Project Report

on

Design and Analysis of Solid core and Liquid core Photonic crystal fiber for Slow light generation

Submitted in partial fulfillment of

the requirements for the award of the degree of

Master of Technology

in

Microwave and Optical Communication Engineering

Submitted by

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CANDIDATE'S DECLARATION

I, Rahul Kumar, Roll No. 2K16/MOC/10 student of M.Tech (Microwave and Optical Communication), hereby declare that the project Dissertation titled "Design and Analysis of Solid core and Liquid core Photonic crystal fiber for Slow light generation" which is submitted by me to the Department of Electronics and Communication and Department of Applied Physics, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or any other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation titled "**Design and Analysis of Solid core and Liquid core Photonic crystal fiber for Slow light generation**" which is submitted by Rahul Kumar, Roll No. 2K16/MOC/10 [Electronics and Communication], Delhi Technological University, Delhi in partial fulfillment of requirement for the award of the degree of Master of Technology in Microwave and Optical Communication Engineering, is a record of the project work carried out by the students under my supervision. To the best of my knowledge, this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

Slow light in general terms is basically reducing group velocity of light. Slow light helps to buffer and process optical signals in time domain. Optical energy is spatially compressed using slow light and also used for enhancing linear and non-linear effects.

Photonic-crystal devices finds use in generation of slow light because they offer wide variety of advantages like on-chip integration, operates at room temperature, wide bandwidth and dispersion free propagation. Photonic Crystal Fiber (PCF) is a type of fiber which makes use of properties of photonic crystals. It has advantage of controlling optical properties and confinement characteristics over traditional optical fiber. PCF has various applications in fiber-optic communications, nonlinear devices, fiber lasers, amplifiers, high-power transmission, highly sensitive gas sensors, and other areas.

When sound waves scatter light in a medium, it is known as Brillouin scattering. It makes use of three waves. Two of them are Optical waves and the third one is Acoustic wave. Scattering process occurs through the conservation of momentum and energy. Stimulated Brillouin Scattering (SBS) takes place when the interference between the pump and scattered light reinforces the acoustic wave by electrostriction or by optical absorption. SBS is the most preferred non-linear technique and has many applications like SBS lasers, microwave oscillators, optical phase conjugation and slow light.

In this project, we have designed two structures of Photonic crystal fiber for slow light generation with tunable properties. One is highly non-linear Chalcogenide Hexagonal Solid core photonic crystal fiber and other is Decagonal liquid core photonic crystal fiber. Both structures are designed using COMSOL MultiPhysics and various properties are compared. Graphs are plotted using MATLAB codes. Effective mode area, Maximum power, Minimum power, Maximum time delay and Confinement loss has been calculated and plotted for tunable slow light generation in the two structures.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my project supervisor, Dr. Ajeet Kumar, for his supervision, invaluable guidance, motivation and support throughout the extent of the project. I have benefited immensely from his wealth of knowledge.
I express my deepest thanks to Miss. Pooja Chauhan for giving helpful advice and guidance. I choose this moment to acknowledge his contribution gratefully.

I extend my gratitude to my university, Delhi Technological University (formerly Delhi College of Engineering) for giving me the opportunity to carry out this project.

This opportunity will be a significant milestone in my career development. I will strive to use the gained skills and knowledge in the best possible way, and I will continue to work on their improvement, in order to attain desired career objectives.

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INTRODUCTION

1.1. THESIS APPROACH:

In this thesis, we are mainly focused on slow light generation bases on SBS in photonic crystal fiber with tunable features. So we have designed and numerically modelled two structure of photonic crystal fiber for slow light generation. There are many ways for generating slow light but we have preferred SBS because it has various advantages over other methods. We have numerically computed various parameters of photonic crystal fiber and compared the results of the two structures. We have analyzed our structure in third optical window i.e.1550 nm.

Software 'Comsol MultiPhysics' has been used for performing modal analysis of proposed structures. Effective Mode area and Confinement loss for fundamental mode have been calculated using 'Comsol MultiPhysics' software. Proposed optical fiber designs are studied for tunable features and other parameters are obtained using Matlab codes.

1.2. THESIS OBJECTIVE

The main objectives of this report are as follows:

- Study of the basics of slow light, concept of non-linearity, various methods to achieve slow light.
- Study and analyses of slow light phenomenon of stimulated Brillouin scattering and study the various advantages and disadvantages of SBS phenomenon.
- Study the basics of Photonic crystal fiber, light guidance mechanism used in PCF, fabrication processes, various advantages and disadvantages of PCF and its applications.
- Design and analysis of As_2Se_3 based chalcogenide Solid core Photonic crystal fiber and CS_2 based Liquid core Photonic crystal fiber for generation of slow light.
- Study and comparison of the two structures of different parameters and the variation of time delay with pump power and other parameters of the Photonic crystal fiber to obtain tunable features.

1.3. THESIS ORGANIZATION

The outcome of the work carried out in this project is organized in six chapters. Chapter 1 consists of the overview and objective of the thesis. Chapter 2 includes the concept of 'slow light', basics of slow light, Stimulated Brillouin Scattering and non-linear processes in optical fibers. Chapter 3 includes the study of basics of Photonic crystal fiber, light guidance mechanisms, fabrications processes used for PCF, advantages & disadvantages and its applications. Chapter 4 deals with the concept of numerical modelling, gives an introduction to our numerical method i.e. Finite element method, steps to apply it and its applications. Chapter 5 deals with the Hexagonal solid core photonic crystal fiber and decagonal liquid core photonic crystal fiber and its parameters for generation of slow light with tunable features. The project work is concluded in Chapter 6 along with the suggestions to the future work that can be done in this field.

Chapter 2

SLOW LIGHT

This chapter deals with the idea of Slow-light and related concept behind it. The concept of non- linearity and non-linear process i.e. SBS, used in our work for slow light generation are presented with various SBS parameters with related formulas. Advantages and disadvantages of SBS based slow light generation is also presented.

2.1. INTRODUCTION

The phenomenon of slow light is hot topic for many researchers in the last few years because it provides greater control over the light matter interactions.

Optical delay lines and time domain optical signal processing consider Slow light as a solution which has led to researchers attention [1,2]. Non-linear enhancement of optical effects [3,4] is more important and this enhancement occurs because optical energy is spatial compressed [5-7]. PCF provides a platform for generating slow light which has compatibility with chip integration. At the same time it offers broader bandwidth and dispersion free propagation [2]. For past few decades, it was not possible to slow down light by reducing group velocity. So, optical signals was first changed into electrical domain for buffering. This much work is done because it finds various applications like optical delay line [8], quantum information processing [9], and optical sensors [10]. Optical device size is reduced because of slow light[11].

2.2. SLOW LIGHT

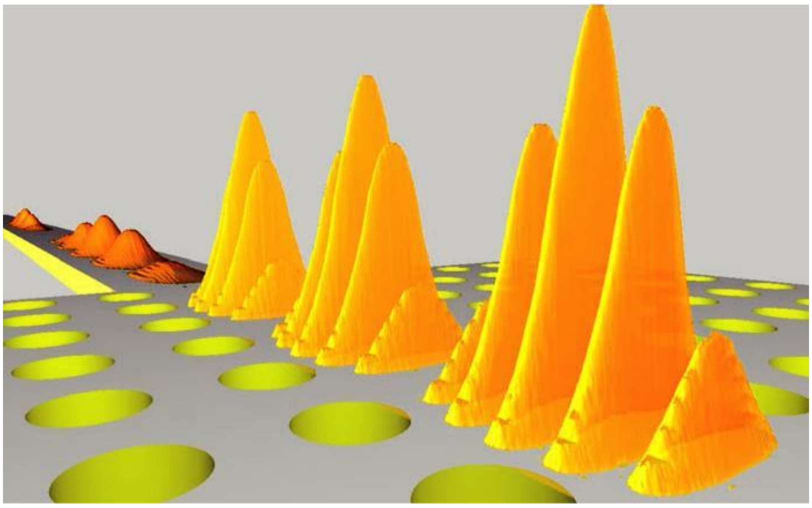

Fig. 2.1: Slow light mechanism[13]

Slow light is defined as the process by which we can reduce the group velocity of light and it is obtained by interacting with the medium. Photonic crystal fiber can used for on chip integration by using the process of slow light as it helps us to control and store light.

There are various techniques for achieving slow light like electromagnetically induced transparency [14], coherent population oscillation [15], stimulated Raman scattering [16], stimulated Brillouin scattering (SBS) [8], and soliton collision [17]. Stimulated brillouin scattering is preferred over other techniques because it can operate at room temperature and tuning can be done for working wavelength [8,18]. When compared with traditional optical fiber, photonic crystal fiber offer wide range of single mode operation over the spectrum of visual and infrared region. Photonic crystal fiber provides very less attenuation compared to traditional optical fiber. Photonic crystal fiber having small core can be used to achieve slow light with optimum power. Hence photonic crystal fiber provides various benefits over traditional optical fiber so it should be studied for tunable slow light generation. Photonic crystal fiber having small core is used for light guiding by hollow air holes running along the fiber which provides high refractive index difference between core and cladding compared to traditional optical fiber. Acousto-optic interaction can be enhanced by confining more light and sound in photonic crystal fiber [19]. Earlier generation of slow light took place by using extremely strong material dispersion. Now Photonic crystal fiber is used for generation of slow light which are made of high refractive index material [20–21], and material dispersion is changed by using array of air hole structure in photonic crystal fiber [22]. Photonic crystal fiber has led to significant reduction in fiber length and also provide tunable time delay and desirable brillouin gain.

2.3. CONCEPT OF NON-LINEARITY

Non linearity of optical fiber is used for generation of technique of Slow light. When light interacts with the medium, it decides whether medium will be linear or non-linear. Intensity of light has also effect on non-linearity. When light intensity is low, it cannot cause medium to be non-linear. Low intensity of light cannot cause non linearity. When we use high intense light then it causes medium to be non-linear.

At basic level, non-linearity is due to bound electrons which has anharmonic motion when electric field is applied. So, the total polarization **P** which is caused by electric dipoles, is not a linear function of the electric field **E**, but is non-linear function of the electric field. The relation is given below:

$$P = \varepsilon_o (\chi^1.E + \chi^2.EE + \chi^3.EEE) \qquad (2.1)$$

where ε_o is Permittivity and $\chi^{(j)}$ is j^{th} order susceptibility. Susceptibility of third order causes non-linearity in optical fiber [23].

2.4. NON LINEAR EFFECTS

- Non-linear refractive index effects
    - Self Phase Modulation
    - Cross Phase Modulation
    - Four Wave Mixing
- Inelastic scattering effects
    - Stimulated Raman Scattering
    - Stimulated Brillouin Scattering

When light depends on refractive index and scattering process, it leads to above mentioned non-linear processes.There are different non-linear methods for slow light generation like electromagnetically induced transparency [5], coherent population oscillation [6], stimulated Raman scattering [7], stimulated Brillouin scattering (SBS) [1], and soliton collision [8].

SBS is preferred among all because it is flexible, compatible with existing communication system, operate at room temperature and wavelength tuning properties.

2.5. STIMULATED BRILLOUIN SCATTERING

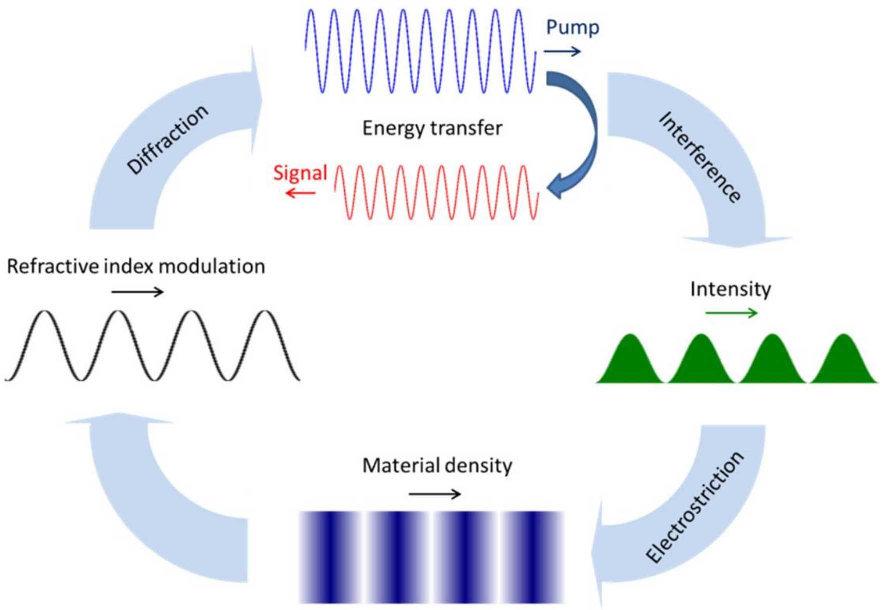

Figure 2.2: SBS mechanism[24].

Stimulated Brillouin scattering was first discovered in 1964 and is the non-linear process and most widely used [24]. SBS can be explained in simple terms as a non-linear process in which high intensity pump wave moving in longitudinal direction in core interacts with signal wave by taking the help of acoustic wave. There is a difference between frequencies of intense pump wave and low intense signal wave and it is this difference which causes slow travelling wave also called as acoustic wave by the process of electrostriction. Movement of this acoustic wave cause travel grating of refractive index in core and travel grating of refractive index causes dynamic Bragg grating in the fiber. This is the reason for the formation of stokes wave because of the high power scattering. When wave coming in opposite direction has same downshifted stokes wave, there is high gain in signal wave [25].

Let ω_p and ω_s denotes pump wave frequency and signal wave frequency and I_p and I_s denotes intensity of Pump and signal wave respectively. According to condition of phase matching, Brillouin frequency shift i.e.Ω_B is equivalent to difference in the frequencies of pump and signal wave. Signal is lesser than pump frequency. The coupled equation for pump and signal wave is shown below with the equations.

Following equations give the coupled equations for the signal wave and pump wave [26].

$$\frac{dI_p}{dz} = -g_B I_p I_s - \alpha_p I_p \quad (2.2)$$

$$\frac{dI_s}{dz} = +g_B I_p I_s - \alpha_s I_s \quad (2.3)$$

For calculation of Brillouin threshold, we have assumed undepleted pump wave. Solution of above equations is below.

$$I_s(0) = I_s\,(L) exp\left(\frac{g_B P_0 L_{eff}}{A_{eff}} - \alpha L\right) \quad (2.4)$$

Where L_{eff} denotes PCF effective length and is given by

$$L_{eff} = \frac{1 - e^{(-\alpha L)}}{\alpha} \quad (2.5)$$

Where α is the attenuation constant, L is the real length and L_{eff} is the effective length.
If E is the electric field distribution inside core of PCF, then the Effective Mode Area (i.e. A_{eff}) is given by:

$$A_{eff} = (\frac{\iint_{-\infty}^{\infty} |E|^2\, dx\, dy)^2}{\iint_{-\infty}^{\infty} |E|^4\, dx\, dy} \qquad (2.6)$$

The Brillouin line width is given by formula shown below.

$$\Gamma_B = 2\pi\Delta v_B \qquad (2.7)$$

Maximum Power is the power beyond which the output pulse gets distorted and can be calculated by following equation.

$$\mathrm{P}_{max} = 21\frac{A_{eff}}{kg_B L_{eff}} \qquad (2.8)$$

Minimum power is the power below which SBS effect cannot take place and PCF does not show non-linear effects.

$$\mathrm{P}_{min} = \alpha\frac{A_{eff}L}{kg_B L_{eff}} \qquad (2.9)$$

SBS induced time delay can be calculated by using formula given below.

$$\frac{\Delta t_d}{L_{eff}} = \left(\frac{g_0 k}{\Gamma_B}\right)P_p \qquad (2.10)$$

Other significant parameter include the time delay slope efficiency which is given by the formula below.

$$S_{dg} = \frac{\Delta t_d}{G_B} = \left(\frac{1}{8.686\pi\Delta\upsilon_B}\right) \qquad (2.11)$$

2.6. ADVANTAGE AND DISADVANTAGE OF SBS BASED SLOW LIGHT

Advantages

- Many media can have SBS phenomenon which helps slow light devices integration in communication systems.
- Power requirement is very low for SBS phenomenon which is an important factor. Significant delay can be obtained at much less power. Time delay and pump power has proportional relationship which helps in easy tuning of delay.
- SBS is compatible and flexible with the current communication system exclusively optical.
- SBS can work at any wavelength and even at room temperature [27].

Disadvantages

- One of the main disadvantage of SBS phenomenon for slow light generation is that delay is saturated at high power. If power is increased beyond that, problem can occur.
- Pulse-width increases when delay increases and it results in less delay [27].

Chapter 3

PHOTONIC CRYSTAL FIBER

This chapter gives an introduction to Photonic crystal fiber, tells us about various guiding methods used in PCF, fabrication method used for it and various advantages & disadvantages of PCF.

3.1. INTRODUCTION

Photonic crystal fibers (PCFs) are fibers which has an internal periodic structure made of capillaries, filled with air, laid to form a lattice pattern. Propagation of light occurs in these defects that are formed in the fiber. Removal of central capillaries leads to the formation of defects. Hence it can be said that it is a new class of fiber. PCF combine the properties of optical fibers and photonic crystals and has unique properties that is not possible in classical fibers. Classical optical fibers find application in telecom and non-telecom areas. At the same time it has some limitations in their structure. They have limited core diameter for single mode operation and material choices are less because for optical fibers, they must have same core and cladding thermal properties which is not the case with PCFs.

PCFs have good design flexibility. We can alter several parameters like pitch ratio, air hole shape and diameter, glass refractive index, and lattice patterns. PCFs can have endless single mode operation because of its design and hence they can operate in all optical range and there is no cutoff for wavelength. There are two methods for light guidance in PCFs. One is index guiding mechanism which is also used in Traditional optical fibers and other is photonic bandgap mechanism.

In PCFs, it is possible to have dispersion as desired as PCFs provide design flexibility. They can be designed to have zero dispersion and any dispersion as required at visible wavelengths.

Photonic crystal fiber was first presented by Yehet al. [28] in 1978. They proposed to clad a fiber core with Bragg grating, which is similar to 1D photonic crystal. A photonic crystal fiber made of 2D photonic crystal with an air core was invented by P. Russell in 1992 and the first PCF was reported at the Optical Fiber Conference (OFC) in 1996 [29].

3.2. PHOTONIC CRYSTAL FIBER

Photonic crystal fibers are also known as micro structured or holey fibers. It has generated interest in the researchers. Today, photonic crystal fibers (PCFs) are established as an alternative fiber technology. There are two main categories of PCF: high-index guiding fibers and photonic band gap. High index guiding fibers are similar to traditional optical fibers, because confinement of light is maintained by modified total internal reflection method. Refractive index difference between core and cladding is positive and presence of air-hole leads to smaller average refractive index. Hence the guiding method is known as Modified because the cladding refractive index is varying value and changes with wavelength which is not the case with traditional optical fibers.

If refractive index of core has a lower refractive index than cladding, guidance of light takes place by photonic bandgap instead of total internal reflection. The fact is that the air-hole structure in cladding is a two-dimensional photonic crystal that is a material with periodic dielectric properties characterized by a photonic bandgap, where light in certain wavelength ranges cannot propagate.

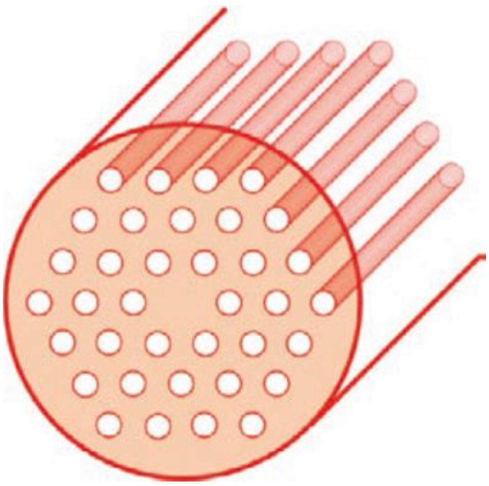

Figure 3.1: Schematic of Solid core PCF with triangular lattice pattern [30].

3.3. LIGHT GUIDANCE MECHANISM

Traditional optical fiber depends on the method of total internal reflection for guidance of light. As refractive index of core is greater than refractive index of cladding which confines light in core. There are two methods for guidance of light. One is Modified total internal reflection which is used in solid core PCF. Other is Photonic Bandgap which is used in hollow core PCF.

3.3.1. Modified Total Internal Reflection

PCF acts as a fiber by following the principle of total internal reflection where core refractive index is greater than cladding. These PCF have solid core surrounded by lattice pattern of air holes in cladding. They are also known as index guiding PCF. They guide light by a technique called Modified total internal reflection.

Basically in solid core PCF, core has silica as a material and cladding has air-hole lattice pattern which helps to decrease core refractive index. Here we modify the refractive index of cladding to make it lesser than core and it helps to guide light using a process called as Modified Total Internal Reflection. PCF has air holes lattice pattern in cladding which causes barriers. As we increase d/Λ, i.e. air filling ratio of PCF, there is trapping of high order modes. It depends on selection of geometry that we can guide only fundamental mode through it [31,33].

3.3.2. Photonic Band-gap Guiding

PCF using this method is very different from other PCFs. As in this case, core refractive index is less than cladding and it does not depends on total internal reflection for guiding light. The mechanism of photonic band-gap is that core has air holes in it and air is used as low loss material as no other material has been able to replace it. Hence light guidance takes place through band-gap. As photons which has band-gap higher than cladding can only pass through PCF. As a result photons having higher band-gap than cladding stops in cladding and rest of the photons goes through the core having air holes. The first band-gap PCF had triangle lattice pattern of air holes. These fibers use band-gap for light guidance i.e. small portion goes into cladding and left ones are reflected back or gets away in core. If we pass white light through these fibers, we get colored modes. It shows that guidance of light took place in only certain wavelengths and are same as band-gap [31,33].

3.4. FABRICATION PROCESS

Fabrication process is an important characteristics of device. Fiber perform is fabricated and fiber is drawn from it in high temperature furnace in tower. There are different techniques for vapor deposition like modified chemical vapor deposition (MCVD), vapor axial deposition (VAD), and outside vapor deposition (OVD) which helps in fabrication of circular perform. This helps in controlling the deposition with much change in methods.

While in PCF, we have several factors like viscosity, gravity, and surface tension which comes into play while fabrication. These factors comes into play in PCF because PCFs have an array of air holes in its design. Traditional fiber has very less difference in core cladding refractive index i.e. 1% while PCFs has larger difference in core cladding refractive index i.e. 50-100% [32]. So the methods used for normal fibers cannot be used for PCFs. We use two methods for fabrication of PCFs which are described below.

3.4.1. Stack and Draw Technique

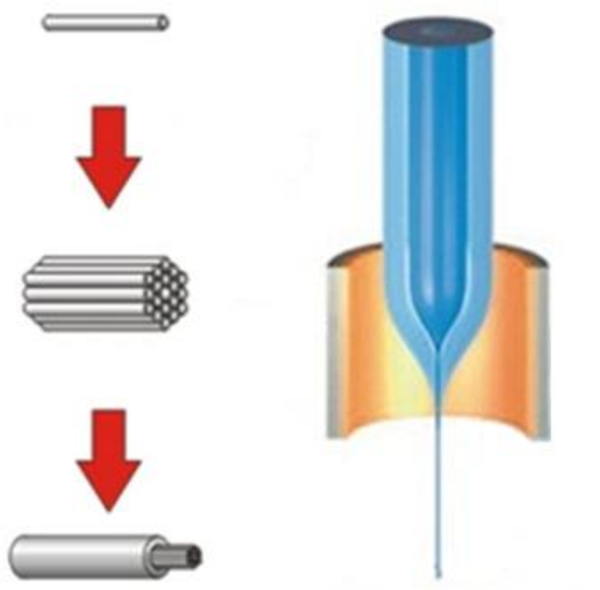

Figure 3.2: Stack and Draw Process [33]

Stack and draw technique was first given by Birks et al. in 1996 and since then it has become most famous technique for PCF. It has several advantages over other techniques as it is comparatively fast, clean, low-cost, and flexible perform manufacture. Air silica pattern is formed by capillary silica tubes and rods and it is being done on perform manufactured. It gives flexible design as we can control shape and size of core. Index profile of cladding also gives design flexibility which was not possible earlier. Now after this, thin wires are used are used to hold these capillaries and intermediate drawing process is used to fuse them. After this process, traditional fiber drawing tower is used for drawing fiber from the preform which can extend from 20 mm to 80–200μm [31,33]. Pressure is applied inside the perform for controlling air hole ratio and drawing speed for process to take place effectively.

3.4.2. Extrusion Fabrication Process

By using extrusion, we form silica-air perform which leads to formation of a new type of fiber that was not possible through earlier process. Extrusion is a process in which die, a tool is getting pushed by material so that we can have cross section as per our desire.

This process is good for glasses other than silica and earlier it used to be tough to form tubes from these glasses which was solved by this process. Die has pattern of holes through which molten glass is passed. Fiber drawing tower is used to draw fiber from bulk glass and any type of structure can be produced. It can be amorphous or crystalline. This process finds use in any type of material whether be polymer or any compound glass. Preform is formed of 16 mm outer diameter and extrusion of outer jacket takes place. By the use canning process, we can reduce preform to around 1.6 mm diameter of cane on fiber drawing tower. This cane is then put into jacket tube and this leads to the drawing of final photonic crystal fiber [33].

3.5. ADVANTAGES AND DISADVANTAGES OF PCF

Here are various advantages of PCF over Traditional optical fiber [34].

- Optical properties and confinement characteristics of material can be controlled.
- It guide light through the air holes and as a result offers very less attenuation.
- PCFs have capacity of handling greater power than traditional fibers.
- Contrast is large because of effective index.
- They have lesser effect of attenuation.
- PCFs have wider control on dispersion as it can be designed for desired dispersion.

Disadvantages of using PCF

- Length is small.
- PCFs are costly as their use is limited.
- Coupling might be another thing that need focus as PCFs are not compatible with different waveguides.

3.6. APPLICATIONS

- PCFs has single mode operation which can be altered according to air hole ratio and it occurs over certain value.
- PCFs can be designed for desired dispersion value which can even be zero.
- Dispersion is designed according to our will and different wavelength of light can travel at different velocities which can be applied in communication system designing.
- PCFs are highly non-linear. Air hole size and core size affect the light guiding capacity of PCF which can be altered for high nonlinearity.
- PCF can be designed to have high effective area which can be done by altering geometrically.
- PCFs are best suited for slow light generation and can solve the problem with all optic system [33].

Chapter 4

MODELLING METHODS

This chapter deals with an idea of different Modelling methods used for solving field problems and we also present in this chapter the technique used for our simulation purposes i.e. Finite element method and its applications.

4.1. INTRODUCTION

For modal analysis, we need different modelling methods. There are various methods to solve the field problems. Field problems have three techniques to solve field problems.

- Numerical Techniques
- Experimental techniques
- Analytical techniques

We prefer Numerical Techniques for our work. There are reasons for it.
Experimental techniques are not flexible for parameter variations and are time taking and costly. Analytical techniques require expertise and lengthy computations.
Due to these reasons, we prefer to use Numerical Techniques.

Numerical Techniques are used for solving many problems in fields like Acoustics, Biosciences, Electro-chemistry, Electromagnetics, Heat Transfer, Microelectromechanical Systems (MEMS), Optics and many others.
There are many numerical techniques used for calculation.

- Finite Difference Method
- Variational Method
- Method of Moments
- Finite Element Method

Among these, Finite Element Method is preferred for our work.
One of the benefits of using the finite element method is that it offers great freedom in the

selection of discretization, both in the elements that may be used to discretize space and the basis functions.
Another benefit of the finite element method is that the theory is well developed. The reason for this is the close relationship between the numerical formulation and the weak formulation of the PDE problem [35].

4.2. FINITE ELEMENT METHOD

Aerospace industry led to the development of Finite Element Method in 1950s and this development was led by Boeing and Bell aerospace in US and Rolld Royce in UK. First presentation of paper on Finite Element Method was published by M.J Turner, R.W. Clough, H.C. Martin and L.J. Topp in 1956 [36].

Partial Differential equation is used to describe various physical phenomenon in engineering. If we try to solve these equations using classical methods, then it would be not possible to get solution. Finite element method is a numerical technique to solve partial differential equation approximately. From engineering point of view, Finite element method is a technique to solve problems like stress analysis, optics, microwave engineering and electromagnetics by simulating using computer.

Finite element method is a method in which solution is obtained using programming on computer. Solution is obtained by solving a group of linear equations in Linear problems in which case we have equal node and unknowns. For getting accurate result, we have to solve thousands of nodes which is practically not possible for us to solve. So we use computer for this purpose. Result is more accurate if the number of nodes is increased but it also leads to increase in computational duration and cost. Finite element method helps us to determine the result at each node and gives a plot for the calculated results which is used in designing processes.
The Finite Element Method consists of the following five steps [37]:

- We preprocess problem by dividing it into elements.
- We develop equations for Elements.
- We determine equation for system by using equations of elements.

- We solve the equations.
- We post process quantities according to our interest and plot the graph of it.

4.3. APPLICATION OF FINITE ELEMENT METHOD

In the following, we will give some examples of finite element applications. The range of applications of finite elements is too large to list, but to provide an idea of its versatility we list the following [36]:

- We can have stress and thermal analysis of electronic chips, electric devices, pipes, engines and aircraft.
- We can analyze seismic activities of dams, power plants, high rise and cities.
- We can analyze cars, trains and aircraft for crashing.
- We can analyze fluid flow in pollutants, air and coolant pond in ventilation systems.
- We can have electromagnetic analysis of antennas, optical fibers and transistors.
- We can also analyze surgical processes like plastic surgery, jaw reconstruction and many like these.

Chapter 5

DESIGN AND ANALYSIS OF PHOTONIC CRYSTAL FIBERS FOR SLOW LIGHT GENERATION

5.1. OVERVIEW

High data rates is the need of the time so fiber optics acts as a backbone of the current Telecommunication systems. Now technology is slowly switching from Electro-optic system to full Optical communication system for high data rates. One of the main problem for this is generation of Slow Light. There are various techniques to slow down light like Stimulated Raman Scattering (SRS), Stimulated Brillouin Scattering (SBS), Electromagnetically Induced Transparency (EIT), Coherent Population Oscillation (CPO) etc. We are using SBS phenomenon for slow light generation because of its various advantages as mentioned earlier. A commercial Finite element method (FEM) based software (COMSOL) is used for the simulations.

5.2. DESIGN OF PROPOSED PCFs

We have designed and analysed two PCF for slow light generation i.e.

- Hexagonal As_2Se_3 based Chalcogenide Solid core Photonic Crystal Fiber

We present a Solid Core PCF for slow light generation. Proposed PCF has hexagonal lattice pattern of Air holes in cladding region. Fig. 5.1 shows the cross sectional view of Proposed PCF. We have used same material for whole fiber i.e. As_2Se_3 based Chalcogenide. We have shown the Electric Field Distribution for fundamental mode at 1.55 µm in Fig. 5.2. We have taken diameter i.e. d, of air holes identical and is changed from 0.96 µm to 1.6 µm while Pitch i.e. Λ, is kept constant at 3.2 µm. In this PCF, we have both core and cladding region of As_2Se_3 based Chalcogenide. We have taken the refractive index of proposed PCF as 2.815.

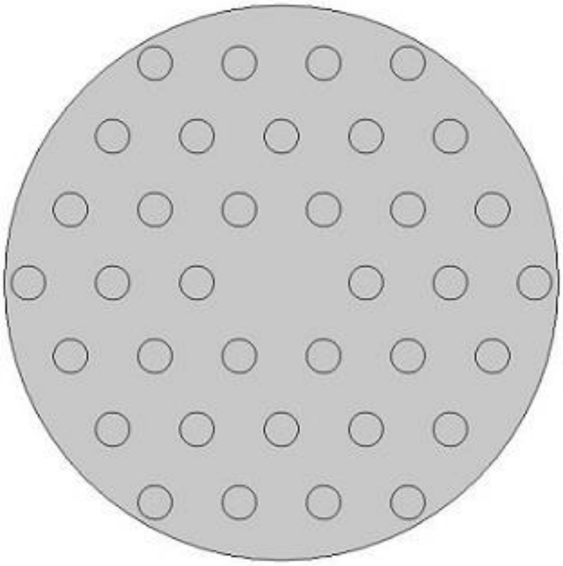

Fig. 5.1: Cross sectional view of Hexagonal Solid core PCF.

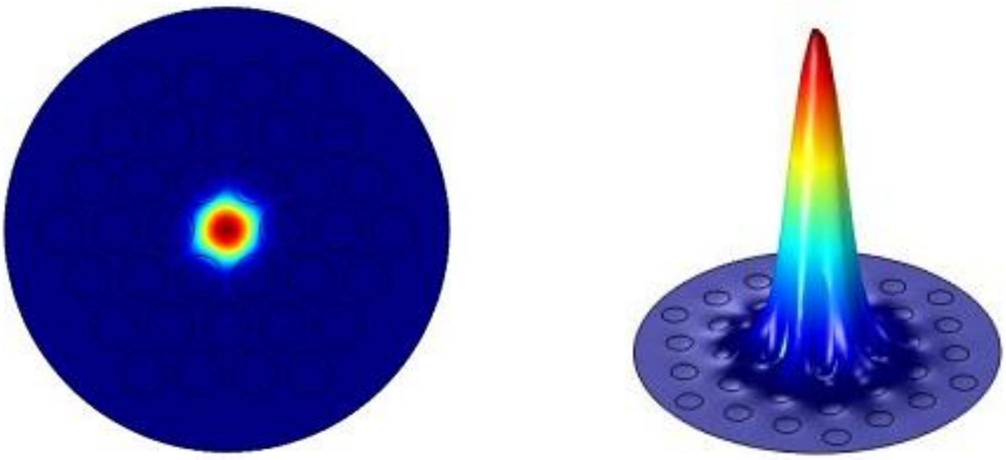

Fig. 5.2: Electric field distribution of Hexagonal Solid core PCF at 1.55 μm at $d/\Lambda = 0.4$.

- Decagonal Liquid Core Photonic Crystal Fiber

We present a Hybrid Solid core PCF for generation of slow light. Proposed PCF has decagonal lattice pattern of Air holes in cladding region surrounding a liquid filled core in the center of fiber. Fig. 5.3 shows the cross sectional view of Proposed PCF. We have used two different material for core and cladding region of fiber. Core is doped with highly non-linear liquid material i.e. Carbon disulfide (CS_2) with refractive index, n as 1.595 and cladding region is made of Silica glass with refractive index, n as 1.44. We have shown the Electric Field Distribution for fundamental mode at 1.55 µm in Fig. 5.4. The PML layer is taken to be 2 µm. We have taken diameter i.e. d, of air holes identical and is changed from 1.2 µm to 2 µm while Pitch i.e. Λ, is kept constant at 4 µm.

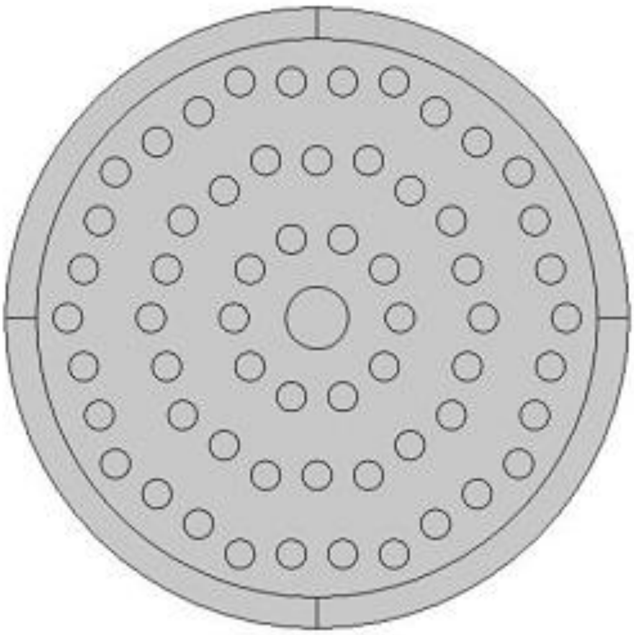

Fig. 5.3: Cross sectional view of Liquid core PCF.

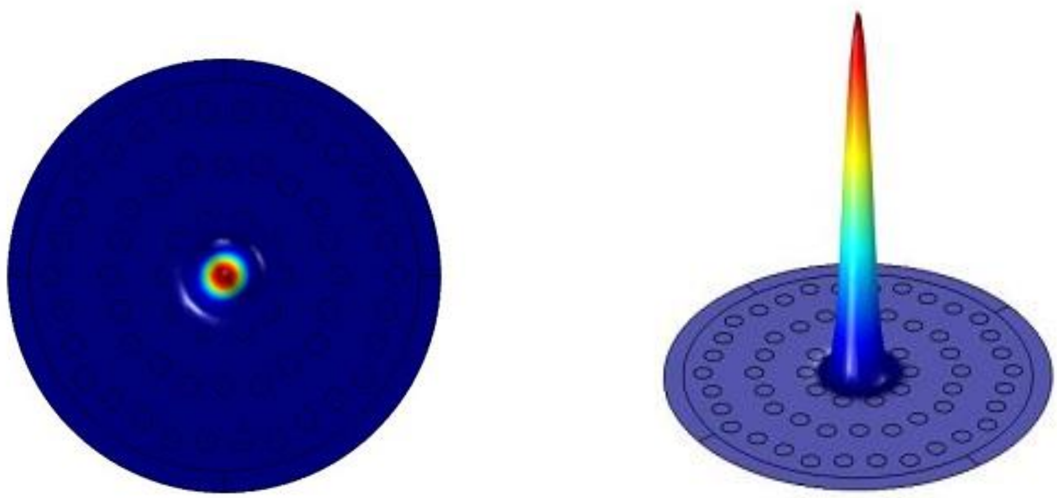

Fig. 5.4: Electric field distribution of Liquid core PCF at 1.55 µm at d/Λ = 0.4.

5.3. SIMULATED RESULTS AND DISCUSSION

We have designed two PCFs for our work and simulation of the proposed PCFs are done using COMSOL MultiPhysics.
Parameters used for our simulation are given below separately for the two PCFs.

- Hexagonal Solid-core Photonic Crystal Fiber
  Fiber Material Loss = 0.90 dB/m
  Polarization Factor = 0.667
  Brillouin Gain Coefficient, $g_B = 6.75 \times 10^{-9}$ m/W
  Brillouin Gain Bandwidth, Δv_B = 23MHz
  Refractive Index, n = 2.815
  Wavelength, λ = 1.55 µm

- Decagonal Liquid-core Photonic Crystal Fiber

  Core Region: Carbon disulfide (CS_2)
  Fiber Material Loss = 0.3 dB/m

Polarization Factor = 0.667

Brillouin Gain Coefficient, $g_B = 1.5 \times 10^{-9}$ m/W

Brillouin Gain Bandwidth, Δv_B = 21MHz

Refractive Index, n = 1.595

Wavelength, λ = 1.55 μm

Cladding Region: Silica (Si)

Fiber Material Loss = 0.2×10^{-3} dB/m

Polarization Factor = 0.667

Brillouin Gain Coefficient, $g_B = 5 \times 10^{-11}$ m/W

Wavelength, λ = 1.55 μm

Using above mentioned parameters, we have calculated major Optical Characteristics like Effective mode area, Maximum Pump Power, Minimum Pump Power, Confinement loss and Total Time Delay. We have taken d/Λ less than 0.5 as it ensures the Single mode operation in the PCF. These parameters are varied according to Air hole ratio i.e. d/Λ and these designs have been analyzed with Finite Element Method (FEM) with the help of software COMSOL Multiphysics and results have been plotted using MATLAB software.

5.3.1. Effective Mode Area

Effective mode area is very important parameter for slow light generation which is used for enhancement of non-linear effects in Photonic Crystal Fiber. Effective mode area is the measure of fiber non-linearity.

Effective mode area is controlled by air-hole diameter i.e. pitch (d/Λ). As we increase pitch, the effective mode area decreases because the core size of PCF reduces. We have plotted graph for the two PCF separately and also compared them with respect to pitch.

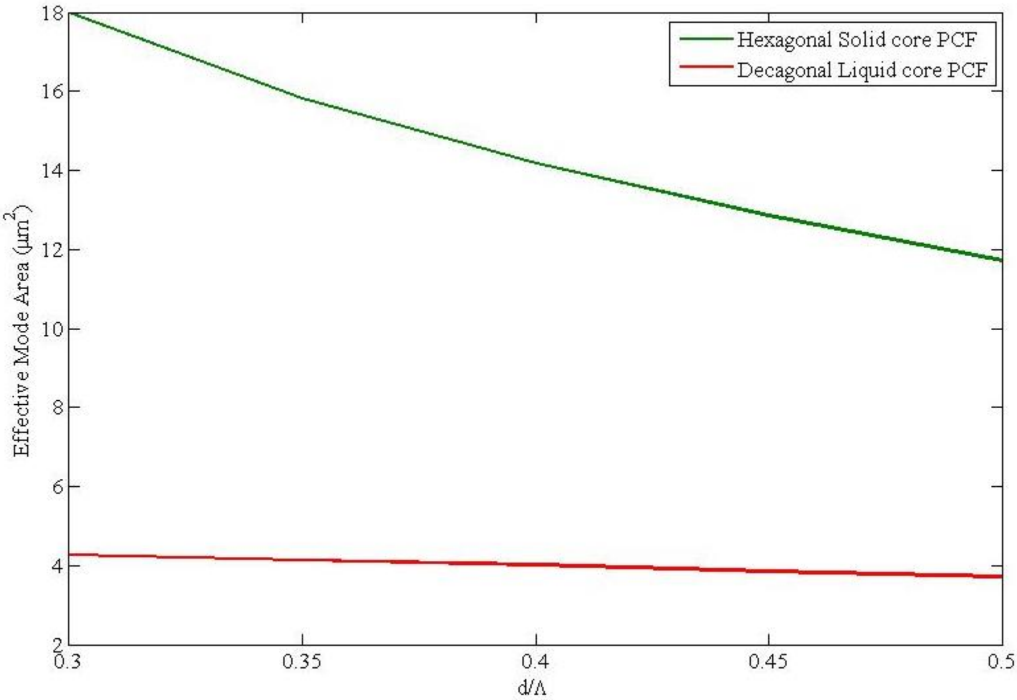

Fig. 5.5: Comparison of Effective mode area with *d/Λ*.

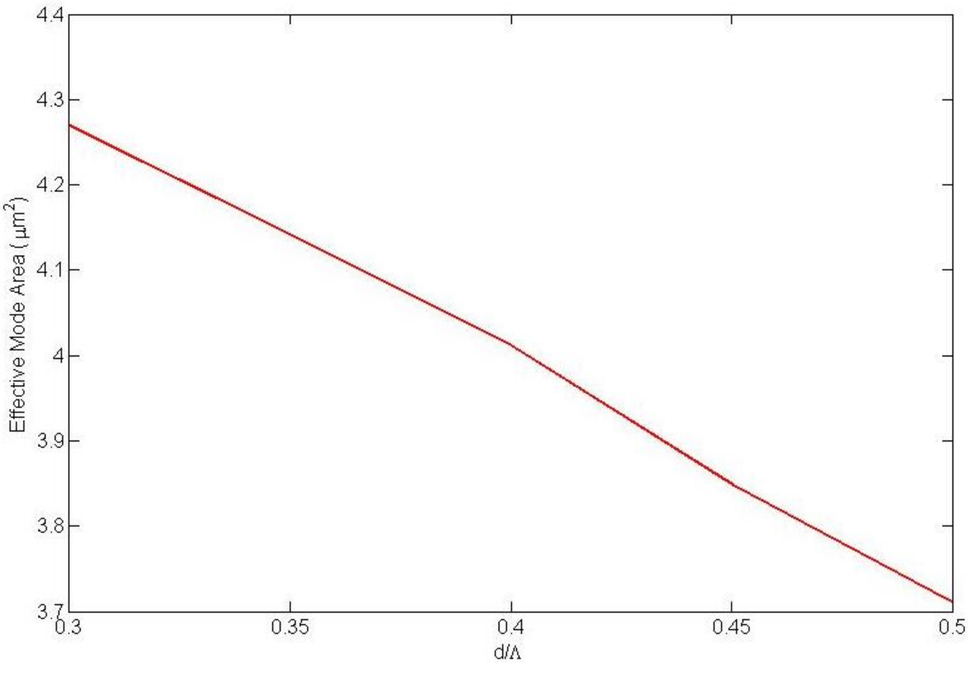

Fig. 5.6: Zoomed in view of Effective mode area variation with d/Λ for Decagonal Liquid core PCF

As we can see in the plot of Effective mode area with pitch i.e. d/Λ in figure, Effective mode area decreases as d/Λ increases i.e. from 0.3 to 0.5. We know Effective mode area and non-linearity are inversely related. So increasing d/Λ decreases Effective mode area and as a result, non-linearity increases.

On simulation, Effective mode area for fundamental mode is found to be 14.18 μm^2 for Hexagonal PCF and 4.012 μm^2 for Decagonal PCF for d/Λ = 0.4.

Hence on comparing the two plots and from the simulated result, we can infer that Decagonal Liquid core PCF has more non-linearity compared to Hexagonal Solid core PCF.

5.3.2. Maximum Pump Power

Maximum Pump Power is the pump power beyond which output will be distorted. When pump power reaches the maximum value, then backscattered wave is generated due to background noise which leads to distortion.

Maximum pump power depends on pitch i.e. d/Λ as can be seen from the graph plotted.

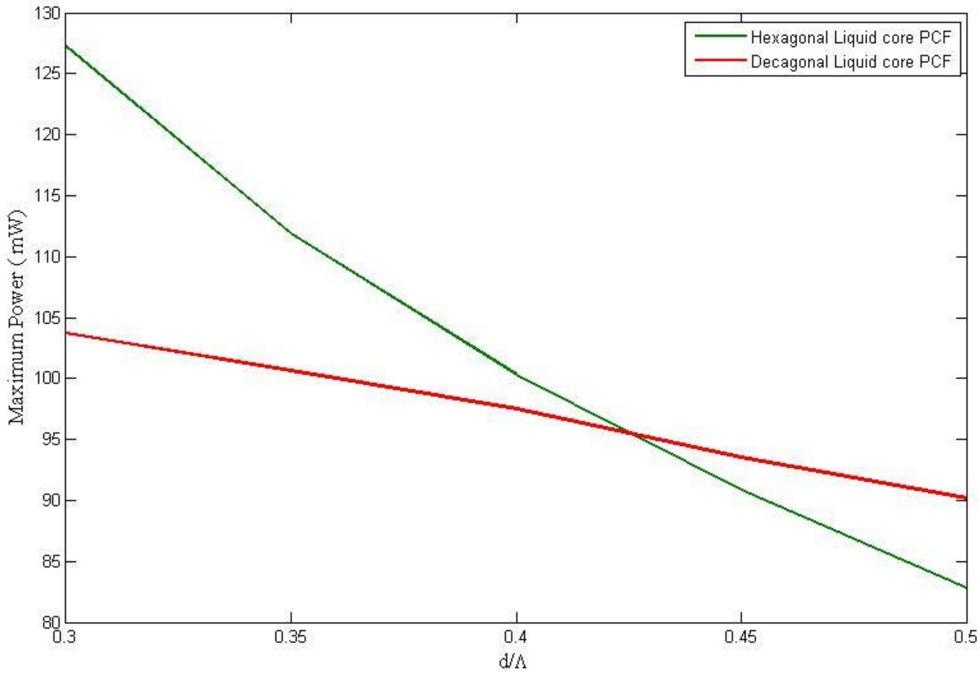

Fig. 5.7: Comparison of the variation of Maximum power with d/Λ.

As shown in Fig. 5.7, as d/Λ increases, Maximum Pump power decreases. It is because on increasing d/Λ, core area decreases and field is getting confined in smaller region.

Maximum pump power is found to be 127.3mW for Hexagonal PCF and 103.72mW for Decagonal Liquid core PCF by using equation (2.8).

5.3.3. Minimum Pump Power

Minimum Pump Power is the pump power below which PCF does not show non-linear effect i.e. SBS effect. It is the threshold power for initiating SBS effect.
Minimum power depends on pitch i.e. d/Λ as can be seen from the plot.

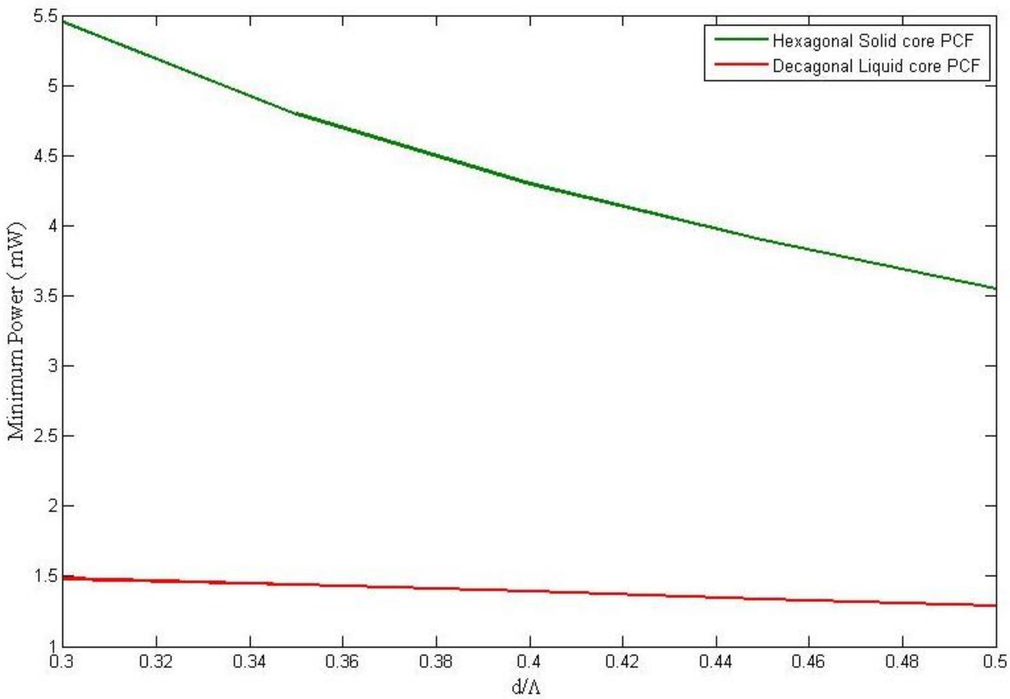

Fig. 5.8: Comparison of the variation of Minimum power with d/Λ.

As we can see from the graph plotted as shown in Fig. 5.8 that as d/Λ is varied from 0.3 to 0.5, minimum pump power decreases.
On simulation, Minimum pump power is found to be 3.55mW for Hexagonal PCF and 1.28mW for Decagonal Liquid core PCF by using equation (2.9).
As the results show that Decagonal Liquid core PCF is better than Hexagonal PCF because it shows the non-linear effect at much lower power.

5.3.4. Confinement Loss

Confinement loss is defined as the attenuation which is caused by waveguide geometry.
This is the loss which occurs exclusively in PCF.
We know that as confinement loss decreases, there is more confinement of light. So more field is confined in PCF. It has a result of increasing Brillouin Scattering which consequently enhances Brillouin gain.
We can see in the graph plotted as we increase the value of d/Λ from 0.3 to 0.5, Confinement loss decreases.

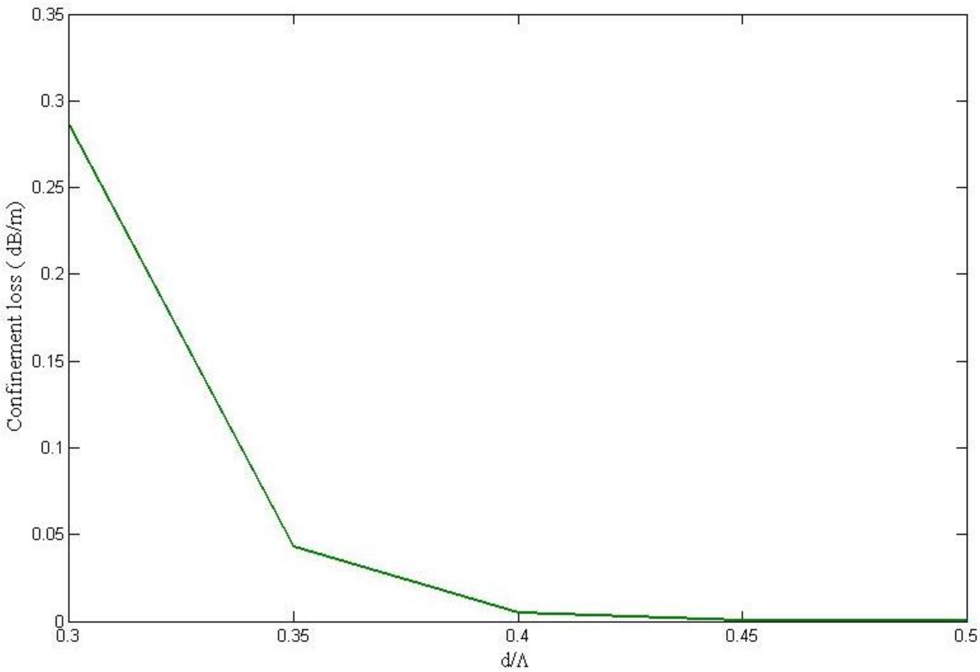

Fig. 5.9: Variation of Confinement loss with d/Λ for Hexagonal Solid core PCF

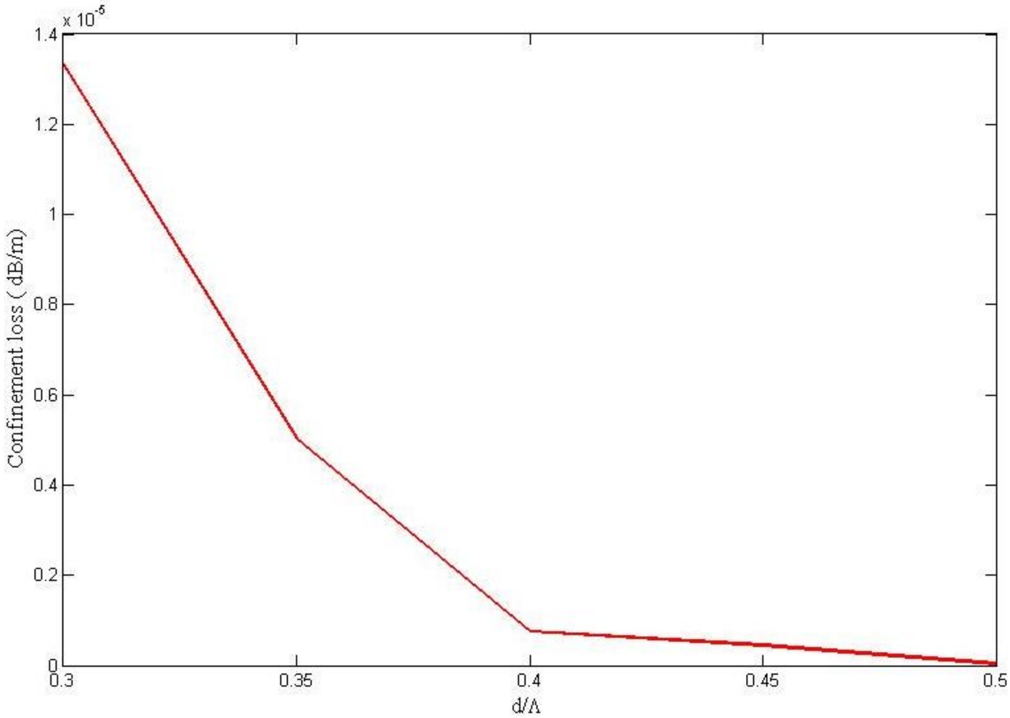

Fig. 5.10: Variation of Confinement loss with d/Λ for Decagonal Liquid core PCF

As we can see from the two graphs plotted that Confinement loss decreases as we increase the value of d/Λ from 0.3 to 0.5.

On simulation we found the confinement loss for Hexagonal PCF as 51×10^{-4} dB/m and for Decagonal Liquid core PCF as 0.75×10^{-6} dB/m for d/Λ = 0.4. We can clearly from simulated results that Decagonal Liquid Core PCF has very less confinement loss as compared to Hexagonal PCF.

5.3.5. SBS Induced Total Time Delay

Variation of Total Time delay with Pump Power is shown in Fig. 5.11.

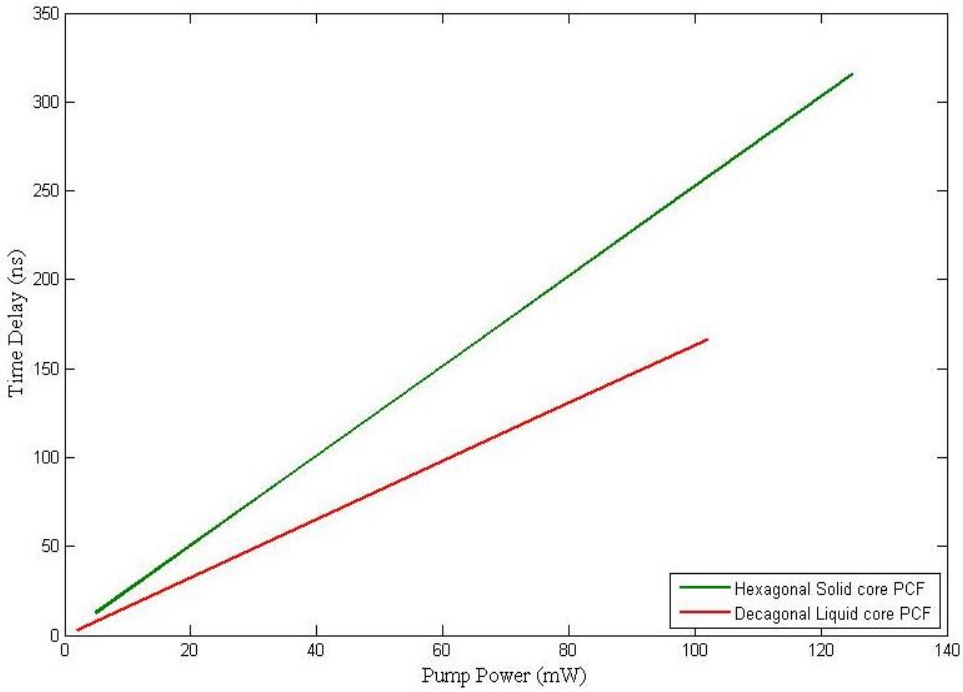

Fig. 5.11: Variation of Time delay with Pump power for the two PCFs

We have calculated Time Delay by using equation (2.10) for the two structures.

- Hexagonal As_2Se_3 based Chalcogenide PCF

  For this PCF, we calculated the maximum pump power and minimum power as 127.23mW and 3.55mW respectively. For these values, we calculated the change in time delay with pump power between 5mW and 125mW for 1m long PCF. On calculating, we found the maximum time delay of 316ns for input pump power of 125mW.

- Decagonal Liquid core PCF

  For this PCF, we calculated the maximum pump power and minimum pump power as 103.72mW and 1.288mW respectively. For these values, we calculated the change in time delay with pump power between 2mW and 102mW for 1m long PCF. On calculating, we found the maximum time delay of 166ns for input pump power of 102mW.

Chapter 6

CONCLUSION AND FUTURE SCOPE

For the future work we can use PCF in communication systems which can convert it into all optical communication system which can help us save money and extra circuitry needed for communication systems.

6.1. CONCLUSION

In this project, we have numerically modelled two PCF having different lattice pattern for slow light generation with tunable features. Table below provides an overview of this project with all the parameters calculated with their values.

Structure	Specifications	Parameters Calculated
Hexagonal	Core & Cladding = As_2Se_3 based Chalcogenide Operating wavelength = 1.55µm	Effective mode area = 14.18µm^2 Maximum power = 127.23mW Minimum power = 3.55mW Confinement loss = 51×10^{-4} dB/m Time delay = 316ns
Decagonal	Core = Carbon-disulfide (CS_2) Cladding = Silicon (Si) Operating wavelength = 1.55µm	Effective mode area = 4.012µm^2 Maximum power = 103.72mW Minimum power = 1.288mW Confinement loss = 0.75×10^{-6} Time delay = 166ns

We conclude that Decagonal Hybrid Solid core PCF has various attractive features compared to Hexagonal Solid core PCF and we have come to this conclusion on the basis of simulated results and graphs plotted.

Decagonal Hybrid Solid core PCF has advantage of drawing through high quality micro structured fiber which is not the case with the Hexagonal As_2Se_3 based Chalcogenide PCF. Chalcogenide is soft glass therefore it suffers from environmental degradation. In-spite of various advantages of Hexagonal structure, it is very difficult to design Hexagonal PCF with low confinement loss. Therefore other structures are proposed. So, in search of low confinement loss fiber, we have investigated Decagonal structure and we found that it has very low confinement loss i.e. 0.75×10^{-6} dB/m. Decagonal Hybrid Solid core PCF has low effective mode area i.e. high non-linearity which is desired. We have calculated total time delay for both our structures and plotted graph with respect to pump power. Power requirement for both the structure are low but Decagonal structure has comparatively low power.

6.2. FUTURE SCOPE

Slow light based SBS has wide potential application in optical communication systems. For slow light devices to be popular, we need to have better PCF parameters like large tenability range, low power utilization by lowering losses and compactness of the device. Research should be done for enhancing these parameters.

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List of Publications

- **R Kumar**, A Kumar, Stimulated Brillouin Scattering Based Tunable Slow Light in Hexagonal As_2Se_3 based Chalcogenide Photonic Crystal Fiber, IEEE International Conference on Photonics and High Speed Optical Networks (ICPHON 2018), ISBN 978-1-5386-3324-3

- **R Kumar**, P Chauhan, A Kumar, Slow light Generation in Decagonal Liquid Core Photonic Crystal Fiber, Frontiers in Optics/ Laser Science Conference (FIO/LS)

- **R Kumar**, P Chauhan, A Kumar, Decagonal Chalcogenide doped Photonic Crystal Fiber for Slow light generation, PHOTONICS 2018 The international Conference on Fiber Optics and Photonics (accepted).

Stimulated Brillouin Scattering Based Tunable Slow Light in Hexagonal $As_2 Se_3$ based Chalcogenide Photonic Crystal Fiber

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***Abstract*— In this paper, stimulated brillouin scattering-based tunable slow light in highly nonlinear Chalcogenide Photonic crystal fiber has been theoretically investigated. Time delay is calculated for d/Λ=0.4 for single mode operation. Maximum power (pump) and time delay have been calculated for fiber operating at 1.56 μm of wavelength. Change in effective mode area and confinement loss of the fiber are calculated for single mode operation.**

Keywords— Nonlinear optics; Photonics crystal fiber; stimulated Brillouin

I. Introduction

Slow light is to reduce the light propagation speed in the medium [1]. Reducing group velocity of light is Slow light. The velocity of light *c*, is approximately 3×10^8 ms^{-1} in vacuum. It can complete 7.5 round of the world in a second, and can cover 300 mm distance in 1 ns. High speed like this is advantageous for data transmission between two points but it is also difficult to control optical signals in the time domain. Slow light technology is now being seen as a solution to this problem [2]. There are many techniques to slow down light such as stimulated Brillouin scattering [3], stimulated Raman scattering [4], coherent population oscillation [5] and electromagnetically induced transparency [6]. SBS is preferred among all. PCF has varied applications in fiber-optic communications nonlinear devices, fiber lasers, amplifiers, high-power transmission, highly sensitive gas sensors, and other areas [7].

In this paper, we have designed and analyzed Hexagonal As_2Se_3 based Chalcogenide Photonic Crystal Fiber for tunable slow light application using SBS. PCF characteristics have been plotted for different values of d/Λ and simulated using software 'COMSOL Multiphysics'.

II. Design

Fig.1. shows the cross section of proposed PCF. Proposed PCF has air holes array in hexagonal pattern in As_2Se_3 based Chalcogenide glass. In our simulation we have taken the pitch at 3.2 μm and the radius is changed from 0.96 to 1.6 μm. We have taken d/Λ equal to 0.4 for single mode operation.

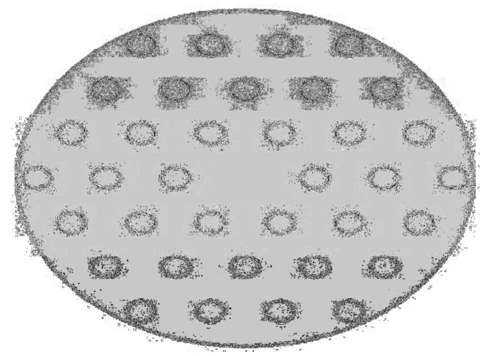

Fig. 1. *Cross section of proposed PCF*

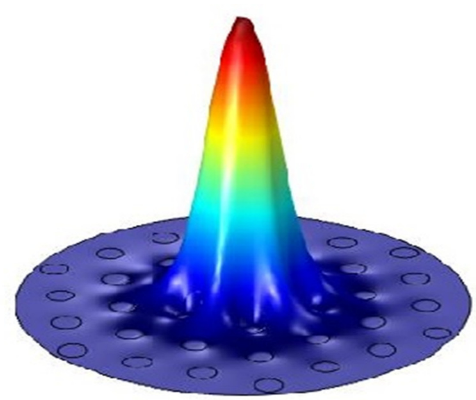

Fig. 2. *Distribution of electric field in Proposed PCF*

Distribution of electric field in the proposed Chalcogenide PCF is shown in *Fig. 2* at 1.56 μm and d/Λ = 0.4.

III. Results and discussion

The following parameters are used for simulation[8].: fiber material loss = 0.90 dB/m; the polarization factor, K = 0.667; the Brillouin gain coefficient, $g_B = 6.75 \times 10^{-9}$ m/W; Brillouin gain bandwidth, $\Delta\nu_B$ = 23 MHz ; Refractive index, n= 2.815

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and the length of the PCF= 1 m at 1.56µm. Using above-mentioned parameters, we have calculated Maximum Pump Power, Minimum Pump Power, Effective Mode Area, Confinement loss and Maximum Time Delay at d/Λ= 0.4 for our design.

A. Change in Effective mode area with respect to d/Λ

Effective mode area (A_{eff}) is varied with d/Λ as shown in *Fig.3*. On simulation, we found the effective mode area to be equal to 14.18 µm^2 at d/Λ = 0.4.

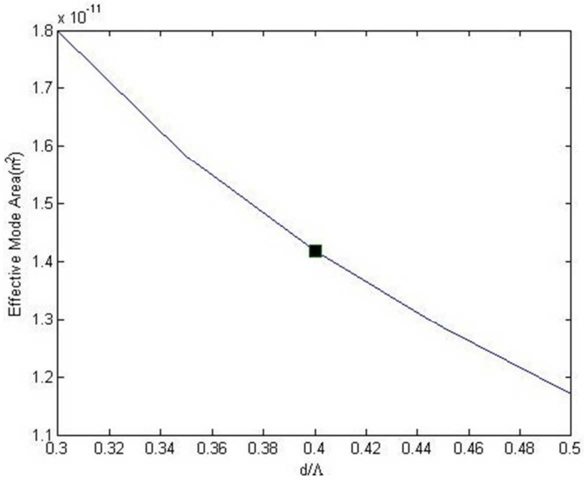

Fig. 3. *Change in Effective mode area with respect to d/Λ*

B. Change in Maximum power (pump) with respect to d/Λ

The core area decreases with the increase in d/Λ value, as a result small region confines the field thus further decreasing power handling capability of proposed PCF and eventually decreasing maximum power (pump) for proposed PCF. If the applied power (pump) is less than the maximum power (pump), undistorted pulse at output is obtained.

In *Fig.4*, the maximum power (pump) is varied from 127 mW to 83 mW when d/Λ changed from 0.3 to 0.5. On simulation, maximum power (pump) is found to be 100.32 mW at d/Λ = 0.4.

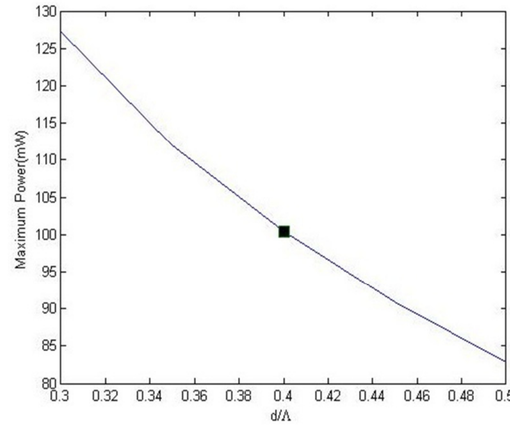

Fig.4. *Change in Maximum power (pump) with respect to d/Λ*

C. Change in Minimum power (pump) with respect to d/Λ

The Minimum power (pump) is the other name for threshold power for induction of stimulated Brillouin scattering. It is the power below which there is no non-linear effects. The minimum power (pump) variation is shown in *Fig.5* with increasing d/Λ value. On simulation, minimum power (pump) is found to be equal to 4.29 mW at d/Λ = 0.4.

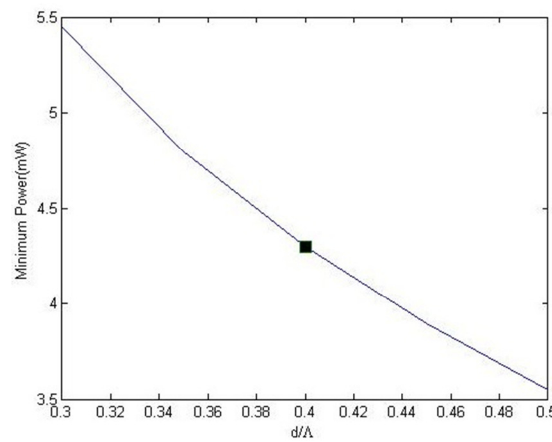

Fig. 5. *Change in Minimum power (pump) with respect to d/Λ*

D. Change in Confinement loss with respect to d/Λ

Confinement loss decreases with the increase of d/Λ value as shown in *Fig. 6*. The confinement loss is found to be 0.00511 dB/m at d/Λ = 0.4.

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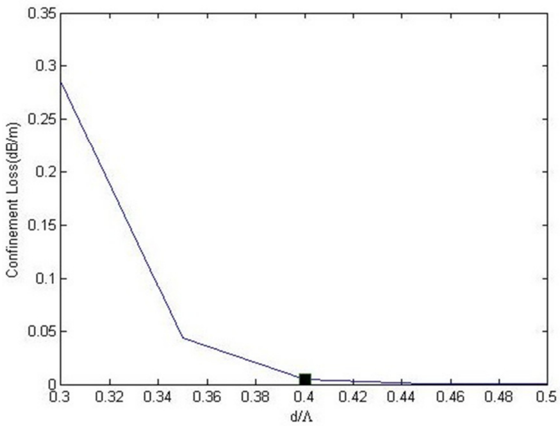

Fig. 6. *Change in Confinement loss with respect to d/Λ*

E. Change in Time delay with respect to Pump power

For single mode operation, the maximum and the minimum power (pump) for SBS operation is found to be P_{max} = 127.3 mW and P_{min} = 3.55 mW. For these values we have calculated the change in time delay for input power (pump) ranging between 5 mW to 125 mW. Time delay (maximum) is found to be 316 ns at input power (pump) of 125 mW. The time delay is varied with the pump power as shown in *Fig. 7*.

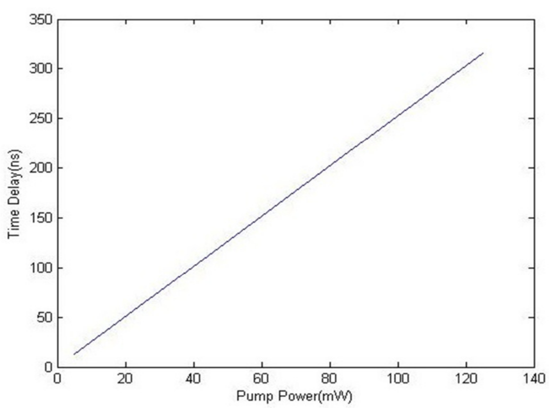

Fig. 7. *Change in Time delay with respect to d/Λ*

IV. CONCLUSION

. In conclusion, proposed PCF which is based on SBS, has been designed and analyzed with tunable features for the generation of slow light. The effective mode area and confinement loss variation have been plotted. The maximum and the minimum power (pump) have been found numerically. The maximum time delay of 316 ns has been obtained for the proposed PCF.

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Slow Light Generation in Decagonal Chalcogenide doped Photonic Crystal Fiber

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Abstract: As_2Se_3 based decagonal PCF has been designed for purpose of generation of slow light with As_2Se_3 as base material. Confinement loss is calculated and time delay of 333.47 ns is obtained for our structure at 1.55µm.

OCIS codes: (060.4370) Nonlinear optics, fibers; (190.5890) Scattering, stimulated; (290.5900) Scattering, stimulated Brillouin.

Introduction:

When light propagation speed is reduced in a medium, the light is termed as Slow light [1]. Many techniques can be used such as stimulated Brillouin scattering [2], stimulated Raman scattering [3], coherent population oscillation [4] and electromagnetically induced transparency [5]. SBS is favored over other methods.

In this paper, a decagonal-shaped liquid core PCF has been designed as shown in Fig 1. The modelling has been done using COMSOL Multiphysics Software.

Design of PCF:

A decagonal liquid core photonic crystal fiber has been designed with pitch at 4 µm and diameter of air holes is varied from 1 µm to 1.8 µm as shown in Fig 1. Perfectly matched layer (PML) of thickness 2 µm is used. The electric field distribution of PCF is shown in Fig 2. The carbon-disulphide parameters used for simulation are [6]: fiber material loss, α = 0.3 dB/m; the Brillouin gain coefficient, g_B = 1.5 × 10-9 m/W; Brillouin gain bandwidth, $\Delta\nu_B$ = 23 MHz; Refractive index, n= 1.595.

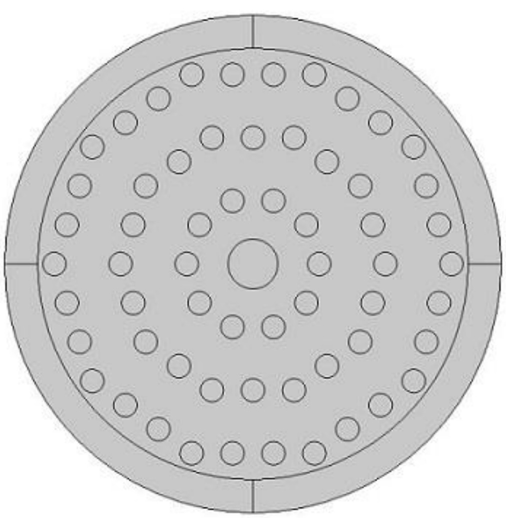

Fig 1: Cross-section of Decagonal Structure

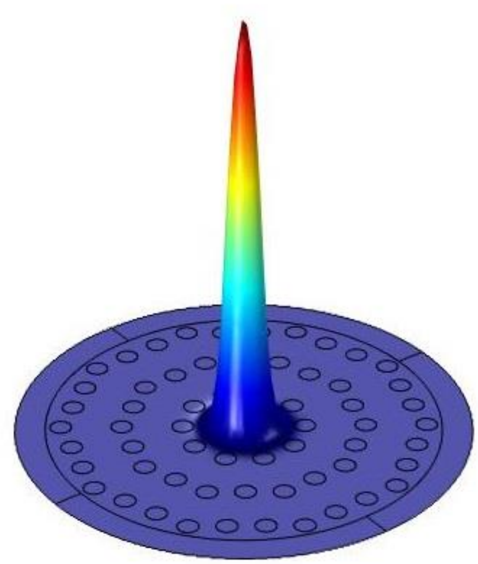

Fig 2: Electric field distribution at 1.55µm

Simulated results:

Fig 3 shows the confinement loss variation with d/Λ. The confinement loss has been calculated at d/Λ = 0.35 and is found to be 0.75 * 10^{-6} dB/m. Fig 4 shows the time delay variation with d/Λ. We have calculated time delay variation for input pump power from 2 mW to 102 mW and is found to be 166.70 ns. The different parameters of proposed PCF like maximum pump power, minimum pump power and effective mode area have been analysed.

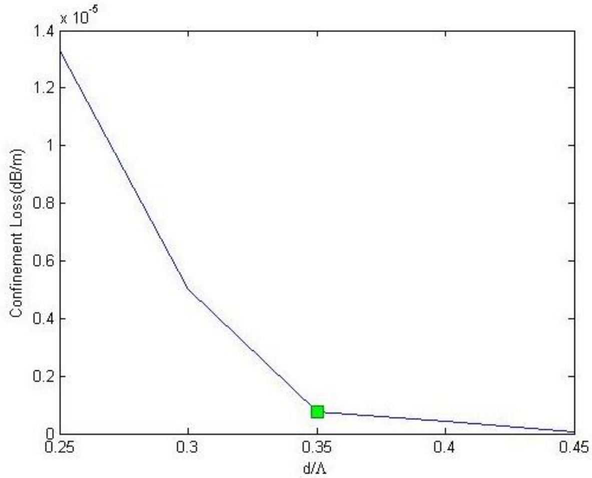

Fig 3: Variation of Confinement loss with d/Λ

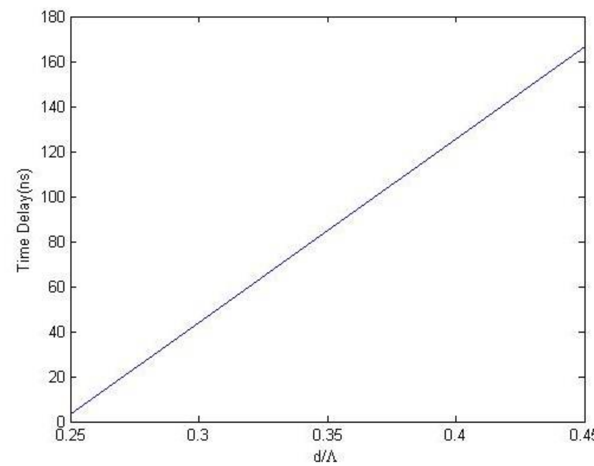

Fig 4: Variation of Time delay with d/Λ

Conclusion:

The proposed PCF has been successfully designed and analysed. Maximum time delay of 166.70 ns is obtained for 1m long liquid core fiber for the pump power of 102 mW. The simulated results show that proposed PCF has been successfully designed with tunable features.

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Decagonal Chalcogenide doped Photonic Crystal Fiber for Slow light generation

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Abstract: As_2Se_3 based decagonal PCF has been designed for purpose of generation of slow light with As_2Se_3 as base material. Confinement loss is calculated and time delay of 333.47 ns is obtained for our structure at 1.55µm.
OCIS codes: (060.4370) Nonlinear optics, fibers; (190.5890) Scattering, stimulated; (290.5900) Scattering, stimulated Brillouin.

Introduction:

Slow light is defined as the process in which we reduce the group velocity of light [1]. There are different techniques for slowing down light like stimulated Brillouin scattering [2], stimulated Raman scattering [3], coherent population oscillation [4] and electromagnetically induced transparency [5]. SBS is preferred over all other techniques.

In this paper, we have designed decagonal array of air holes for our proposed photonic crystal fiber as shown in Fig 1. Proposed fiber has been modelled using COMSOL Multiphysics Software.

Design of PCF:

Proposed fiber has pitch of 4 µm and air holes diameter is changed from 1 µm to 1.8 µm as shown in Fig 1. Perfectly matched layer (PML) is of 1.8 µm. Field distribution of proposed PCF has been shown in Fig 2. The As_2Se_3 based chalcogenide parameters are given here that are followed for simulation [6]: fiber material loss, $\alpha = 0.9$ dB/m; the Brillouin gain coefficient, $g_B = 6.75 \times 10^{-9}$ m/W; Brillouin gain bandwidth, $\Delta\nu_B = 13.2$ MHz; Refractive index, n= 2.815.

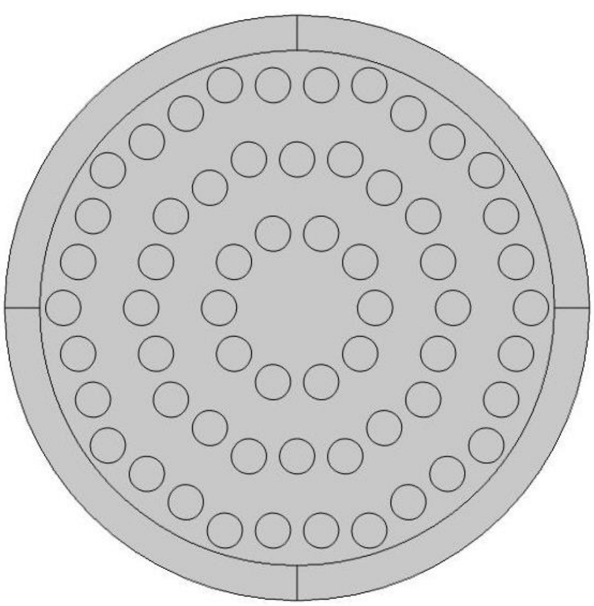

Fig 1: Proposed PCF cross sectional view

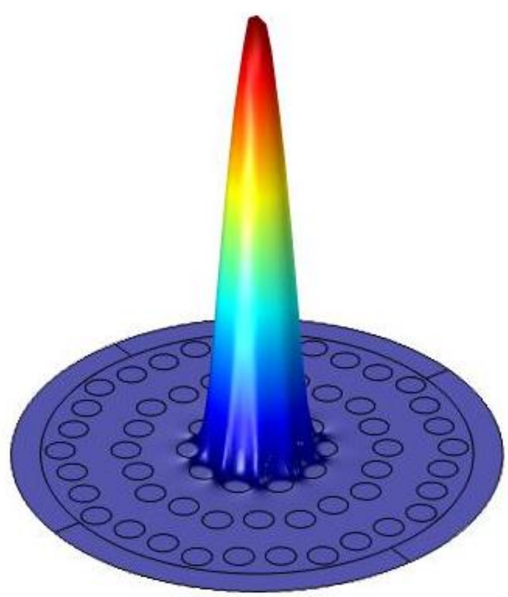

Fig 2: Electric field distribution at 1.55µm

Simulated results:

Fig 3 depicts the variation of confinement loss with d/Λ. We have calculated confinement loss to be 1.393×10^{-7} dB/m at 0.4 pitch ratio. Fig 4 depicts the variation of time delay according to d/Λ. Time delay is calculated by changing the pump power from 5 mW to 165 mW which is measured as 333.47 ns. Various parameters like maximum pump power, minimum pump power and effective mode area have been analysed and calculated.

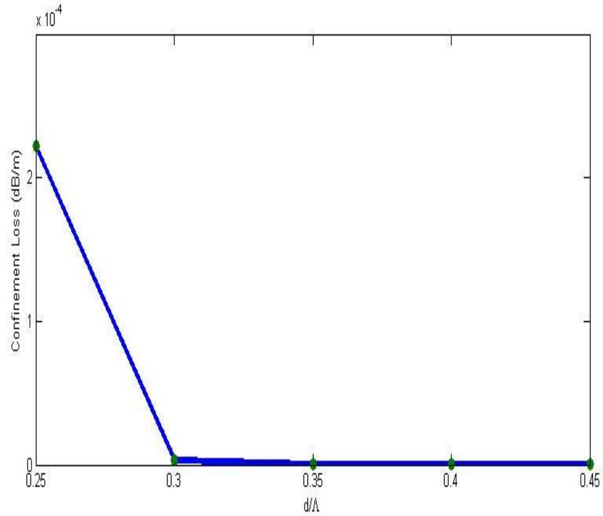

Fig 3: Confinement loss variation with d/Λ

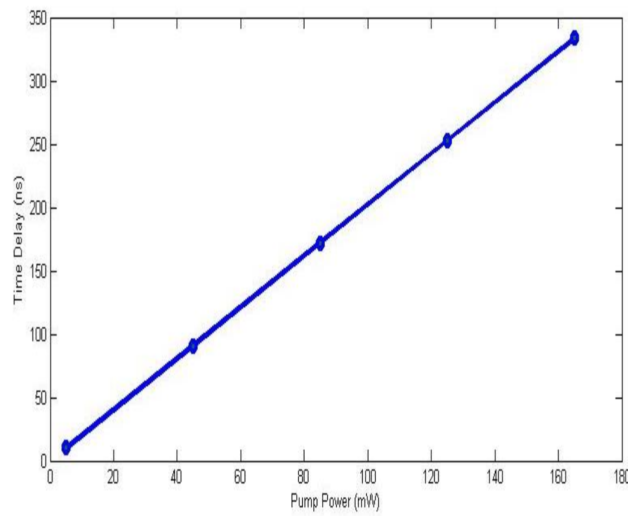

Fig 4: Time delay variation with d/Λ

Conclusion:

We have designed our PCF successfully with careful designing and analysis of our structure according to different parameters. For our structure, we have calculated maximum delay of 333.47 ns for fiber of 1 m length and this delay is calculated for maximum power of 165 mW. Results shows that proposed structure is good for generation of slow light with tuning features.

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