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Modelling and Simulation of Photonic Crystal Fiber Structure for Fiber Laser Applications

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Abstract:
In the present work, we propose the designing and simulation of a photonic crystal fiber (PCF) structure to obtain a perfect solution to the tradeoff between the high birefringence and the confinement loss in elliptical hole PCFs.The effects on PCF parameters after filling the core with Rodhamine –B and Chalcode as background materials, dispersion for same calculated. The results provide a method for reducing confinement loss and suggest an approach for modify the effective index of the fiber core which is used for fiber laser applications.

Keywords **—PCF, Dispersion**

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I. INTRODUCTION

Photonic crystal fibers have attracted increasing due to manipulation in optical properties.In the proposed work it is found that PCF with elliptical air holes improve birefringence [1].In this category of PCFS high birefringence is achieved with ultra low confinement loss is proposed by employing elliptical holes in the fibercore [2].COMSOL software have been used for the simulation of the problem.

II. ADVANTAGES OF PCF OVER CONVENTIONAL FIBERS

In contrast to conventional fibers PCFs have additional design parameters namely pitch, number of rings and hole diameters that offer design flexibility which is not possible in conventional fibers.

As a result PCFs have been reported with attractive features such as [7]

(1)Endlessly single mode operation
(2)High nonlinearity
(3)Ultra-flattened chromatic dispersion
(4)Low confinement loss
(5) PCF has an improved photonic crystal cladding than conventional fibers.
(6) PCFs dispersion properties are highly remarkable.

Ongoing research in photonic crystal fibers (PCFs) includes applications [8] in a wide range of areas as optical signal transmission, high power lasers, non linearfiber optics, optical signal processing and others. The versatility is due to the particular design flexibility of PCFs which allows them to fit a specific application by varying its geometrical characteristics and structure.

III LITERATURE SURVEY

A. OPTICAL FIBER

The The optical fiber is the guided medium of the future. Optical fibers are usually made of silica-glass. A conventional simple mode step index fiber [9] has two regions called core and cladding. The Core is made of glass of a higher refractive index than the cladding. The Index difference is necessarily low, generally up to the 2nd decimal place.

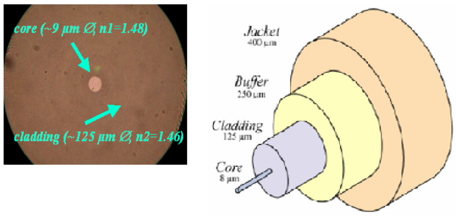

Figure 1.1: Cross Section of a Conventional Optical Fiber

Optical Fibers work because of a phenomenon called Total Internal Reflection (TIR) [6]. When light travels from a rare to a denser medium or vice-versa, there occurs a bending of light. From a denser to a rare medium, bending occurs away from the normal at the boundary. The bending increases with the angle of incidence. At a critical angle of incidence at the boundary, light bends so much that it re-enters the medium from which it originated. This 'reflection' is used to propagate light in the fiber. The dense and rare media are the core and the cladding respectively. If light is launched in such a way that it becomes incident on the core-cladding interface at the critical angle, we get Total Internal Reflection.

There are different types of fibers. They are classified based on the number of modes (Single and Multi-Mode fibers) [9] they can support and on the refractive index profile (Step and Graded Index Fibers). It is important to know about modes that propagate in a fiber. Modes are a set of discrete field patterns in the form of which light propagates in a fiber. There are 4 types of Natural Modes in a fiber: Transverse Electric, Transverse Magnetic, hybrid HE and EH. However the modes that truly exist in a fiber are called Linearly Polarized Modes (LP). These Modes are formed by the combination of natural modes.

A process called 'Drawing' fabricates Optical Fibers. To 'draw' a fiber, a preform has to be prepared. A preform is, simply described as an optical fiber on a much larger scale. A silica glass core-cladding structure is made with a diameter of 10-20 cm and a length of 50-100 cm. The preform has the desired refractive index profile, attenuation and other characteristics. A drawing tower is employed to fabricate the fiber. This is a vertical tower in which the preform is placed. The bottom part of the preform is heated till it melts. The molten piece now starts falling through a column of desired fiber thickness, say 125 micrometer. Monitoring equipment observes the diameter of the fiber as it is drawn and changes the rate of drawing to keep the diameter uniform in case of inconsistencies. A coating is applied over the cladding, and this is cured using UV lamps. The coated fiber is wound into reels. The manufacturer needs to make a compromise between quality and speed of production in this process.

Optical Fibers are very important because of the high data rates that it can support. In the telecommunication industry, it would mean an enormous number of usable channels. The distance that can be covered by optical cables without the use of repeaters is large. And one of the most attractive advantages is the fact that optical signals are immune to electromagnetic interference. This means that signals transmitted through an optical fiber have very little chance of getting distorted because of external EM waves. It also improves the security of transmissions, as they cannot be jammed. The attenuation of light during transmission is very low and is in the order of 0.5dB/Km.

B. PHOTONIC CRYSTAL FIBERS

The history of photonic crystal fibers (PCFs) started as early as in the seventies. However, its impact remained rather marginal until the nineties when the maturity of the technology enabled the fabrication of almost perfect structures. The great flexibility in the design of PCFs led to tremendous progress in various areas of the field of optics, ranging from frequency metrology to medial science and the future prospects have aroused the interest of many research groups [9].

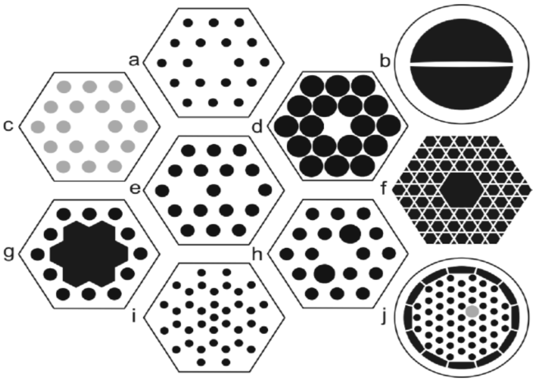

Figure 1.2 Types of PCF

4.FABRICATION OF PCF

Photonic crystal fibers are fabricated in a two-stage process [14, 16]. In the first stage, a preform is formed by stacking capillary tubes and rods made of silica (or whichever glass). This permits a high level of flexibility to control the index profile of the cladding region. In particular, the positioning and/or removal of capillary tubes allow customizing the air/silica structure. In the second stage, the preform is drawn into a very thin fiber using a precision mechanism that feeds it into a hot furnace at a proper speed. The structure of the preform is maintained during the drawing process through careful control of the feeding speed and heating temperature. In this way, very complex designs of structure can be manufactured, e.g., large air-filling fraction, highly birefringent, elliptical holes or triangular core PCFs can be produced. The fibers are then coated with a protective jacket.

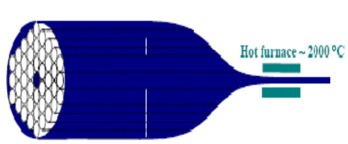

Figure 1.3: Capillary tubes and a silica rod are stacked to form a preform which is subsequently drawn into a thin PCF through a hot furnace.

UNIQUE PROPERTIES OF PCF

1. Fine control of effective refractive index (endlessly single-mode, large mode area). Endlessly Single Mode means that the fiber exhibits single mode properties over a major portion of the spectrum [3].

2. Large index step (0.6 - 0.7) results in high non-linearity, high or low dispersion depending on requirement.

3. Since the entire fiber is made of a single material, it is temperature insensitive. No dopants are needed, and there is no need to find a matching cladding glass

4. Presence of Air holes enables applicability in gas sensors, fibre devices. Design freedom and simplicity (e.g. multicore fibres).

5. Possibility of filling air holes with fluids, which would alter the transmission parameters of the fiber.

6. Low Bending Loss even for large mode area.

7. Extremely strong birefringence.

8.Unusual dispersion properties, e.g. anomalous dispersion in the visible wavelength region.

9. Greater Mode Areas achieved by fusing holes at one end of the fibre by heat treatment.

10. The possibility of a fundamental mode cut-off, making it possible to design Single-polarization fibers (in conjunction with strong birefringence) and the suppression of Raman scattering.

A BIREFRINGENCE

In any ordinary single mode fiber there are actually two independent, degenerate propagation modes. These modes are very similar but their polarization planes are orthogonal. These modes are very similar but their polarization planes are orthogonal [13].These may be chosen arbitrarily as the horizontal and the vertical polarizations. Either one of these two polarization modes constitutes the fundamental HE11 mode. In general the electric field of the light propagating along the fiber is a linear superposition of these two polarization modes and depends on the polarization of the light at the launching point into the fiber.

In ideal fibers with perfect rotational symmetry [5] the two modes are degenerate with equal propagation constants (Kx=Ky) and any polarization state injected into the fiber will propagate unchanged.

In actual fibers [13] there are imperfections such as asymmetrical lateral stresses, on-circular cores and variations in refractive index profiles. These imperfections break the circular symmetry of the ideal fiber and lift the degeneracy of the two modes. The modes propagate with different velocities and the difference between their effective refractive indices is called fiber "Birefringence". It is given by [6]

$$B=n_y-n_x \quad (1.1)$$

Equivalently we may define the birefringence as β=ko (n_Y-n_X),Whereko=$2\pi/\lambda$ is the free space propagation constant.

If light is injected into the fiber so that both modes are excited then one will be delayed in phase relative to the other as they propagate In case of birefringence in crystals such as tumor electric field vector will vibrate in only one direction.

In case of birefringence in fibers the polarization state(x-direction or y-direction) is maintained even after the light covers a finite distance from the propagation point.

IV EFFECTS OF ELLIPTICAL CORE

Elliptical core is a non-circular core in which there are two mutually perpendicular axes known as major axis and minor axis which are of unequal length. The length of major axis is greater than minor axis (and major axis has been taken in the vertical direction).This makes the structure asymmetrical [5] as a whole. In ideal fibers with perfect rotational symmetry the two modes are degenerate with equal propagation constants (Kx=Ky) and any polarization state injected into the fiber will propagate unchanged.

But due to the asymmetry of the elliptical core the degeneracy of the two modes is lifted. The modes propagate with different phase velocities, and the difference between their effective refractive indices is called fiber birefringence. It is given by [6],

$$B=n_y-n_x$$

Equivalently we may define the birefringence as $\beta=k_o(ny-nx)$, where $k_o=2\pi/\lambda$ is the free space propagation constant. The key technique is to destroy the symmetry of the core structure of the PCFs and make the large effective index difference of the two orthogonal polarization fundamental modes.

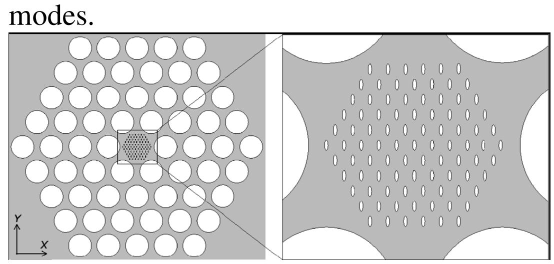

Figure1.4 : Cross section of the proposed PCF with four rings of circular air holes in the fiber cladding and elliptical air microholes in the fiber core.

High birefringence can be achieved by employing elliptical holes in the fiber cladding. In this category high birefringence is achieved when the bulk of the mode energy is in the fiber cladding; thus, the high birefringence is often accompanied with poor energy confinement. In order to overcome this problem elliptical holes are employed in the fiber core to induce the birefringence but circular holes in the cladding to reduce the confinement loss. This ensures that there is a balance between the high birefringence and the confinement loss in elliptical-hole PCFs.

Using PCFs, highly birefringent fibers [8] can be easily realized because the index contrast is higher than conventional fibers and the fabrication process permits the formation of the required asymmetric microstructure near the fiber core. These manifestly birefringent structures allow us to examine the interplay of the unusual dispersive properties of standard PCF with strongly polarization dependent effects. One possible use of highly birefringent PCFs is as polarization maintaining fibers (PMFs).PMFs is essential for [8] coherent optical communication systems and fiber sensor systems.

B CONFINEMENT LOSS

It is defined as the leakage of power from core to the cladding and is deduced from the imaginary part of the effective modal index which is found through simulation. It is given by [8]

$$Lc = 8.686*Im\,[k_o n_{eff}]\ db/m. \quad (2.1)$$

Im stands for imaginary part and $k_o$is called wave number and is given by 2π/λ.

Confinement loss is a function of number of rings employed in the cladding. As the number of rings increases confinement increase and confinement loss starts decreasing [1].In PCFs with an infinite number of air holes, confinement losses do not occur. In fabricated PCFs, however the number of air holes in the cladding is finite, and so the modes of such fibers are inherently leaky. Perfectly matched layers are created around the PCF structure. A PML is strictly speaking not a boundary condition but an additional domain that absorbs the incident radiation without producing reflections. After the PML implementation we get the imaginary part of effectiverefractive index which is used to find confinement loss.

V PROPERTIES OF MATERIALS USED

Rhodamine B

- It is also called Rhodamine 610, C.I. Pigment Violet 1.
- It is tunable around 610 nm when used as a laser dye.
- It is expected to be carcinogenic so it contains a warning on its label [20].

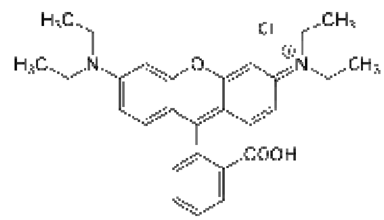

Figure 1: Structure of Rhodamine B

- Rhodamine B is used in biology as a staining fluorescent dye, sometimes in combination with auramine O, as the auramine-rhodamine stain to demonstrate acid-fast organisms, notably Mycobacterium.

Rhodamine 6G

- It is often used as a laser dye.
- It has high photostability, high quantum yield and low cost.
- The lasing range of the dye is 555 to 585 nm with a maximum at 566 nm.

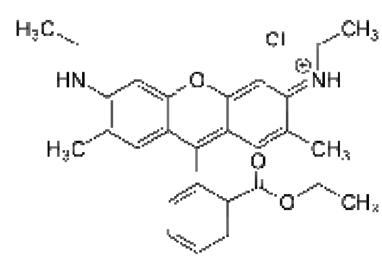

Figure 2: Structure of Rhodamine 6G

Rhodamine 6G is pumped by the 2nd (532 nm) harmonic from aNd: YAG laser.

Rhodamine B is tunable around 610 nm when used as a laser dye.

Coumarin is used as a gain medium in some dye lasers.

VICHALCOGENIDE GLASS

(AS BACKGROUND MATERIAL)

- A chalcogenide glass is a glass containing one or more chalcogenide elements (Group VI in the periodic table e.g. sulfur, selenium or tellurium) as a substantial constituent.
- They are covalently bonded materials and may be classified as molecular solids, that is to say the entire glass matrix may be considered as an infinitely bonded molecule.
- It has a refractive index [19] in the range of 3.3-3.5.
- The physical properties of chalcogenide glasses are

a) High refractive index
b) Low phonon energy

also make them ideal for incorporation into laser and other active devices when doped with rare earth ions.

- Some chalcogenide materials experience thermally driven amorphous crystalline phase changes, enabling the encoding of binary information on thin films of chalcogenides, forming the basis of rewritable optical discs and non-volatile memory devices such as PRAM. Examples of such phase change materials are GeSbTe and AgInSbTe. In optical discs, the phase change layer is usually sandwiched between dielectric layers of $ZnS\text{-}SiO_2$, sometimes with a layer of a crystallization promoting film.

APPLICATIONS

The modern technological applications of chalcogenide glasses are widespread specifically as

i. Mouldable infrared optics including lenses.
ii. Infrared optical fibers as these materials transmit across the full range of the infrared regime of the electromagnetic spectrum.
iii. They can be incorporated into laser and other active devices.

Different combinations of substrate material are used for the solid core (instead of silica) and the materials to be filled in elliptical and circular holes. Chalcogenide glass has been selected as the background material and the laser dyes have been used as materials to be filled in air holes.

VII DISPERSION IN PHOTONIC CRYSTAL FIBER

In general, light waves with different wavelengths travel at different speeds inside materials. The dependence of the speed of light on its wavelength is commonly referred to as dispersion. Dispersion is one of the most important parameter of optical fibers and components and its control [18] is very important as it may strongly affect the performances of communication systems and fiber-optic nonlinear devices.

The important dispersion in a fiber are classified as:

1) Intramodal or chromatic dispersion

2) Intermodal dispersion

Intermodal dispersion is absent in single mode fibers.

There are basically two types of intramodal dispersion which is present in single mode fibers. They are

a) Material Dispersion

b) Waveguide Dispersion

A Material Dispersion

This arises from the variation of the refractive index of the core material as a function of wavelength. This causes a wavelength dependence of the group velocity of any given mode. Due to the wavelength dependence on group velocity, pulse spreading occurs in an optical fiber even when different wavelength follows the same path. It is given by [21]

$$D = -\frac{\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2}$$

The refractive index of a material depends on the wavelength of the electromagnetic wave interacting with the material. This dependence is referred to as the material dispersion [17] and it can be represented using the Sellmeier approximation

$$n(\lambda) = \sqrt{1 + \sum_{k \geq 1} \frac{B_k \lambda_k^2}{\lambda_k^2 - \lambda^2}} \,,$$

Where B_k is the magnitude of the kth resonance of the material located at wavelength λ_k. For silica fibers, the refractive index is well approximated using the following values for B_k and λ_k:

B_1=0.6961663, B_2=0.4079426, B_3=0.8974794 and λ_1=0.0684043 µm, λ_2=0.1162414 µm and λ_3=09.896161µm.

B Waveguide Dispersion

Waveguide dispersion occurs due to the dependence of the light confinement [18] on its frequency as it is guided along a waveguide (e.g., optical fibers).The dispersion occurs because a single mode fiber confines only about 80% of the optical power to the core. Dispersion thus arises, since 20% of the light propagating in the cladding travels faster than the light confined to the core. The amount of waveguide dispersion depends on the fiber design since modal propagation constant β is function of (a/λ).

Δ=n1-n2/n1 (2.4)

V=2*pi*a*sqrt ((n1-n2/n1)*2)/λ (2.5)

$V(dV^2/d\lambda^2) = 0.080+0.549(2.834-v)^2$ (2.6)

$D = -((n2*\lambda/3)*\lambda*10^7*V(dV^2/d\lambda^2)$ (2.7)

C Total Dispersion

It is also known as chromatic dispersion and is given by the sum of material dispersion and waveguide dispersion.

IX METHOD TO FIND DISPERSION

A ALGORITHM

Step 1 Start.

Step 2 Set the wavelength range.

Step 3 Find the effective index of silica material using sellmiers formula.

Step 4 Convert the wavelength and effective index into polynomial function using polyfit function.

Step 5 Find the first and second derivative using polyder function.

Step 6 Find the value of the polynomial using polyval function.

Step 7 Substitute the values obtained in the material dispersion formula.

Step 8 Find the change in refractive index (Δ) using n1&n2.

Step 9 Substitute the value of Δ in the equation for normalized frequency (V).

Step 10 Substitute the value of V and Δ in the waveguide dispersion formula.

Step 11 Add the values of material and waveguide dispersion to find the total dispersion and plot the curve.

Step 12 Stop.

X STIMULATED RESULTS

The simulated results have been shown with different materials in the core, cladding and the background with variation in the number of rings.

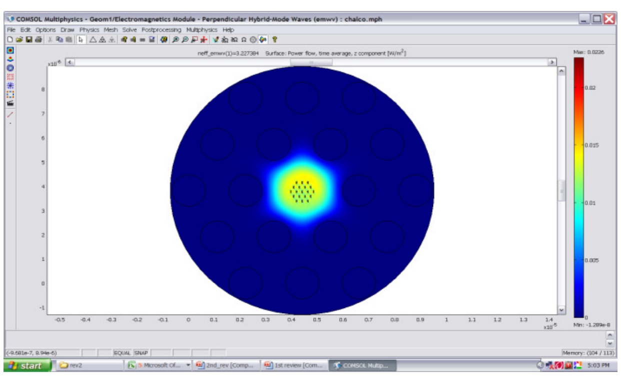

Figure 3 : Electric field pattern for PCF with Chalcogenide Glass as the background material.Pitch=3.3 µm,d1=1.31 µm,d2=0.120 µm,d3=0.031 µm

When two ring PCF was simulated with Chalcogenide glass as the background material instead of silica the above output was obtained.It gives a very high effective index and very high birefringence compared to silica.

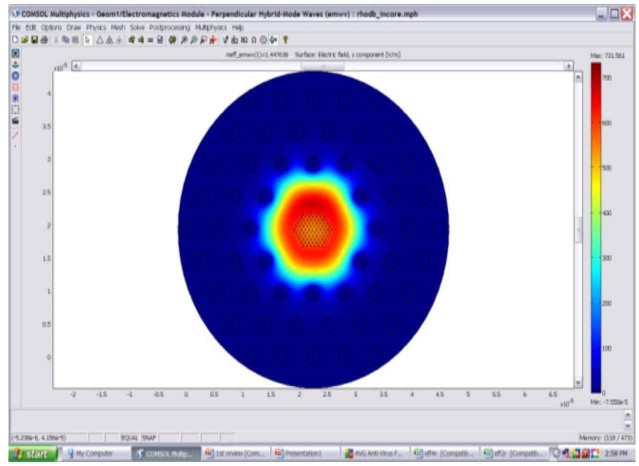

Figure4 : Electric field patern for four ring PCF with Rhodamine-B in the elliptical core. Pitch=4.86µm, d1=1.2µm, d2=.106µm, d3=.146µm

XIGRAPHS AND DISCUSSION

Various simulated structures of PCF has been studied and analysed.The values and graphs obtained for various parameters of PCF has been shown below.

A PCF with elliptical cladding and one missing hole as fiber core

The table below shows the variation of effective refractive index in the x and y direction and the difference in their values (Δn) with respect to normalized frequency for the PCF with elliptical cladding and one missing hole as fiber core.The variation has been plotted and shown in figure 5 and figure 6

Effective refractive index and Δn curve has been plotted for the elliptical cladding PCF.

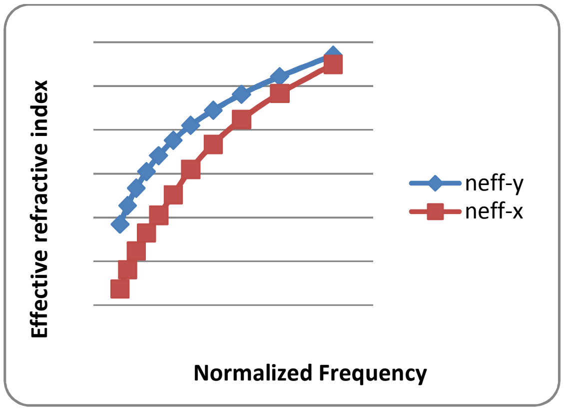

Figure 5: Effective refractive index with elliptical air holes in the cladding

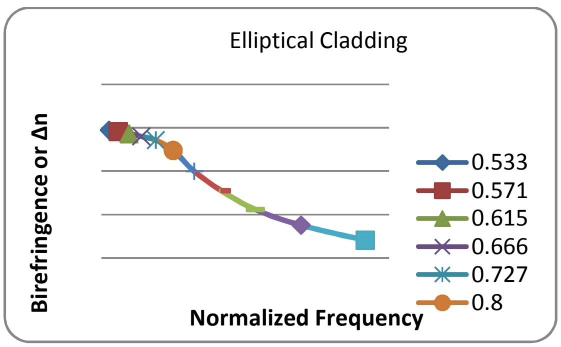

Figure 6 : Δn or birefringence with elliptical air holes in the cladding.

It can be seen that we get a higher order birefringence when elliptical air holes are employed in the cladding as elliptical holes are responsible for breaking the symmetry of the structure and lift the degeneracy of the modes.

Normalized Frequency	ηeff,y	ηeff,x	Δn
0.533	1.378462	1.363705	0.01475
0.571	1.382689	1.368114	0.014575
0.615	1.38669	1.372355	0.014335
0.666	1.390487	1.376467	0.01402
0.727	1.39411	1.380502	0.013608
0.8	1.3976	1.385184	0.0124
0.888	1.401019	1.391014	0.01
1	1.404464	1.396702	0.007762
1.142	1.408087	1.402401	0.0056
1.333	1.412138	1.408359	0.003779
1.6	1.417036	1.414967	0.002069

Table1: Elliptical cladding with one missing hole as fiber core

B Total Dispersion for the PCF structure

Total dispersion is the sum of material dispersion and waveguide dispersion.

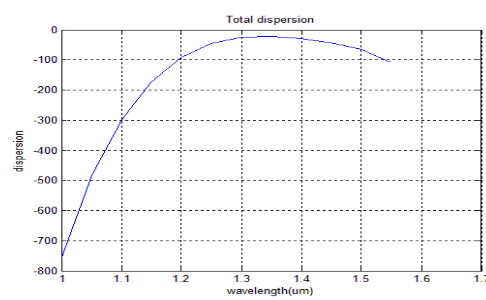

Figure 7 : Total dispersion of PCF structure

It is observed that we get approximately zero dispersion at 1.34µm.Dispersion should be very low for a good PCF structure.

XII CONCLUSION

The finite element method has been used to obtain various parameters of the elliptical core PCF. It has been noted that birefringence remains almost same for all the structures and it is almost independent on the number of rings used in the cladding. It rather depends upon the material which is used in the core, cladding or as background material. It is found highest in the structure with chalcogenide glass as the background material(of the order of 10^{-2}).When the elliptical holes were filled with laser dyes it was found that it operates at very low wavelength(550-650nm) in the visible region and the birefringence pattern is reversed.

Perfectly matched layer was applied in Comsol Multiphysics. Confinement loss was found out for different number of rings (two, three and five) in the cladding. It was found that confinement loss is a function of number of rings employed in the cladding. As the number of rings increase confinement increase and confinement loss starts decreasing. Five ring structure shows minimum confinement loss. The fabrication difficulty is largely released when we apply larger sizes of elliptical holes and a correspondingly lower number of hole rings in the fiber core for fabrication purpose. The simulation environment facilitates all steps in the modeling process defining your geometry, specifying your physics, meshing, solving and then post-processing your results. The advantage of Comsol lies in its versatility, flexibility and usability which can easily be extended with its add-on modules.

REFERENCES:

[1] Han-HsuanYeh and Yuan-Fong Chau, "The Analysis of High Birefringence Photonic Crystal Fiber with Elliptical Air Holes Cladding", 2007

[2] Daru Chen and Linfang Shen, "Ultrahigh Birefringent Photonic Crystal Fiber With Ultralow Confinement Loss", IEEE photonics technology letters, vol. 19, no. 4, pp 185-187 february 15, 2007.

[3] E.F. Chillcce, C.M.B. Cordeiro , L.C. Barbosa, C.H. Brito Cruz," Tellurite photonic crystal fiber made by a stack-and-draw technique"pp. 3423–3428,Aug 2006.

[4] GoëryGenty, Supercontinuum generation in microstructured fibers and novel optical measurement techniques, 2004.

[5] P. R. Chaudhuri, V. Paulose, C. Zhao, and C. Lu, "Near-elliptic core polarization-maintaining photonic crystal fiber: Modeling birefringence characteristics and realization," *IEEE Photon. Technol. Lett.*, vol. 16, no. 5, pp. 1301–1303, May 2004.

[6] M. J. Steel and R. M. Osgood, "Polarization and dispersive properties of elliptical-hole photonic crystal fibers," *J. Lightw. Technol.*, vol. 19, no. 4, pp. 495–503, Apr. 2001.

[7] X.L. Tan1,2,a, Y.F. Geng1,2, Y.P. Zhang1,2, H.Y. Zhang1,2, P.Wang1,2, and J.Q. Yao1,2,"Design of a new type high birefringence photonic crystal fiber", Vol.4 No.1, 1 Jan. 2008.

[8] W. Belardi, G. Bouwmans, L. Provino, and M. Douay, "Form-induced birefringence in elliptical hollow photonic crystal fiber with large mode area," *IEEE J. Quantum Electron.*, vol. 41, no. 12, pp. 1558–1564, Dec. 2005.

[9] Liwei Li and Instructor, "An introduction: Photonic crystal fiber", Class optics and photonics spring, 2008

[10] N. A. Issa, M. A. V. Eijkelenborg, M. Fellew, F. Cox, G. Henry, and M. C. J. Large, "Fabrication and study of microstructured optical fibers with elliptical holes," *Opt. Lett.*, vol. 29, pp. 1336–1338, 2004.

[11] K. Saitoh and M. Koshiba, "Single-polarization single-mode photonic crystal fibers," *IEEE Photon. Technol. Lett.*, vol. 15, no. 10, pp. 1384–1340, Oct. 2003.

[12] A. Ortigosa-Blance, A. Diez, M. Delgado-Pinar, J. L. Cruz, and M. V. Andres, "Ultrahigh birefringent nonlinear microstructured fiber," *IEEEPhoton. Technol. Lett.*, vol. 16, no. 7, pp. 1667–1669, Jul. 2004.

[13] R. D. Meade, A. M. Rappe, K. D. Brommer, J. D. Joannopoulos, and O. L. Alerhand, "Accurate theoretical analysis of photonic bandgap matetrials," *Phys. Rev. B*, vol. 48, no. 11, pp. 8434–8437, 1993.

[14] T. P. Hansen, J. Broeng, S. E. B. Libori, E. Knudsen, A. Bjarklev, J. R. Jensen, and H. Simonsen, "Highly birefringent index-guiding photonic crystal fibers," *IEEE Photon. Technol. Lett.*, vol. 13, no. 6, pp. 588–590, Jun. 2001.

[15] P. G. Agrawal, *Nonlinear Fiber Optics*. San Diego: Academic, 2001

[16] J. Ju, W. Jin, and M. S. Demokan, "Design of single-polarization single-mode photonics crystal fibers at 1.30 and 1.55 µm," *J. Lightw.Technol.*, vol. 24, no. 2, pp. 825–830, Feb. 2006.

[17] Yuh-Sien Sun, Yuan-Fong Chau, Din-Ping Tsai, "Analysis of dispersion properties of elliptic air hole photonic crystal fiber"

[18]P.J. Roberts1, 2, B.J. Mangan1, H. Sabert1, F. Couny1,2, T.A. Birks2, J.C. Knight2 and
P.St.J. Russell2, "Control of dispersion in photonic crystal fibers", J. Opt. Fiber.Commun.Rep. 2, pp. 435–461, 2005.

[19] Kimmo Paivasaari, Victor K. Tikhomirov, JariTurunen, "High refractive index chalcogenide glass for photonic crystal applications**"**, Optical Society of America,2007.

[20] S_. YALTKAYA and R. AYDIN, "Experimental Investigation of Temperature Effect on the Refractive Index of Dye Laser Liquids",pp. 41 - 47,2001

[21] Zhihua Zhang, Yifei Shi, BaominBian, and Jian Lu, "Large Negative Dispersion in Dual-Core Photonic Crystal Fibers Based on Optional Mode Coupling", IEEE photonics technology letters, vol. 20, no. 16, pp-1402-1404,August 15, 2008

