwei Ling, and Pan Liu. "Design of highly nonlinear photonic crystal fibers with flattened chromatic dispersion", Applied Optics, 2014. Publication	<%1
61	osaptesting.osa.org Internet Source	<%1
62	Medjouri, Abdelkader, Lotfy Mokhtar Simohamed, Omar Ziane, Azzedine Boudrioua, and Zoubir Becer. "Design of a circular photonic crystal fiber with flattened chromatic dispersion using a defected core and	<%1

selectively reduced air holes: Application to supercontinuum generation at 1.55µm", Photonics and Nanostructures - Fundamentals and Applications, 2015.
Publication

63	Hasan, Md Imran, S. M. Abdur Razzak, and Md Samiul Habib. "Design and Characterization of Highly Birefringent Residual Dispersion Compensating Photonic Crystal Fiber", Journal of Lightwave Technology, 2014. Publication	<1%
64	T MONRO. "Microstructured Optical Fibers", Guided Wave Optical Components and Devices, 2006 Publication	<1%
65	Samiul Habib, Md., K. M. Nasim, Md. Selim Habib, Md. Imran Hasan, and Redwan Ahmad. "Relative dispersion slope matched dispersion compensating highly birefringent spiral microstructure optical fibers using defected core", Optical Engineering, 2013. Publication	<1%
66	Liao, Jianfei, and Tianye Huang. "Highly nonlinear photonic crystal fiber with ultrahigh birefringence using a nano-scale slot core", Optical Fiber Technology, 2015. Publication	<1%

67	N. ZOU. "Novel Square Photonic Crystal Fibers with Ultra-Flattened Chromatic Dispersion and Low Confinement Losses", IEICE Transactions on Electronics, 03/01/2007 Publication	<%1
68	Russel Reza Mahmud, S.M. Abdur Razzak, Md. Shaikh Salman, Md. Imran Hasan. "Design of a photonic crystal fiber with negative flat dispersion for residual dispersion compensation", 2015 International Conference on Electrical & Electronic Engineering (ICEEE), 2015 Publication	<%1
69	Hossain, Md. Nazmul. "Design of a spiral silica photonic crystal fiber for nonlinear applications in visible region", Optical Engineering, 2011. Publication	<%1
70	Philip St.J. Russell. "Photonic-Crystal Fibers", Journal of Lightwave Technology, 2006 Publication	<%1
71	Mishra, S.S.. "Highly birefringent photonic crystal fiber with low confinement loss at wavelength 1.55@mm", Optik - International Journal for Light and Electron Optics, 201111 Publication	<%1