Large Mode Area

Hexagonal Photonic Crystal Fiber

Submitted by

Dilshad-Uz-Zaman

Student ID: 2010-3-55-001

Professor

Mir Md. Tanvir Nur

Student ID: 2010-3-55-015

Supervised by

Dr. Feroza Begum

Assistant

Department of Electronics and Communication Engineering

East West University

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Dilshad-Uz-Zaman

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Mir Md. Tanvir Nur

Electronics and Communication Engineering Department

East West University

Approval

The thesis title “Large Mode Area Hexagonal Photonic Crystal Fiber” submitted by Dilshad-uz-zaman [ID: 2010-3-55-001], Mir Md. Tanvir Nur [ID: 2010-3-55-015] in the semester of Fall-2014 is approved satisfactory in partial fulfillment of the requirements for the degree of Bachelor of Science in Electronics and Telecommunication Engineering.

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Dr. Feroza Begum

Assistant Professor

Electronics and Communication Engineering Department

East West University

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Abstract

In this project we deal with the Photonic crystal fiber. Here we design a model of hexagonal photonic crystal fiber which contains five air hole rings with perfectly matched absorbing layer. We use COMSOLE Multiphysics to design this model. We use finite element method of COMSOL Multiphysics to design proposed hexagonal photonic crystal fiber. Finite element methods for approximating partial differential equations that arise in science and engineering analysis find widespread application. We have changed the value of pitch which means the distance between two air holes. Our target is to design a model which have large mode area, so that we gradually change the pitch up to 18 µm and fixing the diameter on 0.5 µm. From the numerical result it is found that for the higher value of pitch we obtained large mode area.

Contents

Chapter 1

Introduction

1.1 Optical fiber:

A flexible optically transparent fiber usually made of very thin glass or plastic, through which light can be transmitted by successive internal reflections [1]. Technology based on the use of hair-thin, transparent fibers to transmit light or infrared signals. The fibers are flexible and consist of a core of optically transparent glass or plastic, surrounded by a glass or plastic cladding that reflects the light signals back into the core. Light signals can be modulated to carry almost any other sort of signal, including sounds, electrical signals, and computer data, and a single fiber can carry hundreds of such signals simultaneously, literally at the speed of light. Optical fibers are two basic types:

1. Conventional optical fiber:

   (i) Single-mode fiber

   (ii) Multi-mode fiber

   - step-index
   - graded-index fiber

2. Photonic crystal fiber:

   (i) Index guiding photonic crystal fiber

   (ii)Photonic crystal band gap fiber

1.1.1 Single-mode fiber:

Single-mode fiber is a common type of optical fiber that is used to transmit over longer distances [1]. A single-mode fiber is a single glass fiber strand used to transmit a single mode or ray of light. Single-mode fiber features only one transmission mode. Compared with multi-mode fiber, it can carry higher bandwidths.

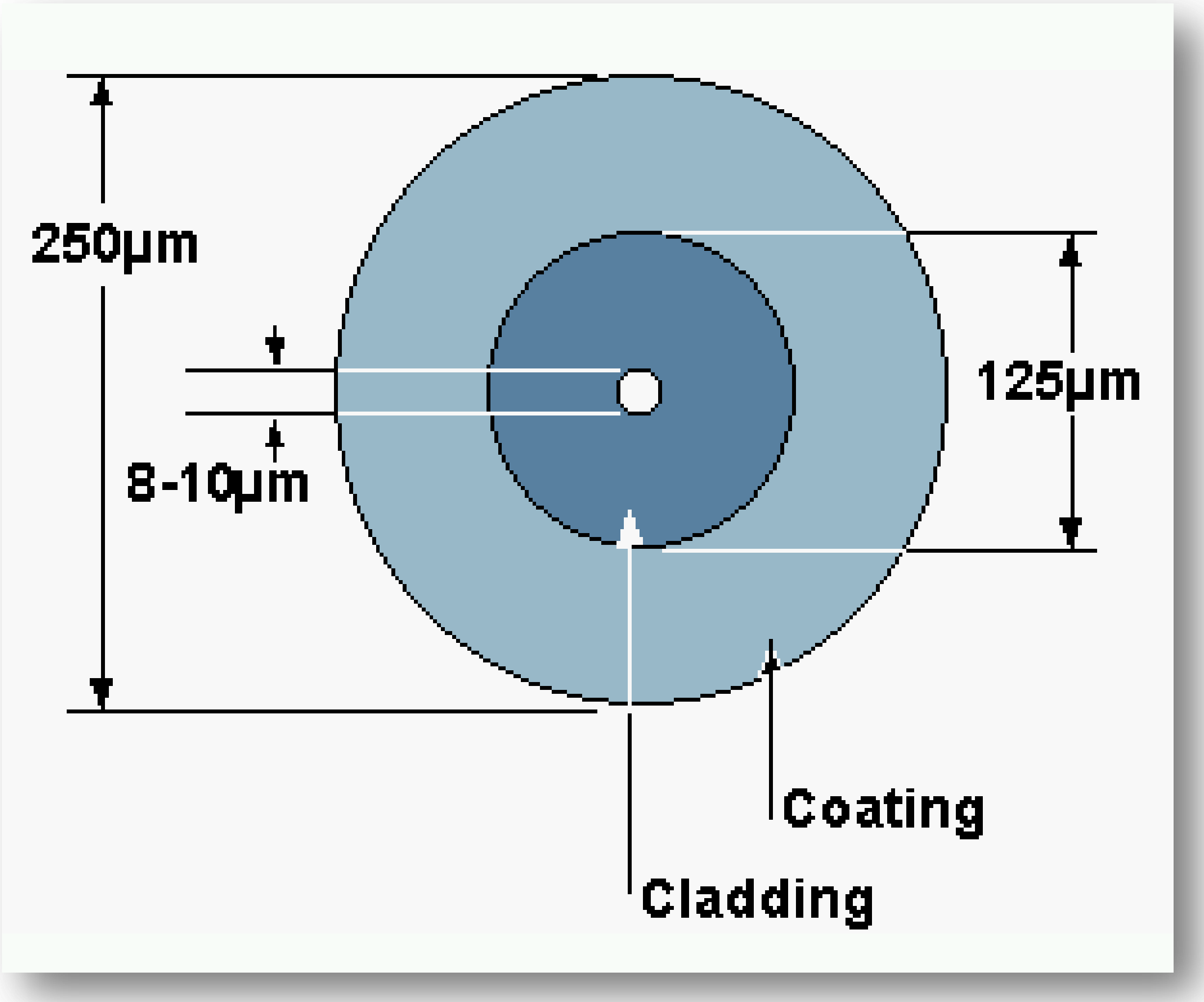


Fig. 1.1: Single mode fiber.

1.1.2 Multimode fiber:

Multi-mode fiber is a type of optical fiber designed to carry multiple light rays or modes simultaneously, each at a marginally different reflection angle inside the optical fiber core [1]. Multi-mode fiber is mainly used to transmit across comparatively shorter distances, as the modes are more likely to disperse over longer extents.

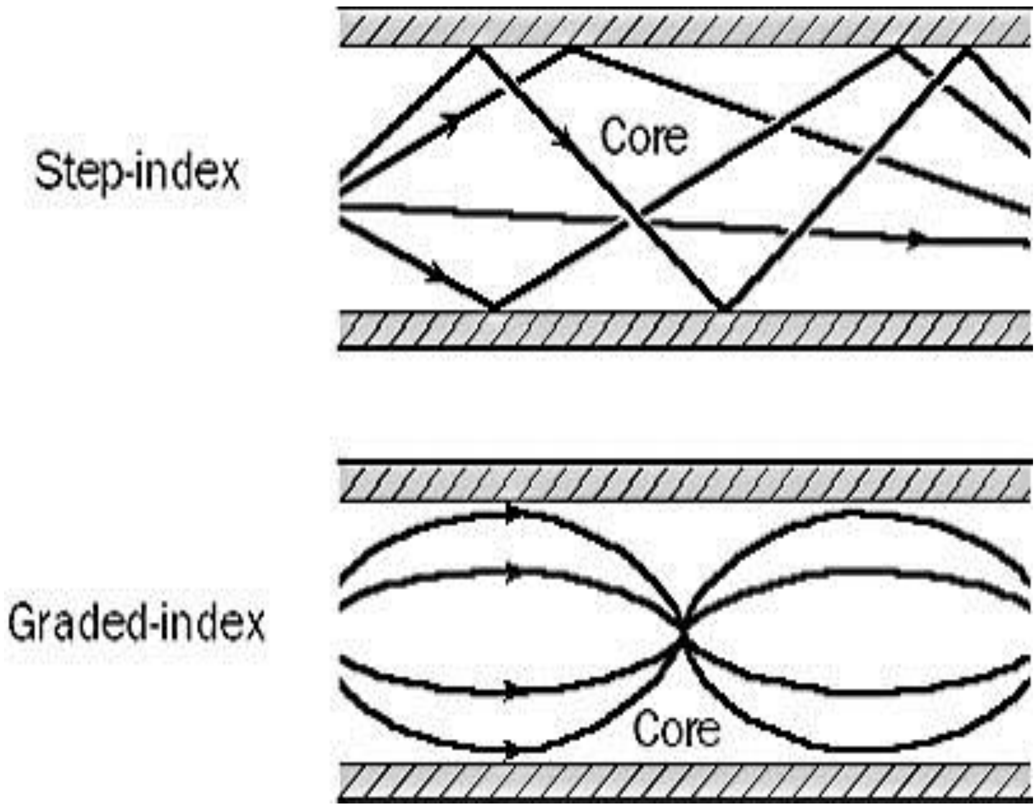


Fig. 1.2: Step index multimode fiber and graded index multimode fiber.

1.1.3 Structure:

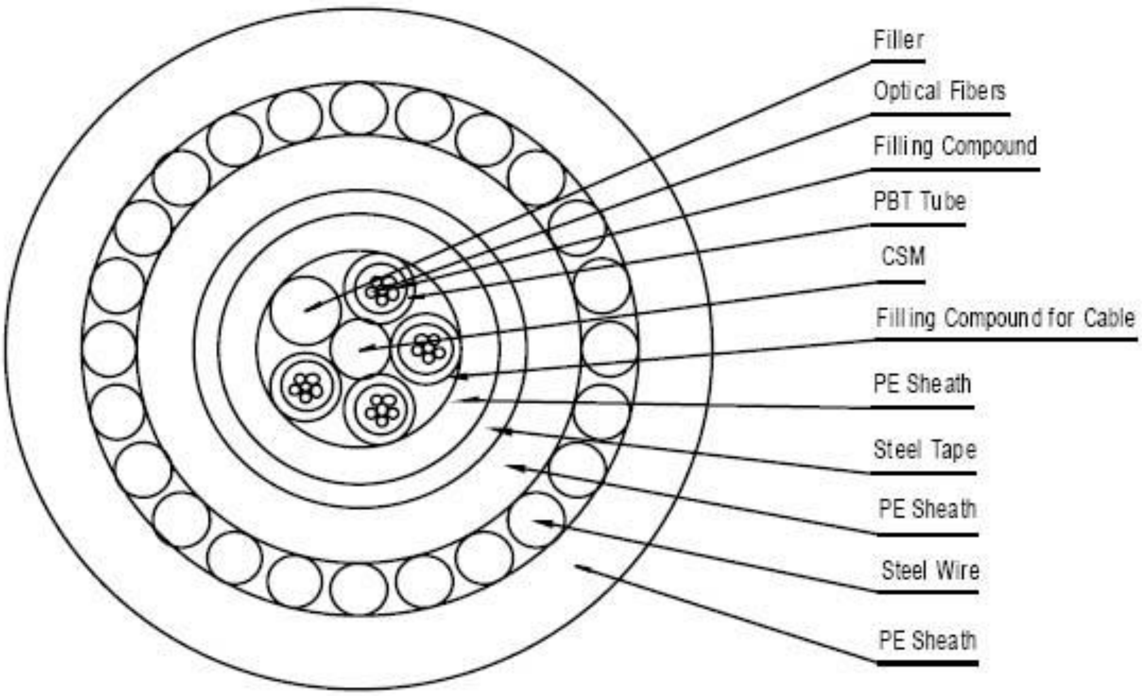


Fig. 1.3: Structure of optical fiber.

Core - Thin glass center of the fiber where the light travels.

Cladding - Outer optical material surrounding the core that reflects the light back into the core.

Buffer coating - Plastic coating that protects the fiber from damage and moisture.

Primary buffer: It protects the fiber and is made up of plastic.

Secondary buffer: It is used for color coding identity.

Kevler: It protects the whole fiber as it is five times stronger than steel.

Jacket: It is used to protect the fiber from weather.

1.2 Ray theory of transmission:

In optical fiber light propagates within the fiber by total internal reflection, we have to consider the refractive index of the fiber. A ray of light travels more slowly in an optically dense medium than in one that is less dense, and the refractive index gives a measure of this effect. Total internal reflection is a phenomenon that occurs when light travels from a more optically dense medium to a less optically dense one, such as glass to air or water to air. When light travels from an optically dense medium to a less optically dense medium, the light refracts away from the normal. If the angle of incidence is gradually increased, one will notice that at a certain point, the refracted ray deviates so far away from the normal that it reflects rather than refracts. This results whenever the refracted angle predicted by Snell's Law becomes greater than 90 degrees. The critical angle, c, is defined as the angle of incidence (inside the higher-index material) for which Snell's Law predicts a 90-degree angle of refraction, this would mean the light follows the surface rather than entering the low-index material.

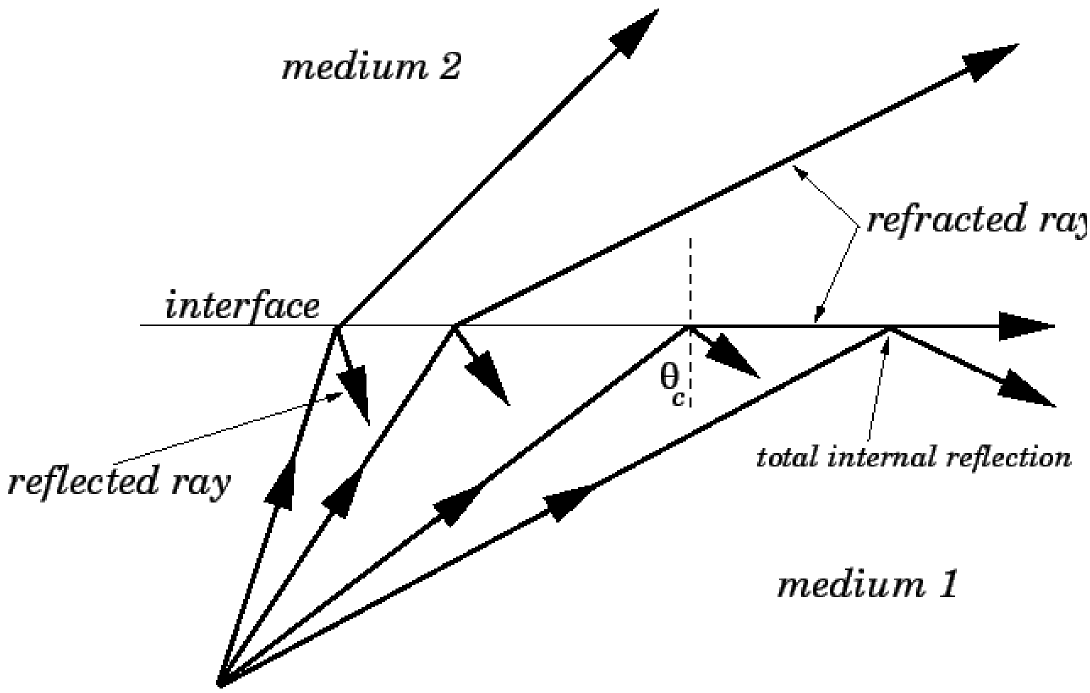


Fig. 1.4: Total internal reflection.

One can calculate the critical angle using Snell's Law:

$$n_1 \sin \varnothing_1 = n_2 \sin \varnothing_2 \qquad (1)$$

or,

$$\frac{\sin \varnothing 1}{\sin \varnothing 2} = \frac{n2}{n1} \qquad (2)$$

It may also be observed that a small amount of light is reflected back into the originating dielectric medium. Here the light should be stay in core so the condition is that the incident light angle Θ is greater than critical angle$\varnothing_c$ and the core refracted index is greater than cladding refracted index.

$$\text{Critical angle, } \varnothing_c = \sin^{-1} \frac{n2}{n1} \qquad (3)$$

1.2.1 Acceptance angle:

The angle over which light rays entering the fiber will be guided along its core. It can be seen that a ray that meets the first core-cladding interface at the critical angle. This ray meets the fiber core at an incident angle of α, this incident angle α is defined as the acceptance angle of the fiber.

Any light ray's incident at the fiber core with an angle greater than α will not be refracted sufficiently to undergo Total Internal Reflection at the core-cladding interface, and therefore, although they will enter the core, they will not be accepted into the fiber for onward transmission. Acceptance angle is measured in air (refractive index ≈ 1) outside the fiber. The acceptance angle normally is measured as Numerical Aperture (NA).

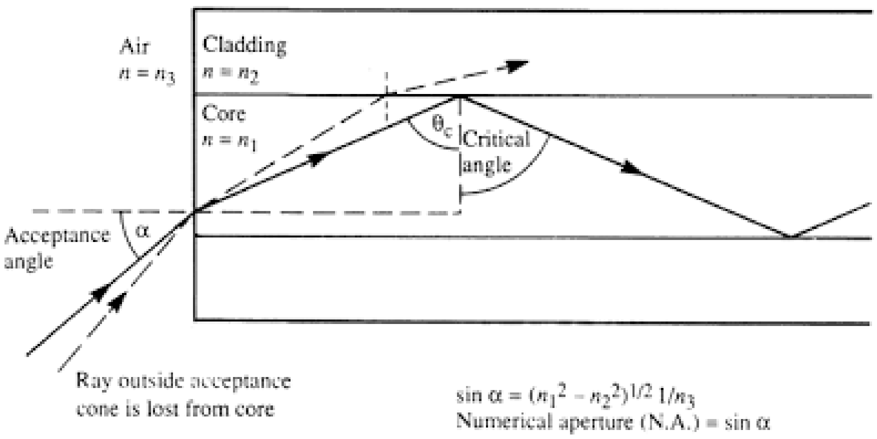


Fig. 1.5: Acceptance angle.

1.2.2 Numerical aperture:

In optics, the numerical aperture of an optical system is a dimensionless number that characterizes the range of angles over which the system can accept or emit light. By incorporating index of refraction in its definition, NA has the property that it is constant for a beam as it goes from one material to another provided there is no optical power at the interface. The exact definition of the term varies slightly between different areas of optics. Numerical aperture is commonly used in microscopy to describe the acceptance cone of an objective, and in fiber optics.

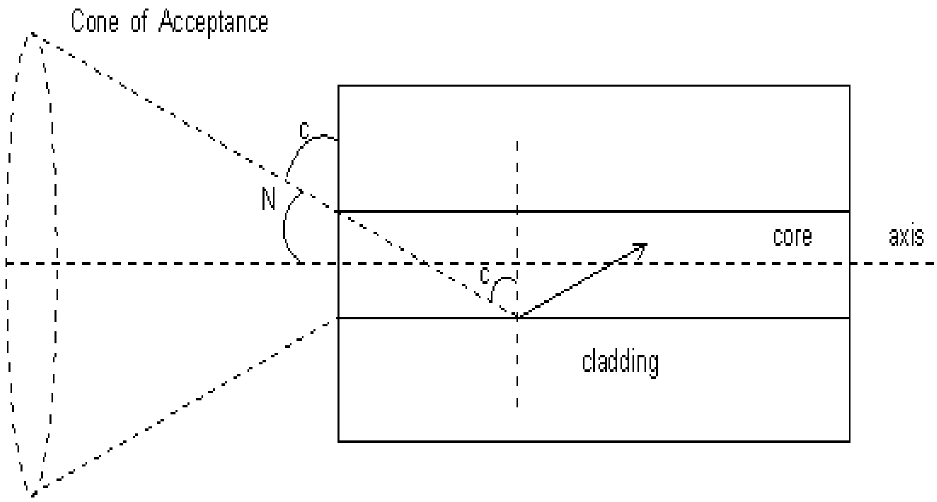


Fig. 1.6: Numerical aperture.

1.3 Optical fiber communication system:

For optical fiber communication the information source provides an electrical signal to the transmitter. The electrical stage of the transmitter drives an optical source to produce modulated light wave carrier. Semiconductor LASERs or LEDs are usually used as optical source here. The information carrying light wave then passes through the transmission medium i.e. optical fiber cables in this system. Now it reaches to the receiver stage where the optical detector demodulates the optical carrier and gives an electrical output signal to the electrical stage. The common types of optical detectors used are photodiodes, phototransistors, photoconductors etc. Finally the electrical stage gets the real information back and gives it to the concerned destination [2].

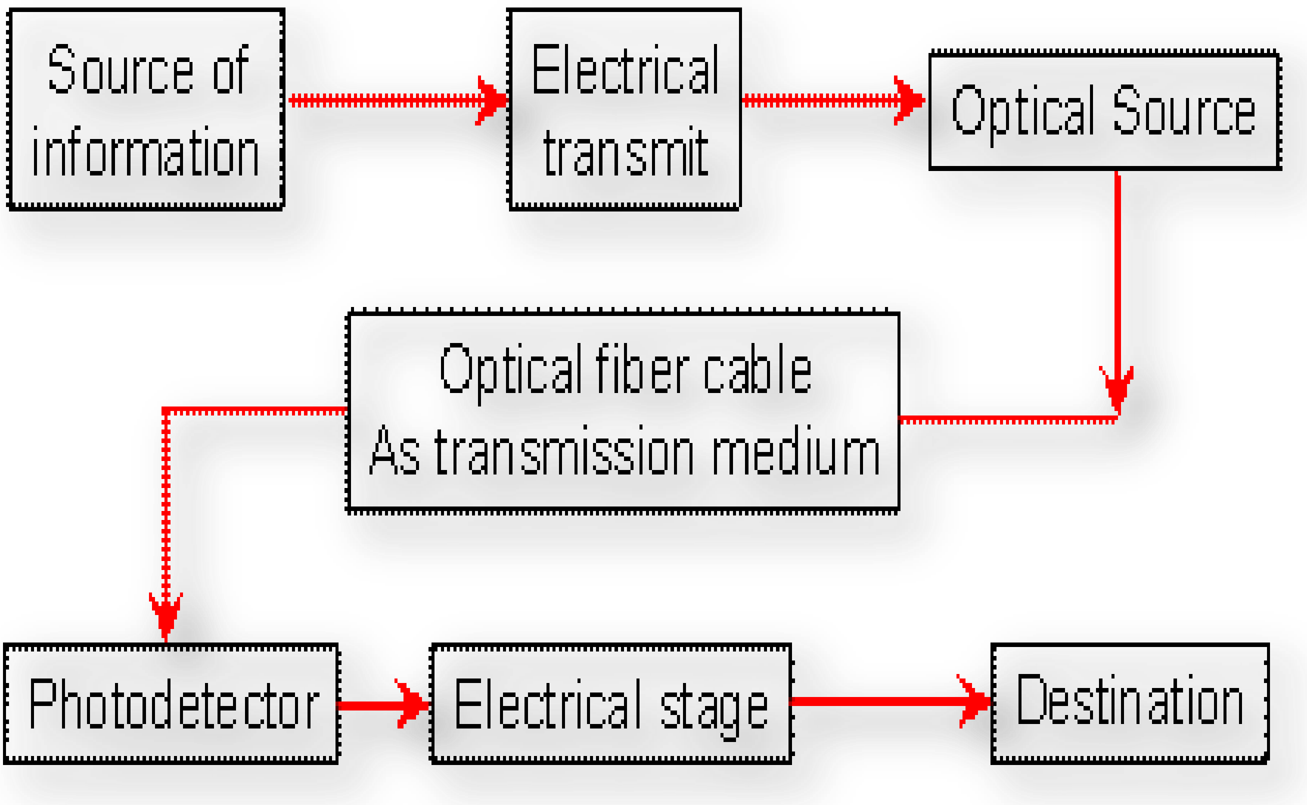


Fig. 1.7: Optical communication system.

1.4 Photonic crystal fiber:

Photonic crystal fiber is a kind of optical fiber that uses photonic crystals to form the cladding around the core of the cable. Photonic crystal is a low-loss periodic dielectric medium constructed using a periodic array of microscopic air holes that run along the entire fiber length. Photonic crystals with photonic band gaps are constructed to prevent light propagation in certain directions with a certain range of wavelengths. Contrary to normal fiber optics, Photonic crystal fibers use total internal reflection or light confinement in hollow core methods to propagate light.

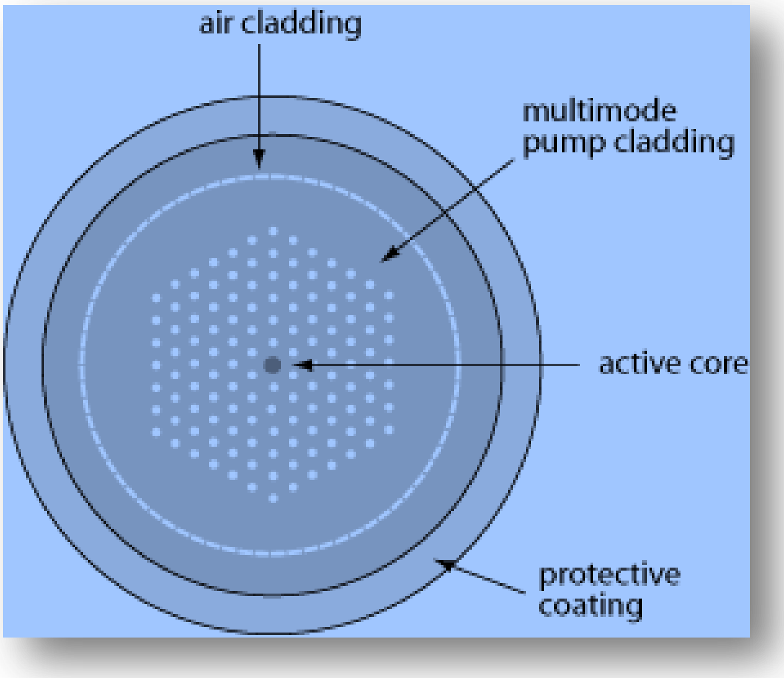


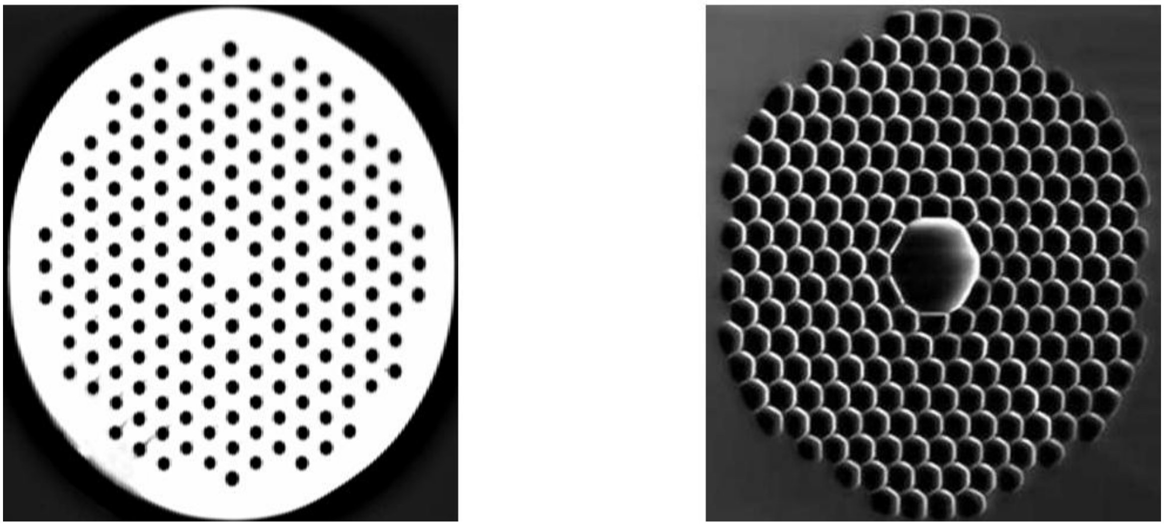
Fig. 1.8: Photonic crystal fiber.

1.4.1 Index guiding photonic crystal fiber:

Have a solid core like conventional fibers. Light is confined in this core by exploiting the modified total internal reflection mechanism.

1.4.2 Photonic crystal band gap fiber:

Have periodic microstructure elements and a core of low-index material. The core region has a lower refractive index than the surrounding photonic crystal cladding [3]. The light is guided by a mechanism that differs from total internal reflection in that it exploits the presence of the photonic band gap.



(a) (b)

Fig. 1.9: Structure of (a) index guiding photonic crystal fiber and (b) photonic crystal band gap fiber.

1.5 Construction strategies:

Photonic Crystals are classified mainly into three categories according to its fabrication method depends on the number of dimensions that the photonic band gap must exist in. That is, One Dimensional (1D)photonic crystal, Two Dimensional (2D)photonic crystal and Three Dimensional (3D) photonic crystal [4] .

1.5.1 One-dimensional photonic crystals:

In a one-dimensional photonic crystal, layers of different dielectric constant may be deposited or adhered together to form a band gap in a single direction. It can be either isotropic or anisotropic, with the latter having potential use as an optical switch. This type of photonic crystal can act as a mirror (a Bragg mirror). These concepts are commonly used in dielectric mirrors optical fiber and optical switch.

1.5.2 Two-dimensional photonic crystals:

In 1996 Thomas Krauss first established the two-dimension photonic crystal at optical wavelengths. In two dimensions, holes may be drilled in a substrate that is transparent to the wavelength of radiation that the band gap is designed to block. Triangular and square lattices of holes have been successfully employed.

1.5.3Three dimensional photonic crystal:

There are many possible geometries for a three dimensional photonic crystal. In between we emphasize on those geometries that promotes the existence of photonic band gaps. A diamond lattice of air holes, a drilled dielectric known as Yablonovite, the wood pile structure etc. are several examples of three dimensional crystals with a complete band gaps.

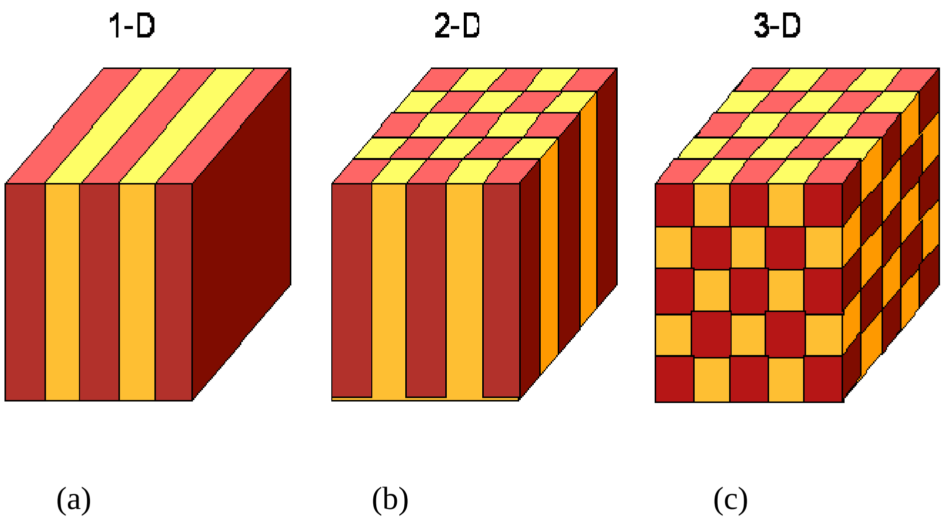


Fig. 1.10: (a) One dimensional, (b) two dimensional, (c) three dimensional photonic crystal

1.6 Maxwell equation:

To study the propagation of light in a photonic crystal we use the Maxwell equation. After specializing case of a mix dielectric medium we use the Maxwell equation as a linear Hermitianeigen value problem. This problem brings the electromagnetic problem hat close with the Schrodinger equation which allows us to well-established the result from quantum-mechanics where the electromagnetic case differs from the quantum-mechanical case. Photonic crystals do not generally have a fundamental scale, in either the spatial coordinate or the potential strength.

So including the propagation of light in a photonic crystal, the Maxwell equation in SI unit is given below:

Faraday's Law: $\nabla\times E = -\partial B/\partial t$ (4)

Ampere's Law: $\nabla\times H = J+\partial D/\partial t$ (5)

Gauss's Law: $\nabla . D = \rho$ (6)

$\nabla . B=0$ (7)

Where E is the electric filed, H is the magnetic field, B is the magnetic flux density, D is the electric displacement, J is the electric current density and ρ is the electric charge density.

So the Maxwell curl equation,

$$\nabla\times E+\partial B/\partial t=o \quad (8)$$

$$\nabla\times H-\partial D/\partial t=J \quad (9)$$

1.7 Properties of photonic crystal fiber:

Focus on the Properties of photonic crystal:

- Effective refractive index
- Chromatic Dispersion, D(λ)
- Confinement loss, L_c
- Effective area, A_{eff}

1.7.1 Effective refractive index:

In homogeneous transparent media, the refractive index *n* can be used to quantify the increase in the wave number (phase change per unit length) caused by the medium: the wave number is *n* times higher than it would be in vacuum. The *effective refractive index* n_{eff} has the analogous meaning for light propagation in a waveguide; the *β* value (phase constant) of the waveguide (for some wavelength) is the effective index times the vacuum wave number:

$$\beta = n_{eff} \frac{2\pi}{\lambda} \tag{10}$$

1.7.2 Chromatic Dispersion, D (λ):

Chromatic dispersion is a term used to describe the spreading of a light pulse as it travels down a fiber when light pulses launched close together (high data rates) spread too much and result in errors and a loss of information [3]. Chromatic dispersion can be compensated for with the use of dispersion-compensating fiber (DCF).

Chromatic dispersion equation is

$$D = -\frac{\lambda}{c} \frac{d^2 \operatorname{Re}|n_{eff}|}{d\lambda^2} \tag{11}$$

Where, Re[neff] is the real part of neff, A is the wavelength, and c is the velocity of light in vacuum.

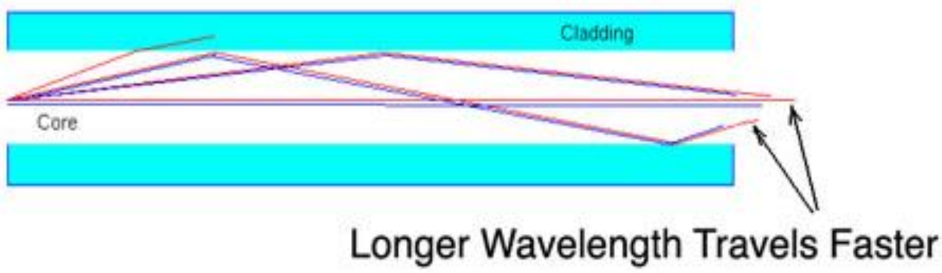


Fig. 1.11: Chromatic Dispersion

1.7.3 Confinement loss, L_c:

Confinement loss is due to the finite air holes in cladding. The confinement loss is calculated from the imaginary part (Im) of the complex effective mode index η_{eff}, using the following equation [3].

Confinement Loss = {40*Π*Im(neff)}/ λ*ln(10 (12)

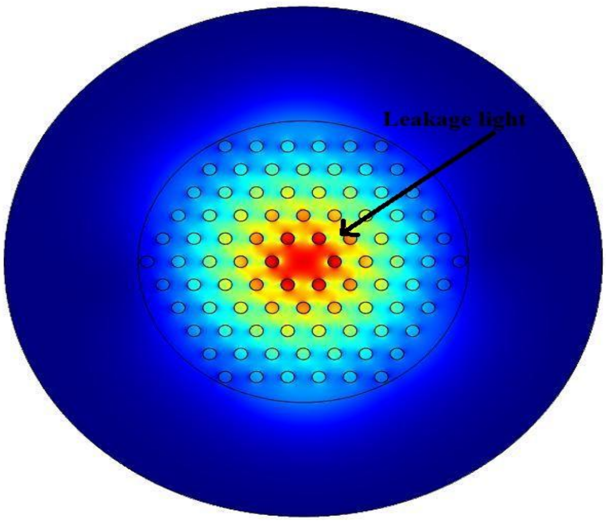


Fig. 1.12: Confinement loss due to leakage light.

1.7.4 Effective area:

The effective area is important parameters. We consider the effective area A_{eff} of photonic crystal fibers (PCFs) with a triangular air-hole lattice in the cladding. It is first of all an important quantity in the context of non-linearites, but it also has connections to leakage loss, macro-bending loss, and numerical aperture. For non-linear measurement the low effective area gives a high density of power and also non-linear effects are dependent the intensity of the electromagnetic field. The intensity I, over the core area A_{core} can be calculated from the power, P_{meas} define as:

$$I = \frac{P_{means}}{A_{core}}$$

The purpose of calculating non-linear effects the effective area has been defines as [3]:

$$\mathbf{A_{eff}} = \frac{2\pi(\int_0^\infty |E_a(r)^2| r dr)^2}{\int_0^\infty |E_a(r)|^4 r dr} = \frac{2\pi(\int_0^\infty I(r) r dr)^2}{\int_0^\infty I^2(r) r dr} \qquad (13)$$

Where, E is the electric field amplitude and I is the optical intensity, A_{eff} is effective mode area.

1.8 Advantages:

Less expensive - Several miles of optical cable can be made cheaper than equivalent lengths of copper wire.

Higher carrying capacity - Because optical fibers are thinner than copper wires, more fibers can be bundled into a given-diameter cable than copper wires. This allows more phone lines to go over the same cable or more channels to come through the cable into your cable TV box.

Less signal degradation - The loss of signal in optical fiber is less than in copper wire.

Light signals - Unlike electrical signals in copper wires, light signals from one fiber do not interfere with those of other fibers in the same cable. This means clearer phone conversations or TV reception.

Digital signals - Optical fibers are ideally suited for carrying digital information, which is especially useful in computer networks.

Non-flammable - Because no electricity is passed through optical fibers, there is no fire hazard.

Lightweight and thin - An optical cable weighs less than a comparable copper wire cable. Optical fibers can be drawn to smaller diameters than copper wire. Fiber-optic cables take up less space in the ground.

1.8 Applications:

- Telecommunication
- Computer Networking
- Fiber optics sensors
- Biomedicine
- Imaging
- Spectroscopy
- Metrology
- Industrial machining
- Military technology.

Chapter 2

Large Mode Area PCF

2.1 Introduction

COMSOL Multiphysics is a comprehensive simulation software environment for a wide array of applications, but structured and user-friendly for all to use. We use COMSOL Multiphysics 4.3b for design and simulating PCF. For calculating dispersion we use MATLAB 13, and plotting the graph we use Origin 6.0. We design a hexagonal photonic crystal fiber where we have changed different parameter like - pitch (Λ), diameter of air hole (d) which is effect on different properties of PCF such as effective mode index, effective area, confinement loss and chromatic dispersion. The benefit of large mode area PCF is endlessly single mode operation - no higher order mode cut-off, handles very high average power as well as high peak power, low nonlinearities, low fiber loss, mode field diameter is wavelength independent, available with core sizes from 5 to 80 microns [3]. Applications are high power delivery, short pulse delivery, mode filtering, laser pig tailing, multi-wavelength guidance, broadband interferometry [4].

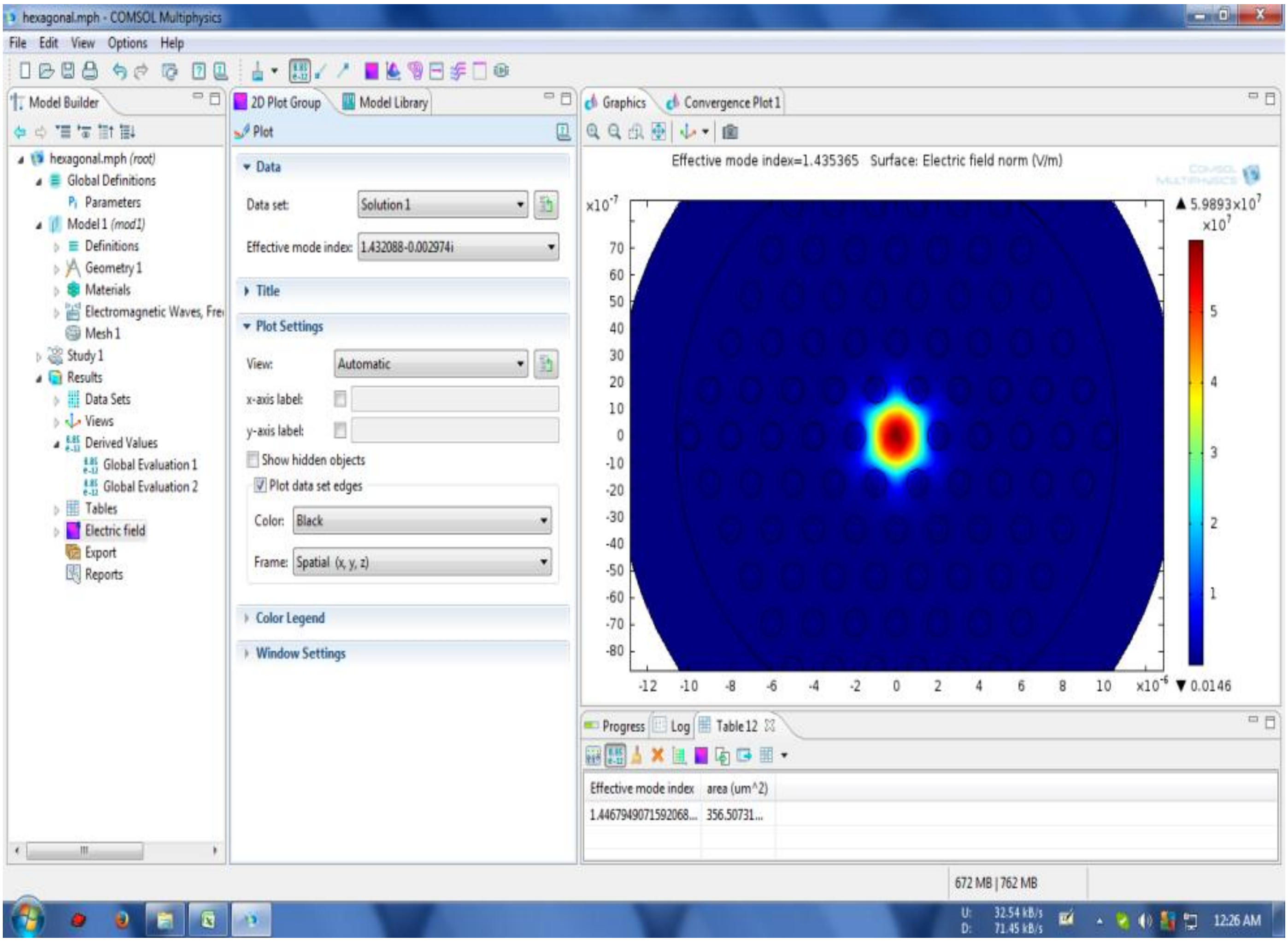


Fig. 2.1: HPCF with five rings using COMSOLE 4.3b.

2.1.1 Design methodology

Figure 1 shows the five ring photonic crystal fiber. Where, air hole diameter is d, and middle point of one air hole to another middle point of another air hole distance i.e. pitch constant or lattice constant is Λ. Here, pure silica is used for background material which refractive index is 1.46 and air holes act as a cladding in hexagonal PCF symmetry. The first ring i.e., the inner most ring contains six air-hole and the other rings contains integer multiple of six air-holes. The key property of a perfectly matched layer (PML) that distinguishes it from an ordinary absorbing material is that it is designed so that wave incident upon the PML from a non-PML medium do not reflect at the interface. This property allows the PML to strongly absorb outgoing waves from the interior of a computational region without reflecting them back into the interior.

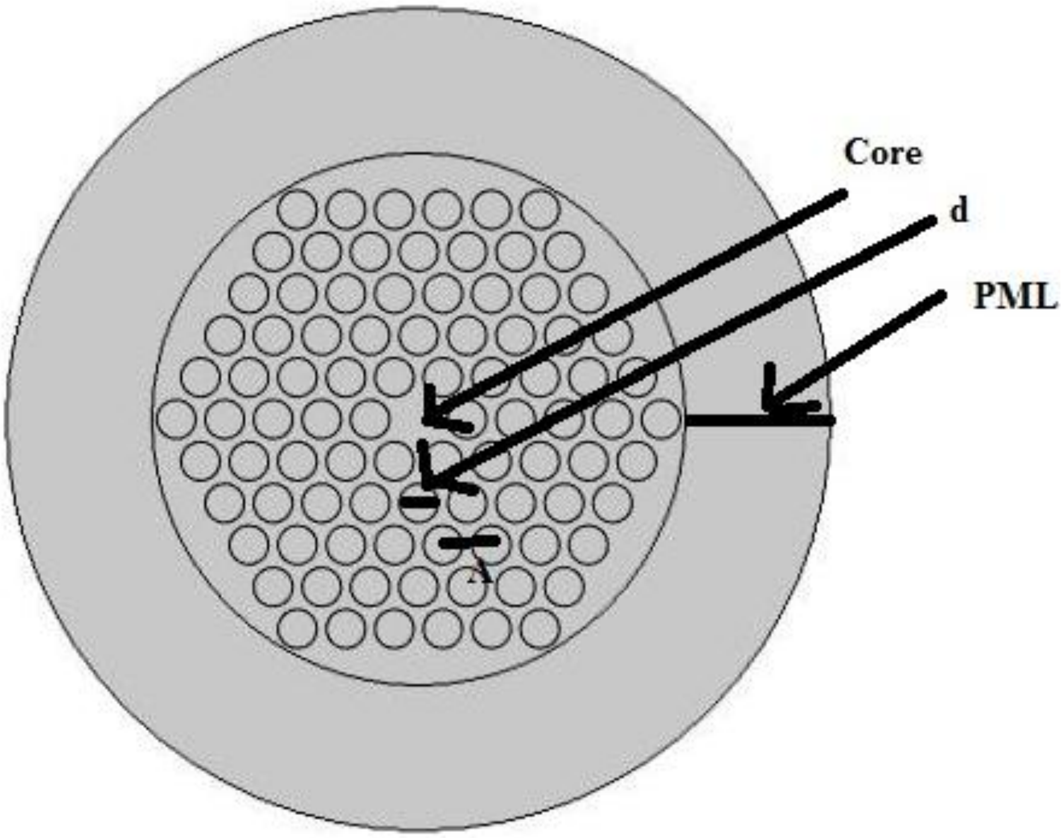
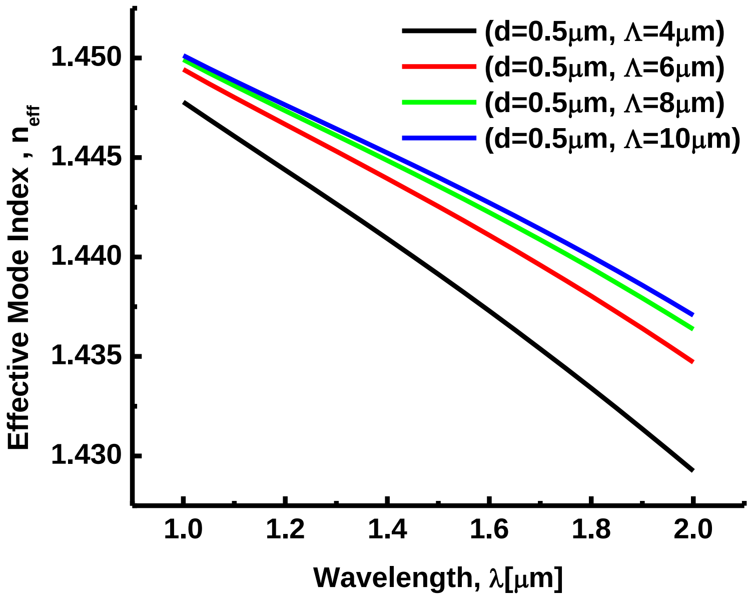


Fig. 2.1: Proposed hexagonal photonic crystal fiber with five rings.

2.2 Simulation result and discussion

2.2.1 Result



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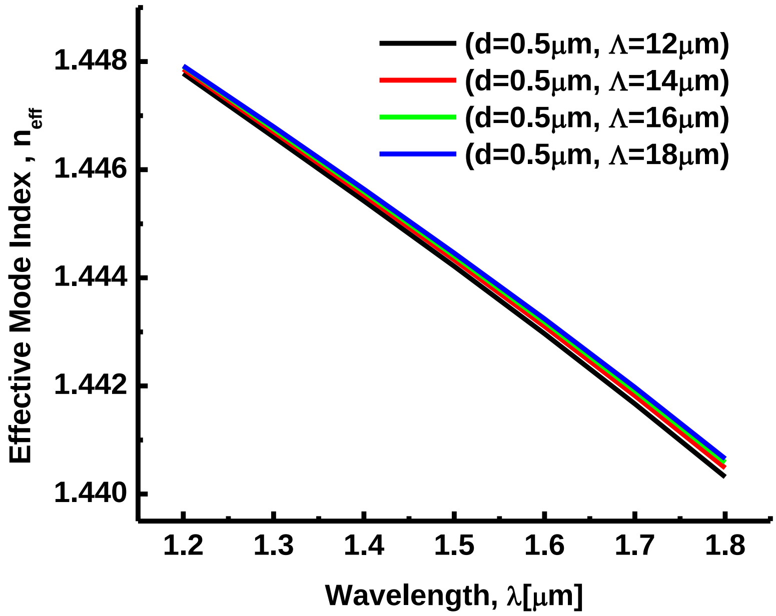
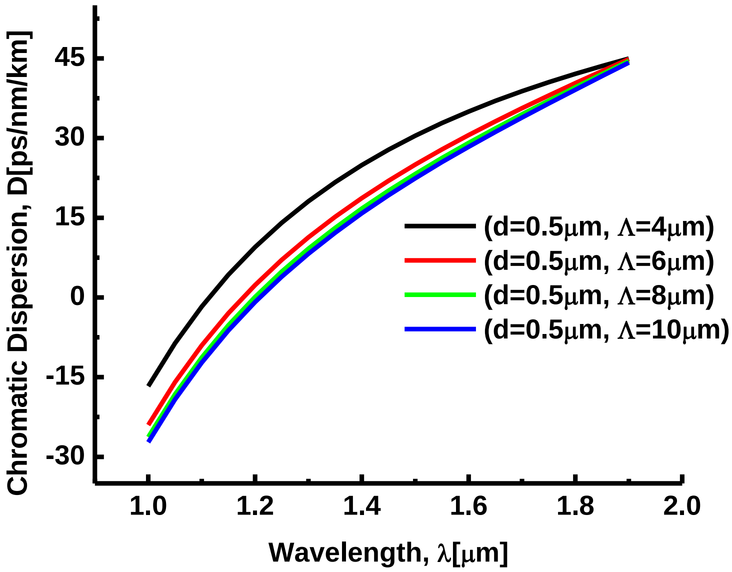


(b)

Fig. 2.2: Wavelength dependence effective mode index for (a) Λ = 4, 6, 8, 10 μm; d = 0.5 μm and (b) Λ = 12, 14, 16, 18 μm; d = 0.5 μm.



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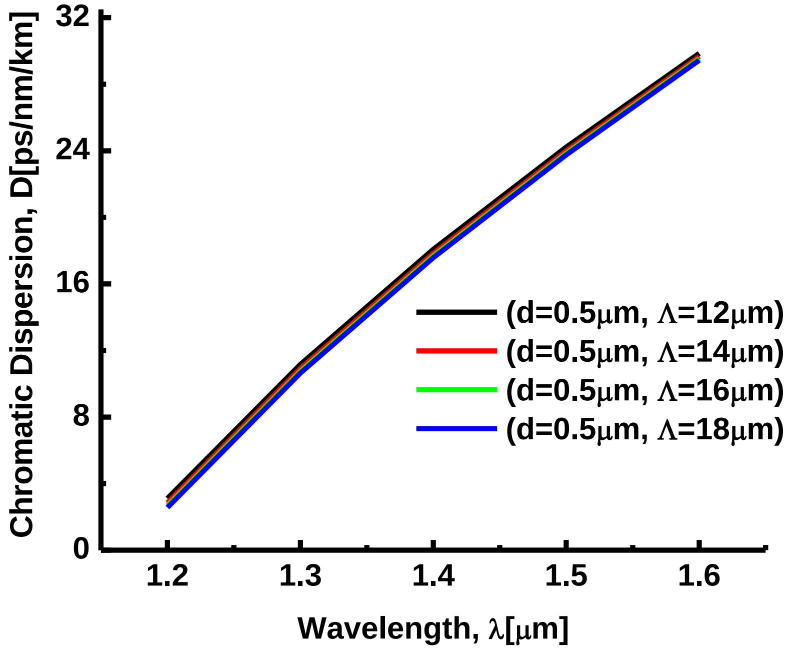
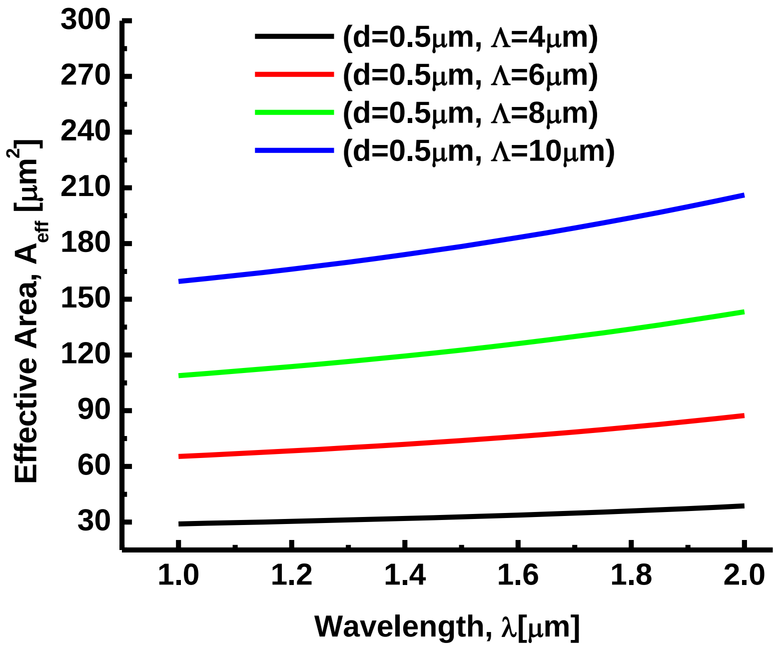
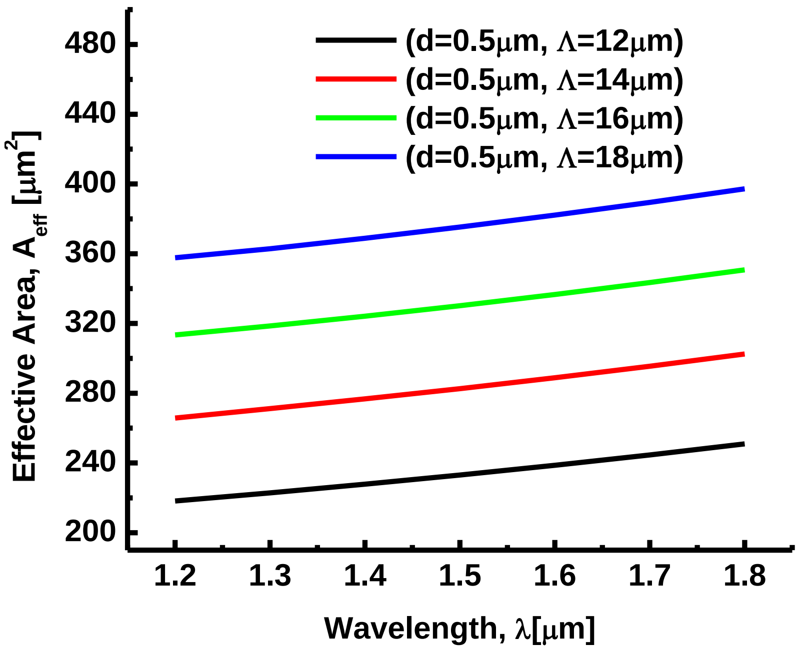


(b)

Fig. 2.3: Wavelength dependence chromatic dispersion for (a) Λ = 4, 6, 8, 10 μm; d = 0.5 μm and (b) Λ = 12, 14, 16, 18 μm; d = 0.5 μm.

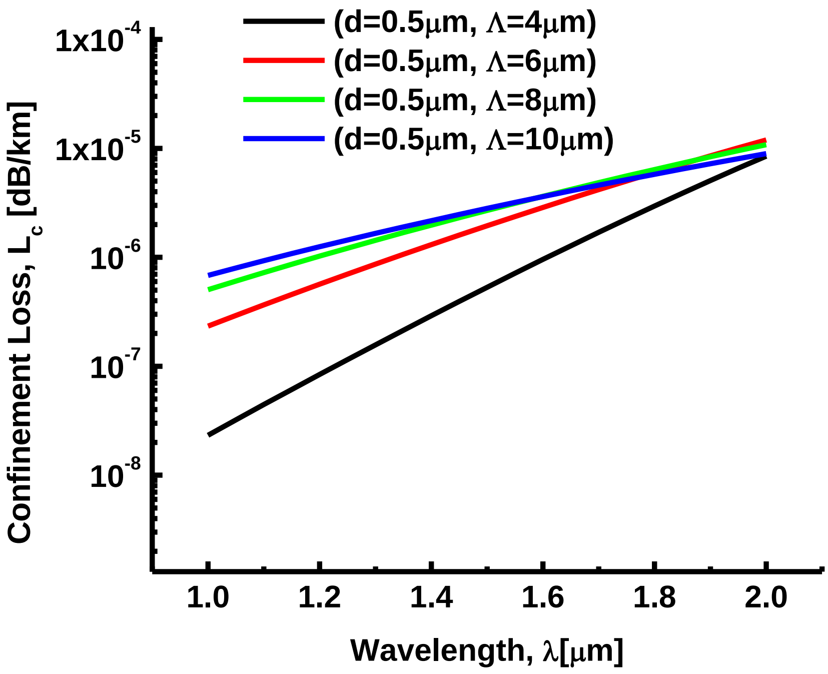


(a)

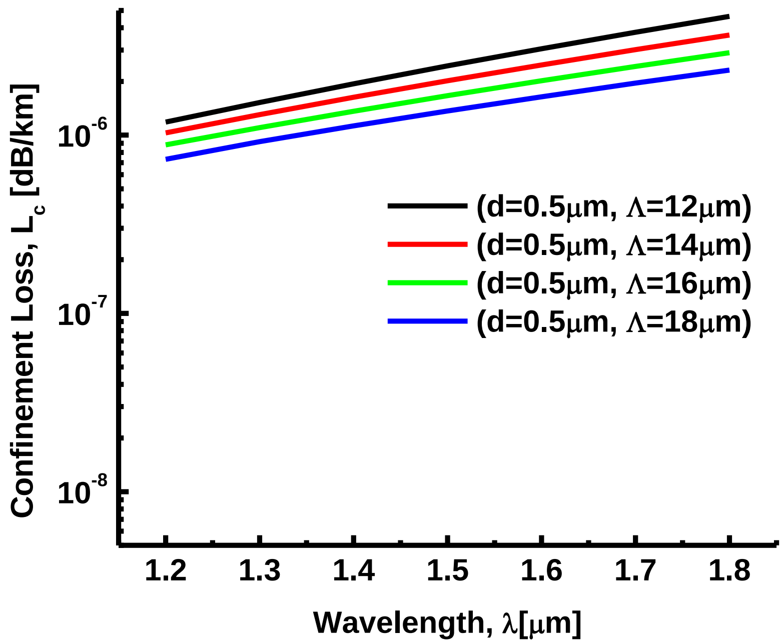


(b)

Fig. 2.4: Wavelength dependence effective mode area for (a) Λ = 4, 6, 8, 10 μm; d = 0.5 μm and (b) Λ = 12, 14, 16, 18 μm; d = 0.5 μm.



(a)



(b)

Fig. 2.5: Wavelength dependence confinement loss for (a) Λ = 4, 6, 8, 10 μm; d = 0.5 μm and (b) Λ = 12, 14, 16, 18 μm; d = 0.5 μm.

2.2.2. Discussion

Wavelength response real part of the effective mode index of hexagonal photonic crystal fiber has shown in figure 2.2 (a) and (b). Figure 2.2 (a) shows that the parameter pitches (Λ) is changed from 4 μm to 10 μm; taking the diameter, d is fixed on 0.5 μm. Figure 2.2 (b) shows that the parameter pitches (Λ) is changed from 12 μm to 18 μm; also taking the diameter, d is fixed on 0.5 μm. We have seen from these figures that effective mode is varies for the wavelength and the parameter pitch. As we increase the wavelength the effective mode index is decreases. We have seen from those figures that increasing the parameter pitch the effective mode index also increases. This is because as the value of pitch is increases the amount of silica on PCF is also increases; hence we know that silica has higher refractive index than air.

Figure 2.3 (a) and (b) represents the wavelength response of chromatic dispersion of photonic crystal fiber. Figure 2.3 (a) shows that the parameter pitches (Λ) is changed from 4 μm to 10 μm; taking the diameter, d is fixed on 0.5 μm. Figure 2.3 (b) shows that the parameter pitches (Λ) is changed from 12 μm to 18 μm; also taking the diameter, d is fixed on 0.5 μm. It is seen from the formula of dispersion that the chromatic dispersion is depend on real part of effective mode index. We calculate the chromatic dispersion using the value of effective mode index on MATLAB by dispersion formula. It is also observed that the dispersion is varied with the variation of pitch and wavelength.

Wavelength response real part of the effective area of hexagonal photonic crystal fiber has shown in figure 2.4 (a) and (b). Figure 2.4 (a) shows that the parameter pitches (Λ) is changed from 4 μm to 10 μm; taking the diameter, d is fixed on 0.5 μm. Figure 2.4 (b) shows that the parameter pitches (Λ) is changed from 12 μm to 18 μm; also taking the diameter, d is fixed on 0.5 μm. It is seen from those figure that higher the value of pitch larger the value of effective mode area. When the value of pitch increases the Gaussian function radius increases which increase the effective area. Wavelength has also effect on effective area.

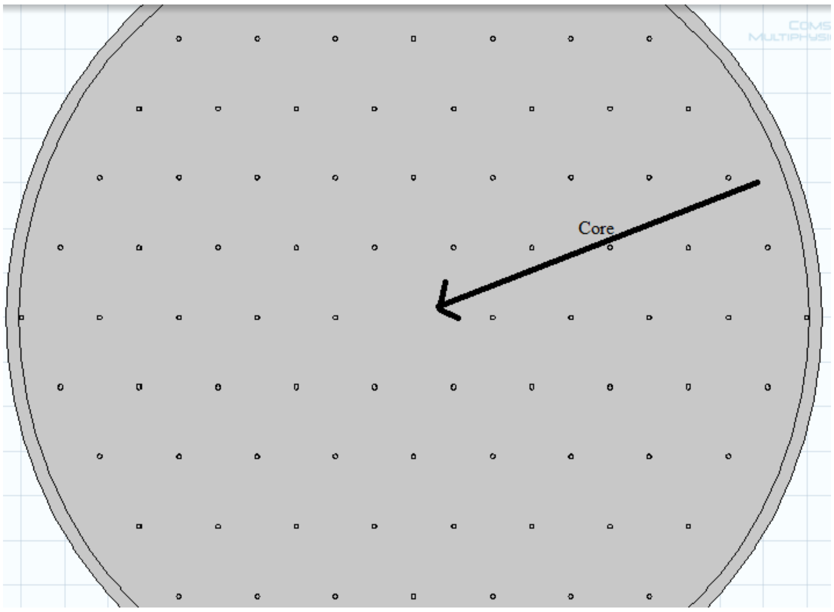
Figure 2.5 (a) and (b) represents that, confinement loss is a function of wavelength of photonic crystal fiber. Figure 2.5 (a) shows that the parameter pitches (Λ) is changed from 4 μm to 10 μm; taking the diameter, d is fixed on 0.5 μm. Figure 2.5 (b) shows that the parameter pitches (Λ) is changed from 12 μm to 18 μm; also taking the diameter, d is fixed on 0.5 μm. As the value of pitch increases the leakage of light also increases, hence we have seen from those figure that the value confinement loss increases.

2.3 Result and discussion of optimum large mode area

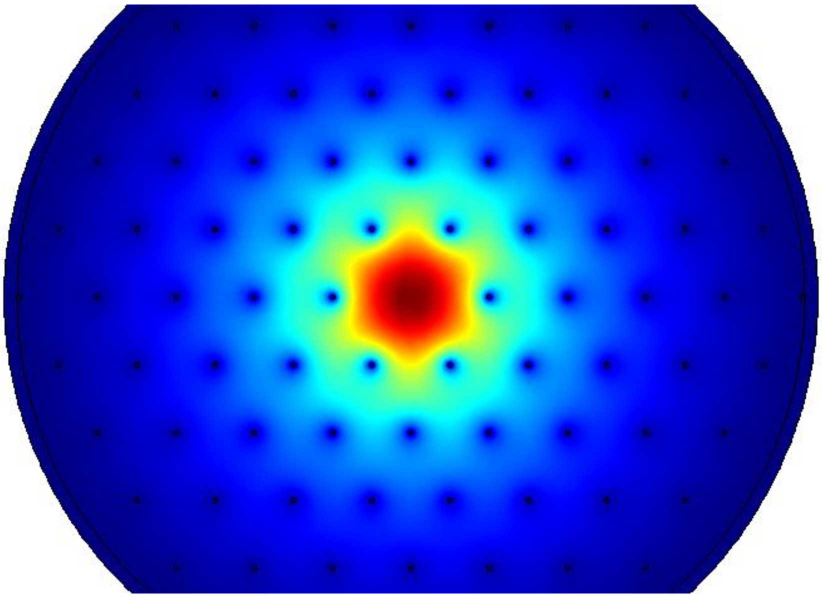
2.3.1. Overview

Conventional single-mode fibers suffer from small core, leading to limited output power due to generally a single-mode fiber diameter about 8 μm ~10 μm. In order to allow higher output power and improve the influence of external force, currently photonic crystal fibers (PCFs) have overcame the mentioned shortcomings, such as endlessly single-mode operation, large mode area (LMA). We present the results of numerical analysis showing that large period can be obtained in LMA PCFs. One of analysis methods corresponds to finite-element method (FEM) with perfectly matched layer boundary conditions. This method respects the sufficient reliability, efficiency, and accuracy for the PCFs. In this paper, we proposed several PCF models to increase the effective mode area up to 400 μm^2**.**

We consider the effective area A_{eff} of photonic crystal fibers (PCFs) with a triangular air-hole lattice in the cladding. It is first of all an important quantity in the context of non-linearities, but it also has connections to leakage loss, macro-bending loss, and numerical aperture. Single-mode versus multi-mode operation in PCFs can also be studied by comparing effective areas of the different modes.



(a)



(b)

Fig. 2.6: (a) Large mode area PCF with five ring of air hole with pitch =18, diameter=0.5, (b) simulated figure of PCF with light passing through the center of fiber core.

2.3.2. Result

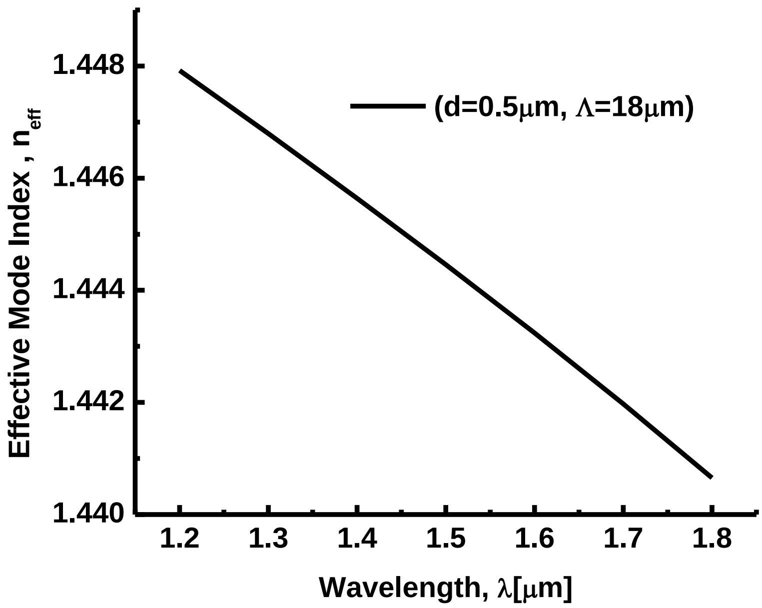


Fig. 2.7: Wavelength dependence effective mode index for Λ = 18 μm and d = 0.5 μm.

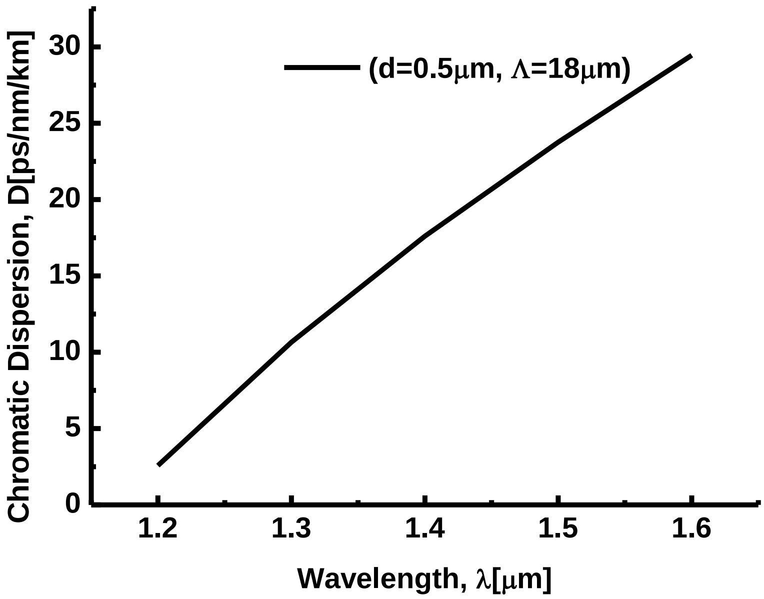


Fig. 2.8: Wavelength dependence chromatic dispersion for Λ = 18 μm and d = 0.5 μm.

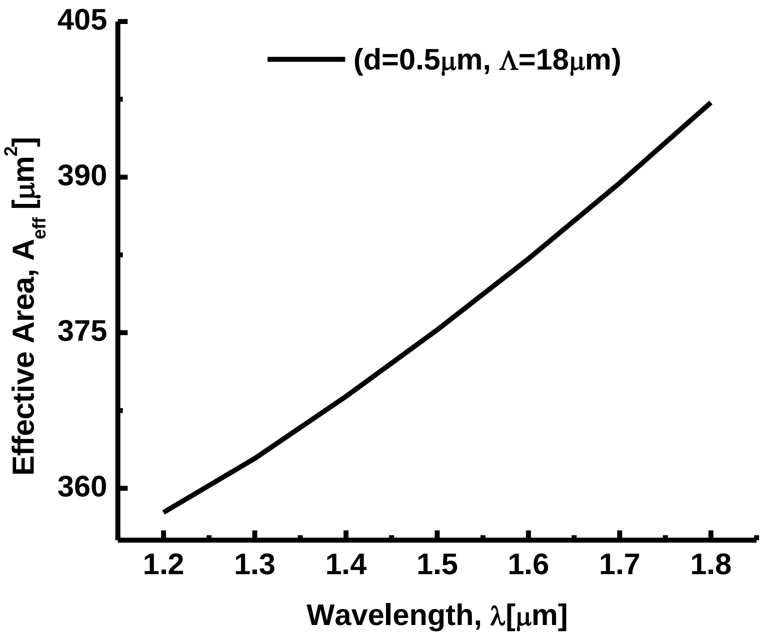


Fig. 2.9: Wavelength dependence effective area for Λ = 18 μm and d = 0.5 μm

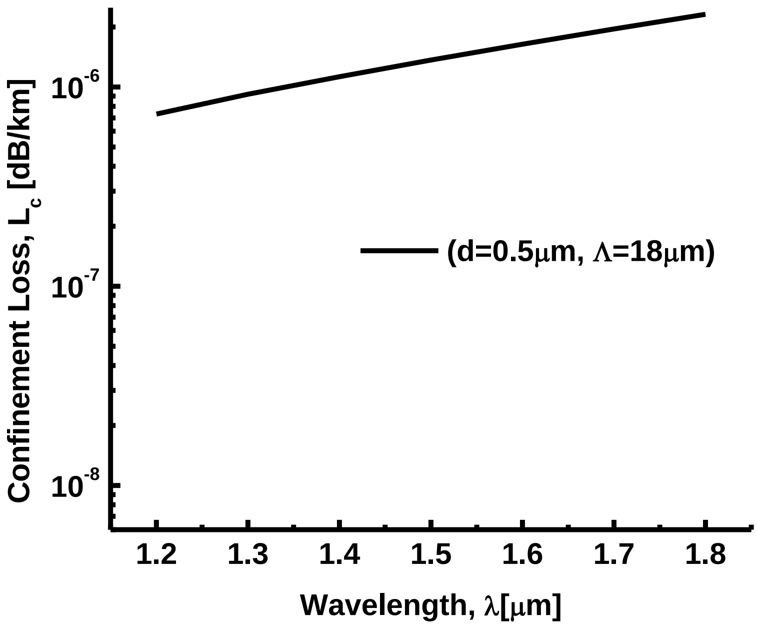


Fig. 2.10: Wavelength dependence confinement loss for Λ = 18 μm and d = 0.5 μm

2.3.3. Discussion

Fig. 2.7 (a) and (b) shows wavelength response of the real part of the effective mode index of pitch Λ = 18μm for a fixed air hole's diameter d=0.5. It is seen from those figure that wavelength also affect effective mode index. As we increase wavelength effective mode index decreases. It is also observed that for the higher value of pitch (Λ=18) the effective mode also higher.

Fig. 2.8 (a) and (b) shows wavelength response chromatic dispersion of photonic crystal fiber where pitch Λ = 18μm for a fixed air hole's diameter d=0.5. As we increase the wavelength the dispersion value is also changed. It is seen from the value of MATLAB and the formula of dispersion that the chromatic dispersion is depend on real part of effective mode index. It is also observe that the dispersion is varied with the variation of pitch and wavelength.

Fig. 2.9 (a) and (b) shows wavelength response real part of the effective area of photonic crystal fiber where pitch Λ = 18μm for a fixed air hole's diameter d=0.5. It is seen that highest value of pitch (Λ=18) larger the value of effective mode area. When the value of pitch increases the Gaussian function radius increases which increase the effective area. Wavelength has also effect on effective area.

Figure 2.10 (a) and (b) represents that, confinement loss is a function of wavelength of photonic crystal fiber, where pitch Λ = 18μm for a fixed air hole's diameter d=0.5. Figures shows that highest value of pitch (Λ=18) larger the value of confinement loss. It is because difference between two air hole is increases, so that leakage of light increases.

Chapter 3

Conclusion

We have designed index guiding hexagonal photonic crystal fiber with five rings of air hole. Our target was to achieve large mode area for the proposed hexagonal photonic crystal fiber. We use finite element method of COMSOL Multiphysics to design proposed hexagonal photonic crystal fiber. Finite element methods for approximating partial differential equations that arise in science and engineering analysis find widespread application. We have changed different parameter such as pitch and diameter with different wavelength and observed that the variation of different properties such as effective mode index, effective area, confinement loss and chromatic dispersion. For the higher value of pitch effective mode area also increases. When the area is increases the more light will pass through the core.

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