East West University

B.Sc. ENGINEERING THESIS

Modal Analysis of a Dual-Core Photonic Crystal Fiber Using COMSOL Multiphysics

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Authors :	***Supervisor :***
Abu Sayed (2015-2-55-009)	Zahidur Rahman
Md. Noor Hossain Akand (2015-1-58-045)	Lecturer, Dept. of ECE
Md. Abdullah Al Farabi (2015-2-55-001)	East West University

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Authors

We, Abu Sayed, Md. Noor Hossain Akand and Md. Abdullah Al Farabi declare that this thesis titled, "**Modal Analysis of a Dual-Core Photonic Crystal Fiber Using COMSOL Multiphysics**" and the work presented in it are our own. We confirm that:

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- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where we have consulted the published work of others, this is always clearly attributed.
- Where we have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely our own work.
- We have acknowledged all main sources of help.
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Signed:

Abu Syed		Farabi
Abu Sayed	**Md. Noor Hossain Akand**	**Md. Abdullah Al Farabi**
ID: 2015-2-55-009	ID: 2015-1-58-045	ID: 2015-2-55-001

Abstract

Photonic crystal fibers (PCF) are a new generation of optical fiber that guide light via a periodic air-silica. It has become a promising novel technology with several possible applications in wave guides, nonlinear optics, fiber lasers, sensory systems etc. Careful design of the photonic structure causes the fibers to behave in interesting new ways and one of main aims of this thesis is to analyze Dual-core PCF using Modal Analysis on COMSOL Multiphysics. Our main focus is to study the dynamic properties of Dual Core Photonic Crystal Fiber in a particular frequency domain.

Acknowledgements

All praise belongs to Allah, the Lord and the Sustainer of the worlds. May peace and blessings of Allah be upon our Prophet Muhammad. We take this opportunity to pray for our parents so that Most Merciful Allah may take care of them with mercy as they have shown mercy during our weakness.

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Dedicated to our parents…

Chapter 1

Introduction

Photonic crystal fiber is considered as an exceptional sort of fiber which has an internal unique structure made of capillaries, loaded up with air, laid to form a hexagonal lattice. Light can propagate along the fiber because of it's structure. An imperfection is acknowledged by removing at least one central capillaries. Photonic Crystal Fibers are modern and a new class of optical fibers. Using properties of optical fibers and photonic crystals they have a progression of novel properties difficult to accomplish in traditional fibers. Regular optical fibers perform very well in telecom and non-telecom applications, but there is a series of fundamental limits related to their structures. The fibers have inflexible structure standards to satisfy: constrained center width in the single-mode system, modular cut-off wavelength, restricted material decision. The structure of PCFs is truly adaptable. There are a few parameters to control the nature of propagation: cross section pitch, air hole measurement, refractive index and sort of grid. Appropriate structure for a specific undertaking enables one to acquire perpetually single mode fibers, which are single-mode in all optical range and a cut-off wavelength does not exist. Also, there are two controlling components in PCF: an) Index Guiding System and b) Photonic Bandgap System.

1.1 Review of Literature

Optical fiber theory was found during the 1970s. At present, it's the foundation of media transmission frameworks because of the huge measure of data it can convey. Well planned optical Fibers with proper material are additionally utilized for an assortment of different applications, including sensors, fiber lasers, drug, light and substantially more. Standard advance record optical fiber guides light by all out interior reflection, which happens just if the center has a refractive index higher than the external cladding. Light propelled in the center is totally reflected at the interface center/cladding and is, in this way guided in the center. Another method for managing light began to show up in 1987, when Yablonovitch and John found that compound of dielectric materials, intentionally made with an auxiliary size of a similar request of size as the wavelength of light, gave the likelihood of another wonder named Photonic Band-Gap (PBG). These tale intermittent structures were called photonic gems so as to stress their occasional nature and PBG in light of the fact that they displayed recurrence interims where no field arrangement existed. A light episode on a PBG material with a recurrence inside its PBG is reflected from the material since the light isn't permitted to proliferate through it. Just light with certain wave vectors is permitted to spread in the structure. On the off chance that a deformity, for example an anomaly in the standard example, is presented some place in this structure, the wavelengths illegal in the intermittent material are currently permitted to "remain" in the imperfection as the photonic precious stone running along the deformity keeps them from "getting away".

Figure 1.1: Photonic Crystal Fiber

The refractive list isn't required to be higher than that of the occasional material. By utilizing this thought light can be caught inside an empty center (imperfection). Along these lines, light can even be guided in air. This is the fundamental thought behind PBG Photonic Crystal Fibers (PCFs): they have a 2D occasional dielectric structure invariant the longitudinal way that encompasses an imperfection. Thusly they can guide light along the longitudinal course. The principal optical fiber with photonic gem cladding was exhibited in 1996 by Knight Et Al. This fiber did not control by the PBG impact but rather by a rule that is like Total-Internal-

Reflection (TIR). In 1998 Knight et al. exhibited the first PCF which guided light by the PBG impact. This fiber spoke to the beginning of another period of optical fiber innovation. A short history of PCF is appeared in Table 1. The possibility of a photonic gem fiber was displayed just because by Yeh Et Al. in 1978. They proposed to clad a fiber center with Bragg grinding, which is like 1D photonic crystal. A photonic crystal fiber made of 2D photonic crystal with an air hole in the center was designed by P. Russell in 1992 and the first PCF was showed at the Optical Fiber Conference (OFC) in 1996.

Table 1.0: Overview of PCF Developments

Year	Development
1978	Idea of Bragg fiber
1992	Idea of the photonic crystal fiber with air core
1996	Fabrication of single-mode fiber with photonic coating
1997	Endlessly single mode PCF
1999	PCF with photonic bandgap and air core
2000	Highly birefringent
2000	Super continuum generation with PCF
2001	Fabrication of a Bragg fiber
2001	PCF laser with double cladding
2002	PCF with ultra-flattened dispersion
2003	Bragg fiber with silica and air core
2004	Chalcogenide photonic crystal fiber
2005	Kagome lattice PCF
2006	Hybrid PCF
2007	Silicon double inversion technique for manufacturing polymer
2009	Hollow-core photonic bandgap fiber
2013	Double cladding seven core photonic crystals
2014	PCF based nano-displacement sensors
2015	Design of quiangular PCF
2015	Integration of PCF fiber laser

1.2 Basics of PCF

1.2.1 Types of PCF

There are 2 types of Photonic Crystal Fiber:

1. Index-guided Fiber
2. Photonic Bandgap Fiber

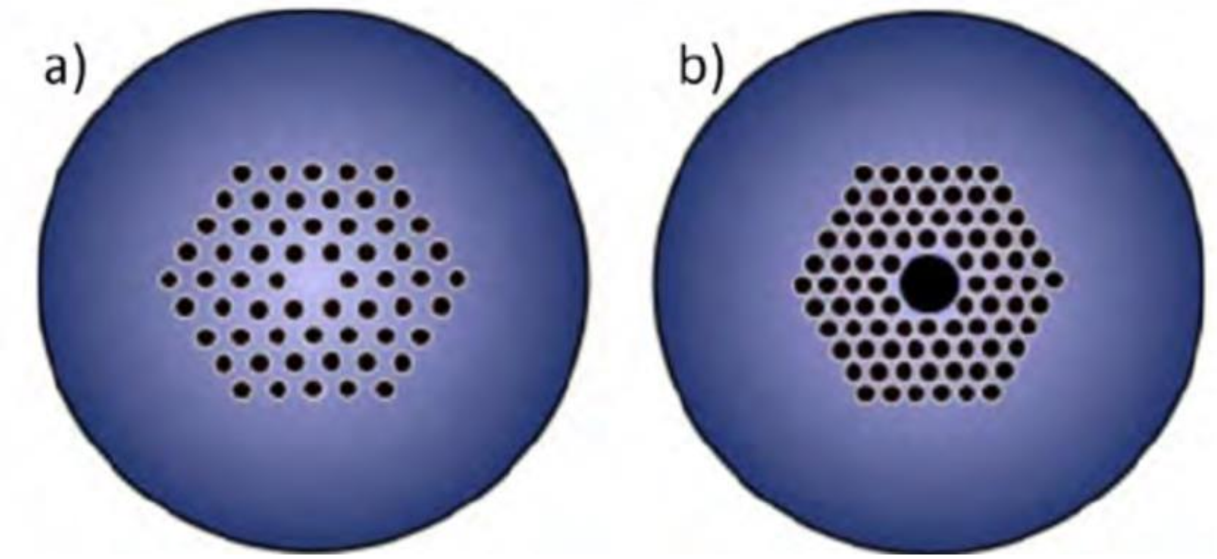

Figure 1.2: Types of PCF: (a) Index-guided Fiber (b) Photonic Bandgap Fiber

Index-guided Fiber

It’s also called holey fiber. It consists of a solid core and the pattern of holes surrounding that core. Here, the effective refractive index of the cladding is lower than the core due to the presence of holes in it. Light is guided into the core by total internal reflection at the core and air interface. Along the fiber, the fundamental frequency is guided along the fiber length through the solid core of the fiber and the higher-order modes are leaked in the holes surrounding the core. Thus the light travels through the fiber by the mechanism of modified total internal reflection. So, the necessity of different materials for the cladding is basically for creating the environment of total internal reflection. The fundamental frequency depends on the core diameter, hole diameter, lattice pitch and structure. Figure - (a) Shows the Solid core fiber or Index guided fiber.

Design features of the solid core PCF include endlessly single-mode at all wavelength, the large mode at short wavelength, highly nonlinear multiple cores. Moreover, solid core PCF find its application in super continuum generation and endlessly single-mode fiber.

Photonic Bandgap Fiber

It consists of the hollow core. In this, the center air hole has a larger diameter as compared to the diameter of the surrounding hole. Due to this, the core refractive index becomes lower than the cladding and the principle of conventional fibers do not apply to these fibers. Due to this geometry, there is an occurrence of photonic band gap which is analogous to the electronic band gap in semiconductors. Due to the presence of this photonic band gap, there exists a certain set of frequencies which are not allowed to pass through the fiber. This gap is defined by the geometry of the fiber. The light is guided along the fiber length even though the core refractive index is lower than that of the cladding. This property is in sharp contrast to the conventional fibers which require a core of relatively higher refractive index for light to be guided along the fiber. This unique property provides flexibility in the choice of material for the fiber. Depending on the fiber geometry, the bandgap can be shifted to cover the entire optical domain. Figure - (b) Shows Photonic bandgap fiber or Hollow fiber.

1.2.2 SC and ST Connectors

Connector types that are commonly used for interfacing fiber-optic cabling to systems administration gadgets. Both are accepted by the Electronic Industries Alliance/Telecommunications Industry Association (EIA/TIA) 568A standard.

SC represents Subscriber Connector and is a standard-duplex fiber-optic connector with a square shaped plastic body and push-pull locking highlights. SC connectors are normally utilized in information correspondence, CATV, and communication situations.

ST represents Straight Tip, an elite fiber-optic connector with round clay ferrules and blade locking highlights. ST connectors are more typical than SC connectors.

1.2.3 Photonic Instrumentation

Microscopic photonic devices (PD), such as integrated optical circuits and photonic crystals are characterized by physical scales typically 2 to 4 orders of magnitude smaller than traditional optical instruments. They have a number of unique properties which make them very attractive to modern astronomy including no internal alignment or maintenance once manufactured, simple deployment due to their small size, avoidance of lossy air/glass interfaces and ease of scaling in manufacture. Generally their operation is described in terms of the optics of the vectorial electromagnetic field rather than the intensity field appropriate for macroscopic devices. To realize instrumentation for extremely large telescopes (ELT's) that is both affordable and efficient is a daunting task. Projected instrument sizes and cost are very large with complex and non-profitable optical paths. The small size of photonic devices holds out the possibility of reduced size and cost.

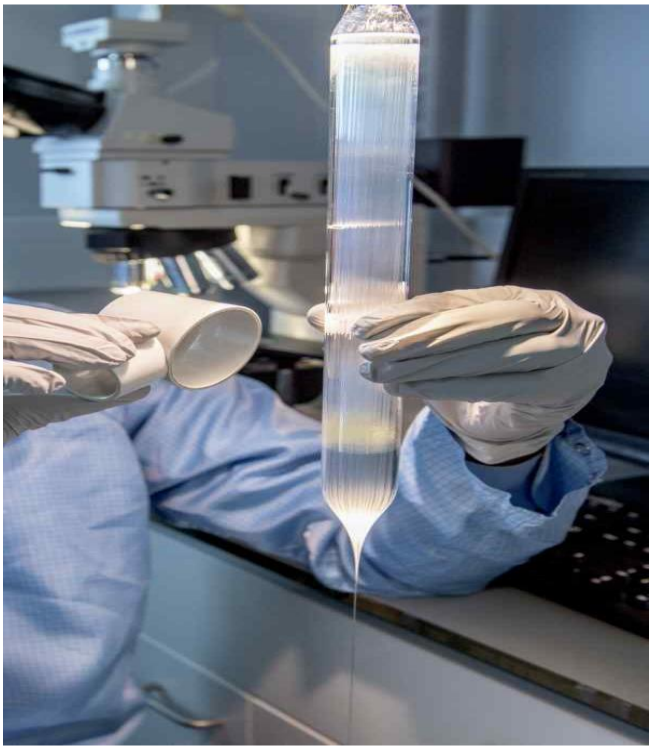

Figure 1.3: Inspection of a preform for a photonic crystal fiber

The image has been kindly provided by the Optoelectronics Research Centre, University of Southampton

Furthermore, their ease of deployment and multiplexing via small coherent bundles make them potentially very attractive to massively multiplexed integral-field spectroscopy-an important requirement for future astronomical facilities. Considering also that many advances in astronomy have been made possible by instrumentation that fully exploits the vectorial electromagnetic field, such as interferometry and, more recently, phase apodisation, so the potential to revolutionize astronomical instrumentation and explore new regions of observational parameter space is clear. Many optical components already exist in the form of PD's for common tasks including dispersion and interferometry.

Chapter 2

Design of Dual Core Elliptical Hole PCF

2.1 Structure of Dual Core Elliptical Hole PCF

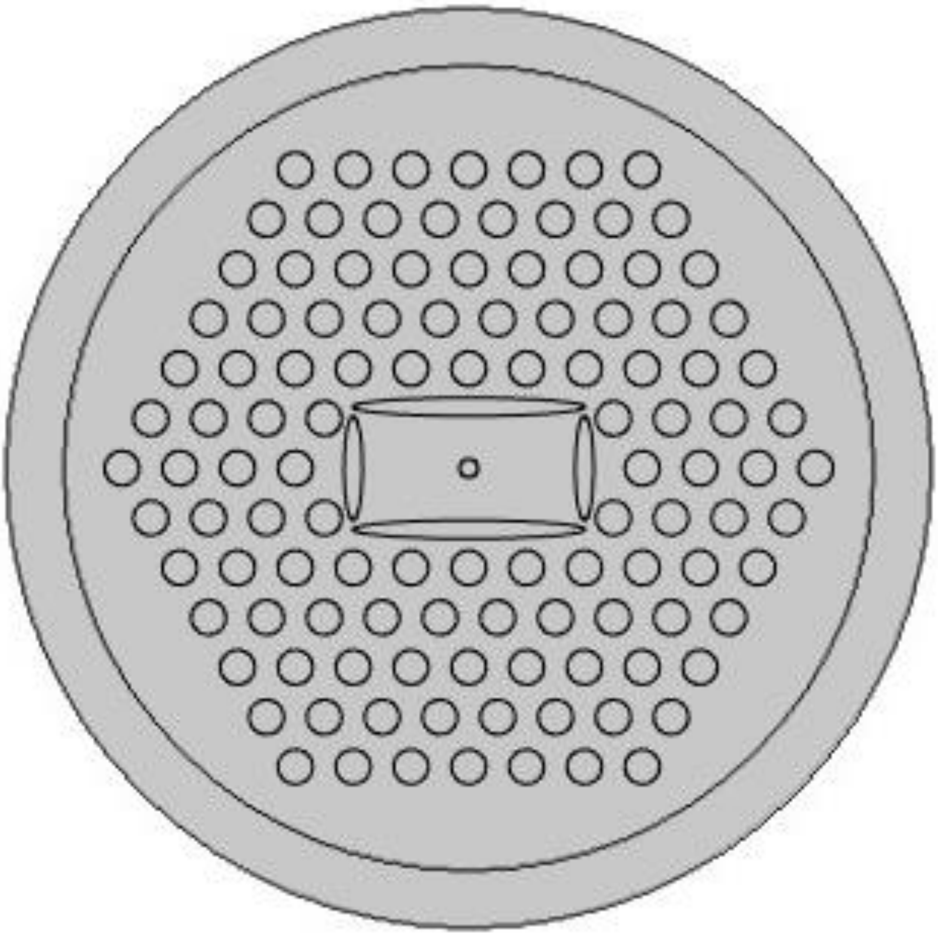

Figure 2.1: Elliptical Photonic crystal fiber.

The attributes of the dual-core photonic crystal fiber (PCF) sensor are examined by utilizing the limited component strategy (FEM), and the structure is improved by the numerical simulation results. The outcomes demonstrate that whether the four air holes far away from the geometric center point of the PCF are loaded up with analyte has no impact on the wavelength sensitivity of the sensor which means those holes can be supplanted by little air gaps. The wavelength sensitivity can be tuned by altering the spans of the other huge air openings which are with respect to fluid gaps.

2.2 Fundamental Modes in Dual-Core PCF

2.2.1 Fiber Modes

A fiber mode relates to a particular wave equation solution that meets the suitable boundary conditions and has characteristics that do not alter its spatial distribution with propagation. There are two modes: mode of guidance and mode of leakage. In an optical waveguide, a mode is called a guided mode, a mode whose field declines monotonically outside the core in the transverse direction and which does not lose radiation power. A waveguide leak mode or tunneling mode has an electrical field that declines monotonically in the transverse direction for a finite distance but becomes oscillatory anywhere beyond that finite range. Such a mode gradually leaks out of the waveguide as it travels down it, creating attenuation even though the waveguide is perfect in all respects. By continually radiating this energy out of the heart as they move along the fiber, they are partly restricted to the core attenuated.

2.2.2 Dual-Core PCF Fundamental Modes

In dual-core PCF we suppose that in lattice nodes there are two crystal defects in the form of strong glass rather than air holes. Air hole separates two strong cores. A basic mode comprises of four parts in dual-core framework, with two parts for orthogonal polarization. There are even and strange mode elements for every polarization.

2.2.3 Optical Modes, Polarization Arrow directions & Phases

Optical field propagates through evanescent field interaction in the weak coupling approximation in the core region of the dual-core PCF in the form of supermodes. Only the supermodes in phase, where all cores have the same phase, have the preferable Gaussian-like far-field distribution of intensity. The following optical modes, polarization arrow directions and phases are taken from COMSOL Multiphysics software.

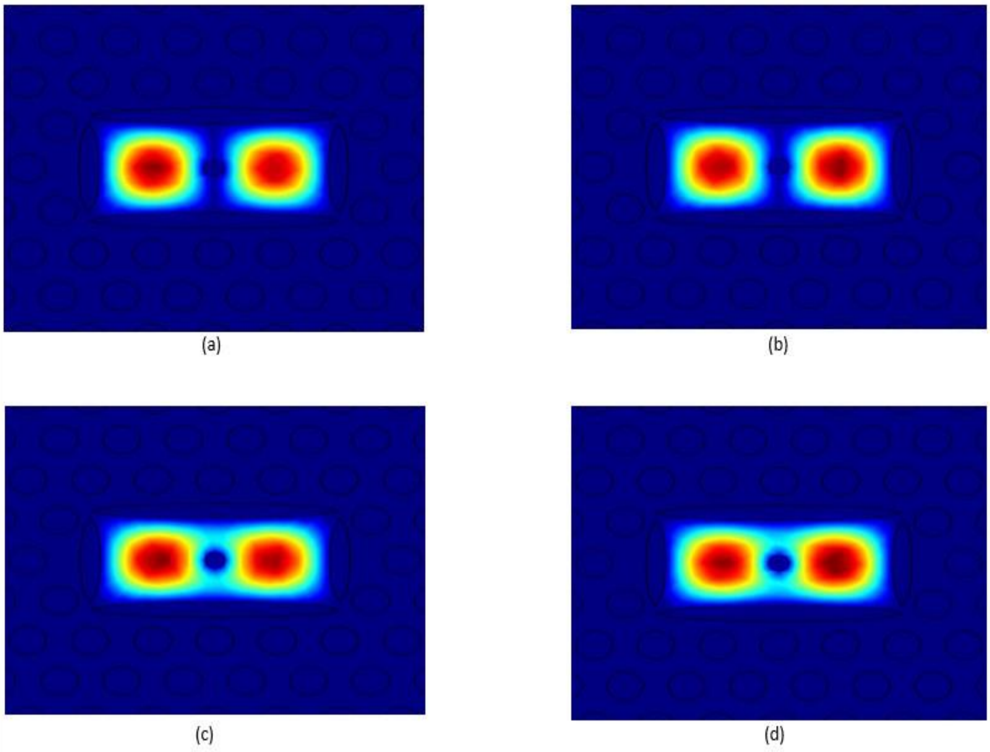

Figure 2.2: Optical modes for different value of refractive index (n)

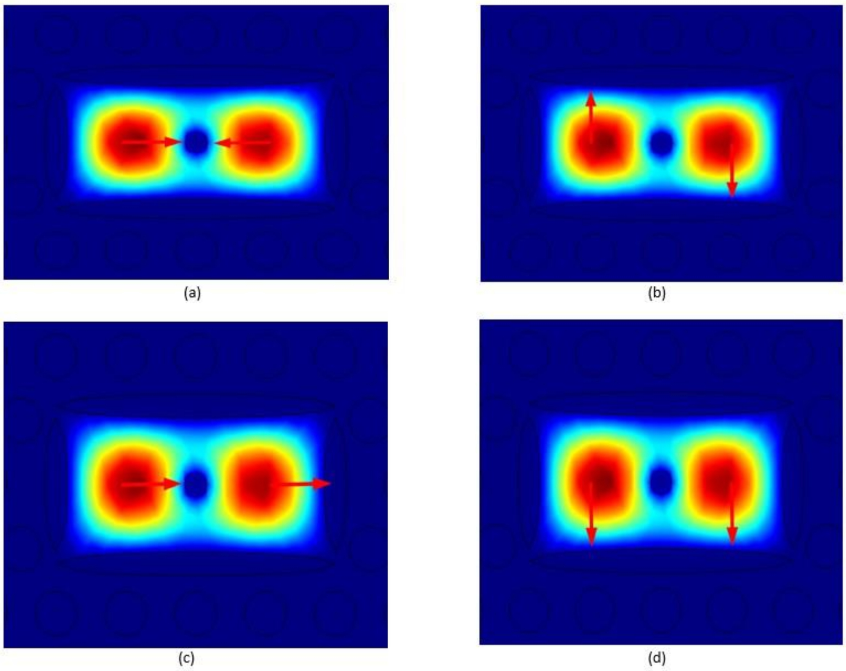

Figure 2.3: Here, (a)Right-Left(RL) polarization direction , (b)Up-Down(UD) polarization direction, (c) Right-Right(RR) polarization direction, (d)Down-Down(DD) polarization direction.

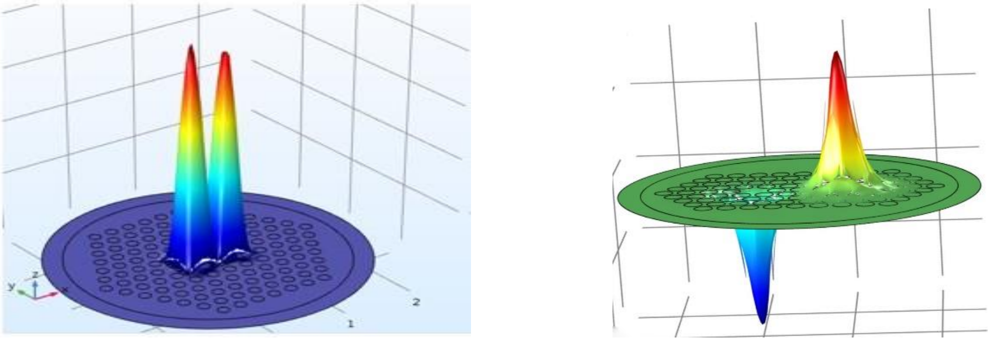

Figure 2.4: X-polarized inphase or even supermode and X-polarized out-of-phase or odd supermode

2.3 Finite Element Method Simulation of Dual-Core PCF

We use the finite element method (FEM) based on edge / nodal hybrid components and completely matched anisotropic layer (PML) border conditions in our study. Simulations are carried out using the COMSOL Multiphysics software available commercially. The spectral dependence of the refractive index for silica is calculated from the simpler form of the Sellmeier equation and is considered in the simulations.

2.4 Dual Core PCF Linear properties

Linear characteristics are those characteristics of fibers that are not dependent on energy or intensity, but are dependent on the fiber materials and compositions.

2.4.1 Effective Refractive Index

To incorporate both the material and waveguide dispersion in the analysis, the wavelength dependent silica glass refractive index is obtained using the Sellmeier expansion expressed as

$$\varepsilon_r(\lambda) = 1 + \sum_{n=1}^{3} \frac{A_n \lambda^2}{\lambda^2 - B_n},$$

Where, A_n and B_n are Sellmeier coefficients. For silica glass, their values are: $A_1 = 0.69675$, $A_2 = 0.408218$, $A_3 = 0.890815$, $B_1 = 0.0047701[\mu m^1]$, $B_2 = 0.0133777[\mu m^2]$ and $B_3 = 98.02107[\mu m^2]$. The wavelength (λ) is in μm.

2.4.2 Confinement Loss

The attenuation or confinement loss is due to the interaction of propagating optical pulse with waveguide structure through which light propagates and it can be calculated as

$$\text{Confinement Loss} = \frac{40\pi}{ln(10)\lambda} Im(n_{eff})\,[\text{dB/m}],$$

Where, I_m (n_{eff}) is the imaginary part of the effective refractive index.

2.4.3 Birefringence

The fiber acquires birefringence (double refraction) when the propagation constants βx and βy are different. It is the property or ability to divide a light beam into two beams, each refracted at a different angle and each polarized at a right angle. These two states propagate with different phase velocities and the difference between their effective refractive indices is called the fiber birefringence. The degree of modal Birefingence is defined as

$$B_m = \frac{\beta_x - \beta_y}{2\pi/\lambda}.$$

Birefringence is highest in the elliptical-air-hole D*ual-Core* PCF which can be explained from the presence of elliptical air hole around the cores. These elliptical air-holes significantly influence the field distribution along two orthogonal directions.

2.4.4 Dispersion

Dispersion is a linear effect, but it plays a crucial role in influencing the character of a fiber's nonlinear interactions. Dispersion is due to the frequency variation of the guided mode's effective index and depends on material and waveguide contributions. The waveguide dispersion is due to the fiber core and cladding geometry guiding the lightwave that propagates through the fiber. This waveguiding causes the effective mode index to be lower than that of the material index n(*ω*). The net dispersion, which is the sum of material and waveguide dispersion, is characterized by the dispersion parameter D(λ). Although the features of fiber dispersion can be determined analytically for normal fibers with cylindrical symmetry, the dispersion properties of photonic crystal fibers usually involve numerical computation. We consider only the chromatic dispersion of the basic directed mode for the outcomes described in this thesis.

The Group Velocity Dispersion (GVD) or β_2 parameter is related to the chromatic dispersion of the fiber (D) according to the following equation

$$D(\lambda) = \frac{d\beta_1(\lambda)}{d\lambda} = -\frac{2\pi c}{\lambda^2}\beta_2(\lambda),$$

Where, $\beta_1(\lambda)$ and $\beta_2(\lambda)$ are the first and second derivative of the propagation constant β of even super-mode.

2.5 Non-linear properties of Dual Core PCF

The nonlinear properties are those properties that are significantly influenced by input pump intensity into optical waveguides. They are discussed in the subsequent subsections.

2.5.1 Effective Area

Effective mode area (A_{eff}) is defined as

$$A_{eff} = \frac{\left[\iint |F(x,y,\omega_0)|^2 dxdy\right]^2}{\iint |F(x,y,\omega_0)|^4 dxdy},$$

Where, $F(x,y,\omega_0)$ is the transverse modal distribution. Large A_{eff} greatly increase the energy conversion efficiency and concurrently, less anomalous dispersion enhances the solitonic SC broadening.

The DC-PCF acts as SC-PCF at up to certain wavelengths. This wavelength is reduced by using elliptical air-holes around the heart, but it also decreases the efficient region. The explanation is likely that a bigger proportion of air-filling will result in a greater containment of the optical field to the fiber core at short wavelengths. Then the evanescent field could hardly pair and supermodes would not be able to form.

2.5.2 Nonlinearity Coefficient

Nonlinearity coefficient which is a measurement of the nonlinearity of an optical waveguide is related to the effective mode area according to

$$\gamma = \frac{\omega_0 n_2(\omega_0)}{c A_{eff}(\omega_0)},$$

Where the nonlinear refractive index (n_2) of the silica is 3.0×10^{-20} [m^2/W] and *c* is the velocity of light.

2.6 Generalization

The reason for using Dual-core elliptical PCF is because it has a large area of mode that supports high intensity and high power stability. In addition, a greater coefficient of nonlinearity. Thus, between these two parameters there is a tradeoff. In this respect, elliptical-air-hole DC-PCF is best suited and has low loss of containment.

Chapter 3

Results

3.1 Effective Index

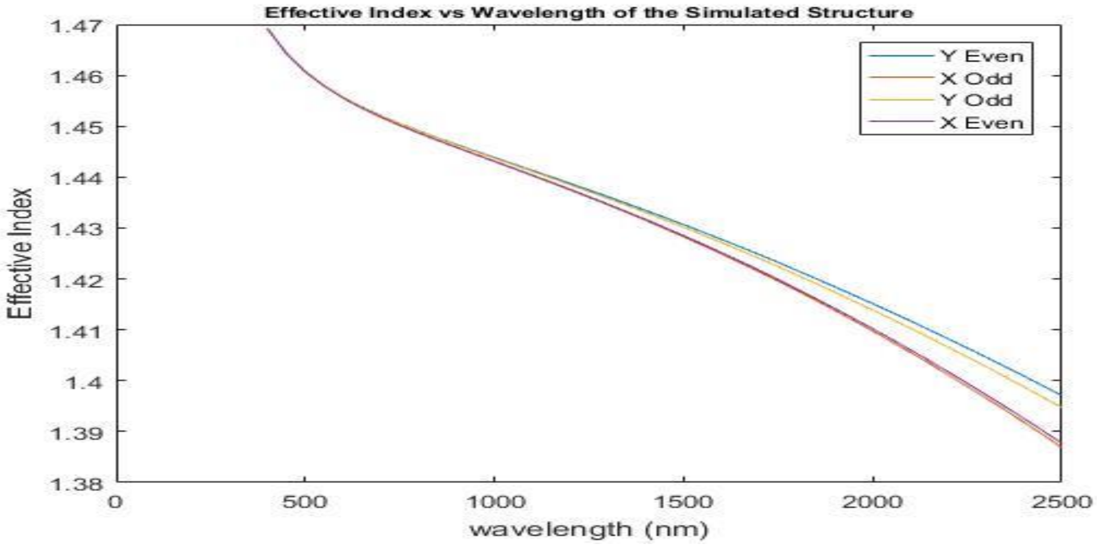

Figure 3.1: Effective index vs Wavelength

3.2 Propagation Constant (Beta)

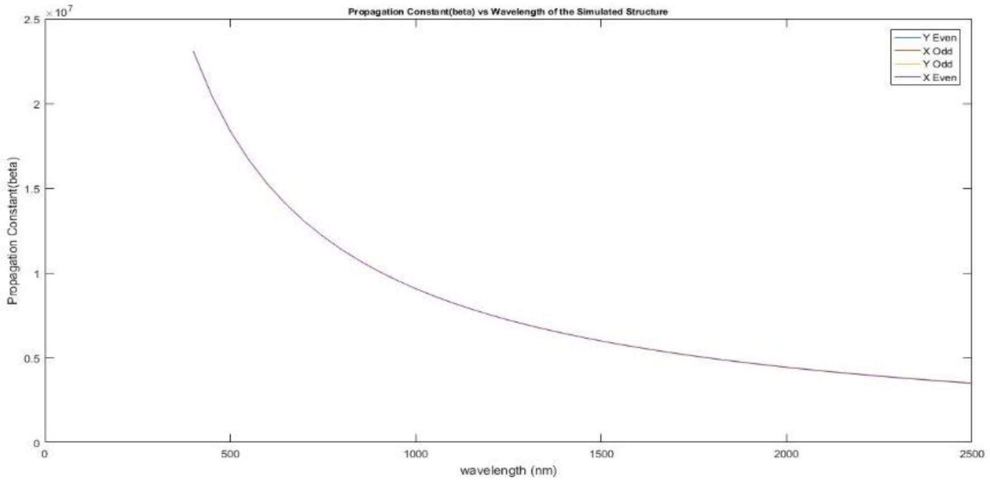

Figure 3.2: Propagation Constant (Beta) vs Wavelength

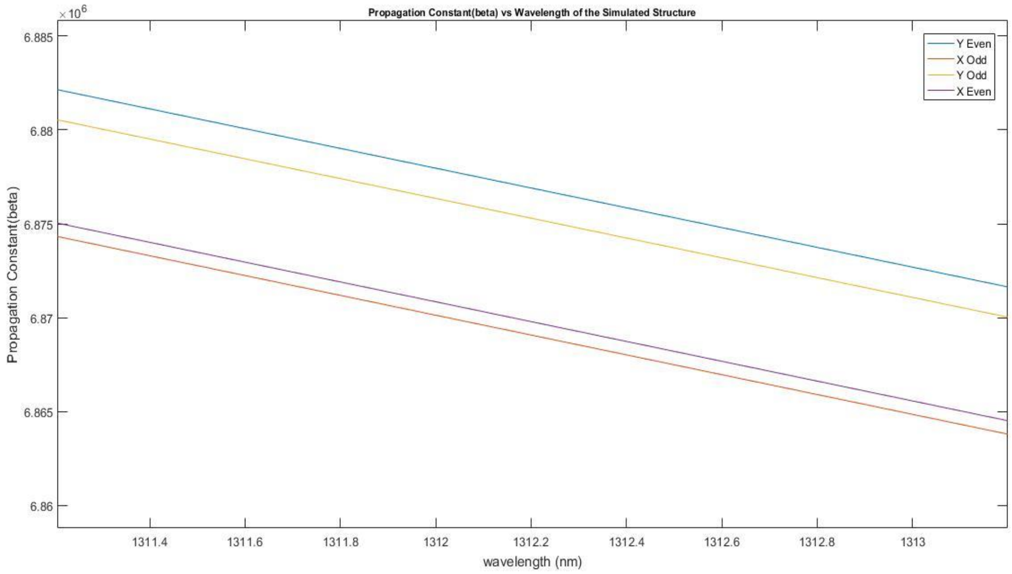

Figure 3.3: Propagation Constant (Beta) vs Wavelength (Zoomed)

3.3 Attenuation Constant (Alpha)

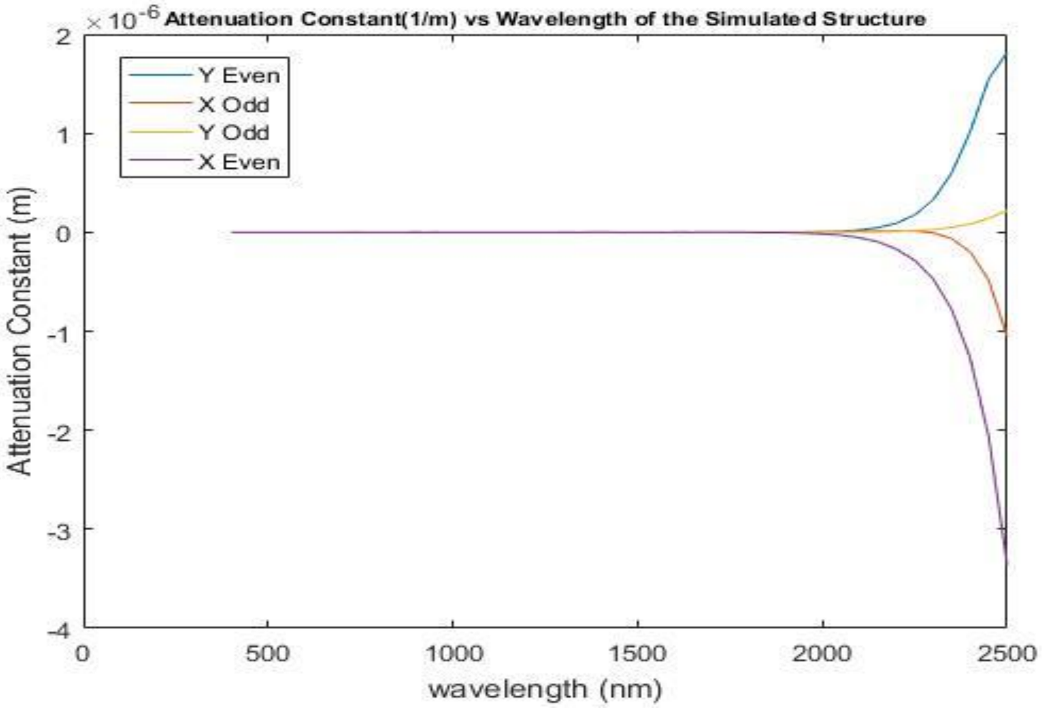

Figure 3.4: Attenuation Constant (m^{-1}) vs Wavelength

3.4 Effective Area

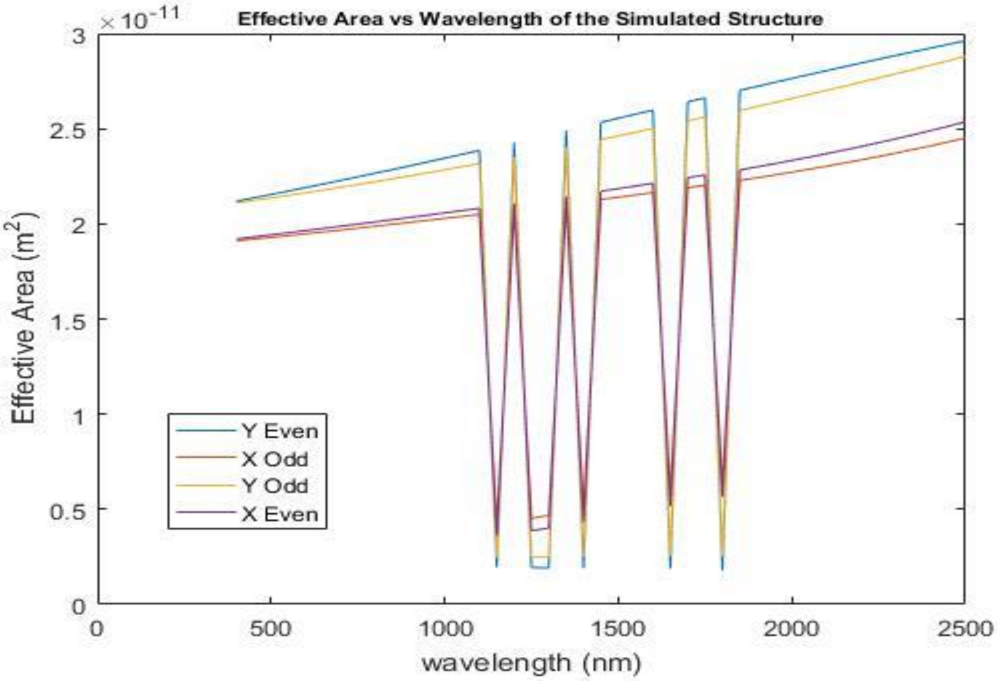

Figure 3.5: Effective Area vs Wavelength

Chapter 4

Conclusions

4.1 Conclusion of the works

In this work, we design a Dual Core-PCF structure of elliptical air-hole. Dual Core-PCF with elliptical-air-hole is most suitable and has low confinement loss. The influence of the parameters of the dual-core PCF was numerically simulated, and an optimized structure was proposed. A challenging technique for the Dual Core-PCF based sensor is how to connect the Dual Core-PCF to the light source or the optical spectrum analyzer, since the fiber core size and the distance between the two fiber cores of the Dual Core-PCF is too small compared with the fiber core of the single mode fiber. Considering the index change effect the Dual Core-PCF can also be designed for pressure sensing, strain sensing, temperature sensing.

4.2 Scopes of Future Works

Photonic-crystal fibers (PCFs) are among the most specialized optical light guides. Ranging from fibers with low levels of nonlinearities supporting high-power pulses to highly nonlinear counterparts for super continuum generation, PCF is an attractive and versatile technology. It is based on a micro structured arrangement of low- and high-refractive-index materials. The high-index background material is typically undoped silica while the low-index region is usually provided by air holes along the fiber length. They can be made using a stack-and-draw fabrication process, which is based on stacking glass capillaries and rods into a preform, allowing precise control of the core and cladding-index properties. Rare-earth and stress-element components are introduced simultaneously. Once the desired preform has been constructed, it is drawn into a fiber.

Chapter 4. Conclusions

Lasers play a significant role in many industrial and material-processing applications. In recent years, fiber lasers have made advances, sometimes replacing more traditional lasers because of advantages in efficiency, beam quality, scalability, and operating cost. Achieving reliable high-power performance is a remaining challenge, since various components in fiber-laser systems struggle with power levels exceeding a few hundred watts. PCF solves this problem with design characteristics that are not available in conventional fibers, including larger single-mode areas and the use of secondary cladding based on air holes, enabling higher damage thresholds than for the polymers used in conventional fibers. In addition, PCF offers similar benefits in fiber-based coupling and power-combining components within the high-power fiber-laser system.

PCF can also be used in broadband super continuum devices in metrology, optical-coherence tomography, and spectroscopy. Passive highly nonlinear PCFs can be pumped with short pulses to produce a super continuum of power distributed over a wide bandwidth, exhibiting the high brightness characteristics of fiber lasers and the broad spectral coverage of white-light sources. This is a combination not offered by other technologies. Highly nonlinear PCFs can be tailored to support various pump wavelengths with flexible design of small core, high numerical aperture and dispersion to achieve superior super continuum generation.

Bibliography:

[1] P. Kaiser and H. W. Astle, "Low-loss single-material fibers made from pure fused silica", **Bell Syst. Tech. J. 53, 1021 (1974)**

[2] J. C. Knight *et al.*, "All-silica single-mode optical fiber with photonic crystal cladding", **Opt. Lett. 21 (19), 1547 (1996)**

[3] T. A. Birks *et al.*, "Endlessly single-mode photonic crystal fiber", **Opt. Lett. 22 (13), 961 (1997)**

[4] J. C. Knight *et al.*, "Large mode area photonic crystal fiber", **Electron. Lett. 34, 1347 (1998)**

[5] D. Mogilevtsev *et al.*, "Group-velocity dispersion in photonic crystal fibers", **Opt. Lett. 23 (21), 1662 (1998)**

[6] R. F. Cregan *et al.*, "Single-mode photonic band gap guidance of light in air", **Science 285, 1537 (1999)**

[7] J. C. Knight *et al.*, "Anomalous dispersion in photonic crystal fiber", **IEEE Photon. Technol. Lett. 12, 807 (2000)**

[8] A. Ortigosa-Blanch *et al.*, "Highly birefringent photonic crystal fibers", **Opt. Lett. 25 (18), 1325 (2000)**

[9] J. K. Ranka *et al.*, "Visible continuum generation in air–silica microstructure optical fibers with anomalous dispersion at 800 nm", **Opt. Lett. 25 (1), 25 (2000)**

[10] T. A. Birks *et al.*, "Supercontinuum generation in tapered fibers", **Opt. Lett. 25 (19), 1415 (2000)**

[11] F. Benabid *et al.*, "Stimulated Raman scattering in hydrogen-filled hollow-core photonic crystal fiber", **Science 298, 399 (2002)**

[12] H. Han *et al.*, "Terahertz pulse propagation in a plastic photonic crystal fiber", **Appl. Phys. Lett. 80 (15), 2634 (2002)**

[13] V. V. Ravi Kanth Kumar *et al.*, "Extruded soft glass photonic crystal fiber for ultrabroad supercontinuum generation", **Opt. Express 10 (25), 1520 (2002)**

[14] W. H. Reeves *et al.*, "Transformation and control of ultrashort pulses in dispersion-engineered photonic crystal fibers", **Nature 424, 511 (2003)**

[15] J. C. Knight, "Photonic crystal fibers", **Nature 424, 847 (2003)**

[16] P. St. J. Russell, "Photonic crystal fibers" (review paper), **Science 299, 358 (2003)**

[17] D. G. Ouzounov *et al.*, "Generation of megawatt optical solitons in hollow-core photonic band-gap fibers", **Science 301, 1702 (2003)**

[18] D. A. Nolan *et al.*, "Single-polarization fiber with a high extinction ratio", **Opt. Lett. 29 (16), 1855 (2004)**

[19] K. Hougaard and F. D. Nielsen, "Amplifiers and lasers in PCF configurations", **J. Opt. Fiber Commun. Rep. 1, 63–83 (2004)**

[20] W. J. Wadsworth *et al.*, "Very high numerical aperture fibers", **IEEE Photon. Technol. Lett. 16, 843 (2004)**

[21] P. J. Roberts *et al.*, "Ultimate low loss of hollow-core photonic crystal fibers", **Opt. Express 13 (1), 236 (2005)**

[22] K. Saitoh and M. Koshiba, "Empirical relations for simple design of photonic crystal fibers", **Opt. Express 13 (1), 267 (2005)**

[23] J. G. Rarity *et al.*, "Photonic crystal fiber source of correlated photon pairs", **Opt. Express 13 (2), 534 (2005)**