Design and Simulation for Highly Nonlinear Solid-Core Photonic Crystal Fiber

Arati Kumari Shah, Rajesh Kumar

ABSTRACT--- ***This paper manages a novel structure of solid-core photonic crystal fiber (PCF) which compares the PCF characteristics. For example, chromatic dispersion, effective area, loss of confinement and non-linearity using Comsol Multiphysics software focused on finite element method (FEM). The simulation results shows that proposed PCF exhibits high nonlinearity of 0.51927 m2/watt at the working wavelength 0.5µm along with maximum number of zero dispersion wavelength (ZDW), low effective area of 6.78*10-13 m2 and very less confinement loss of 6.96*10-9 1.35µm for R=0.9(diameter pitch ratio). Hence, the described PCF is highly nonlinear and minimum dispersion which makes it useful for various applications like supercontinuum generation, biomedical imaging etc.***

Keywords - Solid-Core Photonic Crystal Fiber, Zero Dispersion Wavelength, Non Linear Coefficient, Effective Mode Area, Confinement Loss, Comsol Multiphysics.

I. INTRODUCTION

During the 1990s, PCF advancement and investigation of the wide scope of potential applications pulled in gigantic premium. Photonic precious stone strands (PCF) are a propelled variant of optical filaments with various refractive lists utilizing a miniaturized scale organized material game plan. Much of the time un-doped silica and low list region are the foundation material, commonly given via air voids running along the fiber length [1]. PCF limits light through an empty or strong center utilizing distinctive natural optical properties of falsely made intermittent gem as a cladding utilizing different materials, for example, silicon or polymers with normal/sporadic geometric structures. PCF direct the light by methods for one of two systems: effective indexing direction and photonic-band-gap (PBG) direction. In the viable list PCF, the powerful refractive file of the composite material is lesser than the refractive record of the higher list material, which trends it possible to trap the light in an inside area encircled from the higher-list material by the methodology of complete inside reflection (TIR).Such strands show wide wavelength extend which can be utilized to transmit ultra-short pulses, twist misfortune edge at short wavelengths, and strange scattering properties at obvious and close infrared wavelengths [2].

Then again, just at least one discrete spectra groups comparing to the photonic crystal band-gap are guided by PCF dependent on PBG impact. The modes of guidance are less effective than the cladding region's index. PCF based on the PBG effect is equipped for controlling light guidance within a specific frequency band. PCF produced using un-doped silica creates low misfortunes, keeps up elevated amounts of influence and temperature, and withstands atomic radiation. Such PCF demonstrates developing enthusiasm for a scope of detecting, flag preparing and optical correspondence frameworks applications.

By balance of a few parameter in air openings, for example, plan, pitch, distance across, shape and the refractive index of the fiber material which permits to get attractive ptical properties like endlessly single mode activity, extensive optical non linearity, high birefringence, bearable scattering, expansive optical property.

II. FIBER DESIGN:

The proposed PCF model was designed with circular geometry with regular air gaps lattice arrangement. Two parameters can describe this type of arrangement: pitch, range (periodic length between air holes) and filling term d / range (ratio of air gap size to pitch).Various fascinating PCF properties result in the level of opportunity accessible in structuring pitch and filling factor. In the fiber, the center is encompassed by four progressive hexagonal example rings of air openings with radii 0.4µm, as can see in Fig. 1

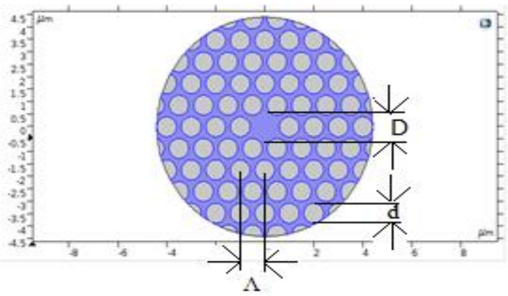

Fig.1. Solid-Core PCF schematic diagram. Air holes are the white circles and silica glass is represented in the blue regions.

In Fig. 1, the PCF comprises of a lacking air gap in the middle of diameter is meant by 'D' and the pitch is named as 'Λ' which estimates the separation among the focuses of the neighboring air gaps. The air-gap measure is named as d/Λ.

III. MODELING AND ANALYSIS

A. Modeling:

Comsol Multiphysics 5.3 has modeled the PCF, following steps in order shown in Fig.2.

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Arati Kumari Shah, Scholar, Department of ECE, NERIST, Itanagar, Arunachal Pradesh, India. (E-mail: arati.shah20@gmail.com)

Rajesh Kumar, Faculty, Department of ECE, NERIST, Itanagar, Arunachal Pradesh, India. (E-mail: itsrk2006@gmail.com)

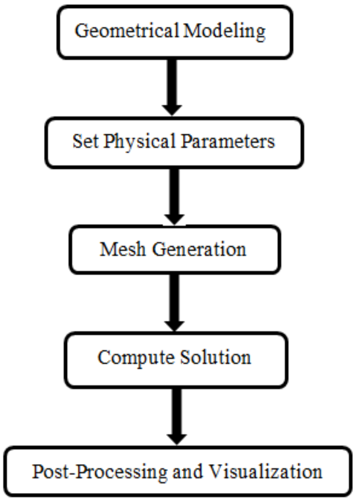


Fig.2 Flowchart for modeling of PCF in Comsol Multiphysics 5.3.

A proposed PCF with round geometry with fitting parameters is intended for geometric demonstrating. In the subsequent stage, utilize the Sellmeier condition to determine the physical parameters, for example, the wavelength of light utilized and the refractive record of air-gaps and silica. This is trailed by construction of triangular mesh. The powerful fiber file is in this manner determined utilizing Comsol's Finite Element Method (FEM) to comprehend the claim esteem condition for every one of these triangular meshes. Finally, post-processing and visualization tools are used to interpret the results. This includes generating different graphs and plots of fields. Optical waveguide analyzes are based on Maxwell's equation [3] [4].

B. Finite Element Method (FEM):

FEM is a numerical technique for finding estimate solutions of partial differential equations (PDE) as well as integration equations. This method approximates the PDE as an ordinary differential equation system that can be solved by different numerical techniques separately.

It subdivides the object into elements of very small but finite length. This process is called ‘meshing’ and is showing in fig.3 for the proposed PCF. Each mesh component is a set of characteristic equations shall be governed that describe the effective mode index of the fiber-supported modes in its calculation.

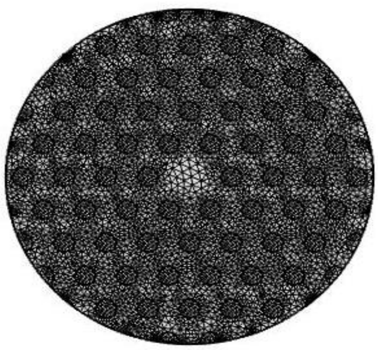


Fig.3. PCF with triangular mesh

IV. KEY PARAMETERS

1. Effective mode index (n_{eff}):

Efficient FEM using commercial full vector finite element software i.e COMSOL Multiphysics 5.3 is utilize to determine the structural features of the defined PCF. To model the leakage and no reflection at the boundary, perfectly matched layer (PML) boundary condition is used. From Maxwell’s curl formula the following vectorial equation is formed

$$\nabla \times ([s^{-1}]\nabla \times E) - k_0^2 n_{eff}^2 [s]E=0 \qquad ...(1)$$

Here E is the intensity of electric field; k_0 is the wave number in the vacuum; [s] introduces the PML matrix; n_{eff} stands for the effective refractive index, the effective refractive index of the base mode is defined as $n_{eff} = \beta/k_0$, where β is the propagation constant. Note that not only the wavelength, but the mode of propagation of the light depends on the effective refractive index. That's why it's also called the modal index. Obviously, the effective index isn't only a material property, yet relies upon the waveguide's whole plan [5].

2. Effective Mode Area:

Effective mode area (A_{eff}) of the PCF is given by the corresponding equations [6]:

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

Here E is the electric field amplitude. The integration is done over the center zone, yet over the entire plane surface. A significant impact of a small effective mode area is that the optical intensities for a defined power level are maximum, making nonlinearities significant.

Small mode region are also generally the result of strong guidance, where bend losses and other external disturbance defects are very weak. If two fiber having various effective mode areas are spliced collectively, It will direct to a few optical power loss call as splice loss. For proficiently coupling strands with generously unique mode territory, certain mode measure converters are once in a while utilized.

Chromatic Dispersion:

Chromatic dispersion is generated by the combined dispersion effects of waveguide and material. In the event of positive dispersion, smaller fibers propagate faster than larger wavelengths. In the other situation of negative dispersion, this system is regarded as normal. For down to earth applications to optical correspondence frameworks, straight and non-direct optics and scattering remuneration, controlling chromatic scattering in PCF is a basic issue. The chromatic dispersion, D [7]:

$$D = -\frac{\lambda}{c}\frac{d^2 \mathrm{Re}[n_{eff}]}{d\lambda^2} \qquad ...(3)$$

Here n_{eff} is found by using the Sellmeiers formula:

$$n^2(\lambda) - 1 = \frac{b_1\lambda^2}{\lambda^2 - a_1} + \frac{b_2\lambda^2}{\lambda^2 - a_1} + \frac{b_3\lambda^2}{\lambda^2 - a_1} \quad \text{…(4)}$$

Where $b_{1,2,3}$ and $a_{1,2,3}$ are the experimentally determined Sellmeiers cofficients.[8]

2. Confinement loss:

Loss of confinement is a phenomenon that penetrates the cladding area as part of the guided light. It occurs mostly in single-material fibers. PCF is generally made of pure silica and therefore the guided modes are intrinsically broken since the core index is equivalent to the as the outer cladding index without air holes. In the core area, light guidance is due solely to a limited number of layers of air holes in mass silica reaching out to infinity, considering that the PCF jacket is a long way from cladding and core regions [9].

The confinement loss (Lc) of the fundamental mode is determined from the nonexistent piece of the complex effective index (n_{eff}):

$$L_c = \frac{40\pi}{\ln(10)\lambda} \mathrm{Im}(n_{eff}) \quad \text{…(5)}$$

Where Im is the imaginary part of the n_{eff}.

5. Non-linearity

Non-linear coefficient of photonic crystal fiber represents very important property during SCG analysis. Nonlinear coefficient (γ) is directly proportional to nonlinear refractive index (n_2) and contrarily corresponding to the effective area (A_{eff}). The non-linear coefficient of PCF is given by the following equations [9]:

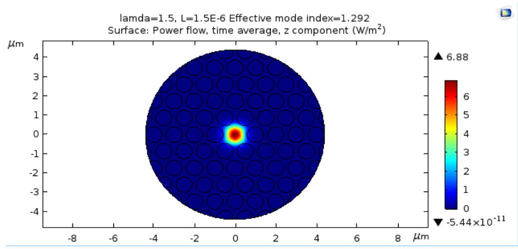
$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \quad \text{...(6)}$$

In particular, the impacts identified with the $\chi(3)$ nonlinearity – Kerr impact, Brillouin dispersing, Raman dissipating are regularly huge, in spite of the generally frail natural nonlinear coefficient of silica: it is possible that they go about as fundamental non-linearites for accomplishing certain capacities, or they comprise restricting impacts in high-power fiber speakers and lasers.

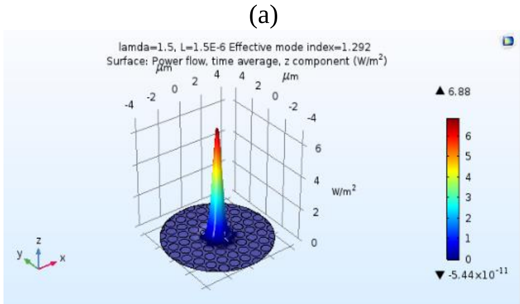
If we limit its mode confinement then the non-linearity could be gained in any fiber. By mixing light mode confinement the considerably higher values of γ can be accomplished by using non-silica glasses with higher intrinsic material non-linearity coefficients than silica.

V. SIMULATION AND RESULTS

FEM has been utilized for the mode analysis of a photonic precious stone fiber shaped by four rings structure with a hexagonal plan of roundabout air gaps on the cladding of unadulterated silica. The simulated output for the proposed design is given in Fig.5 which speaks to a very restricted light bar. The diagrams of different PCF parameters are plotted inside a wavelength scope of 0.5μm to 1.5μm.[10].



(a)



(b)

Fig.4 (a) Intensity profile of the proposed PCF design (b) 3D view of designed PCF

A. Graphical Results:

1. Plot of Effective mode index:

The value of effective mode index was obtained directly after simulation. It varies with wavelength. It is clear from the diagram that the effective mode index is decreasing with increasing wavelength as shown in Fig.5. If increases its ratio R (d/Λ) then its effective mode index is decreases. As a result it decreases its dispersion.

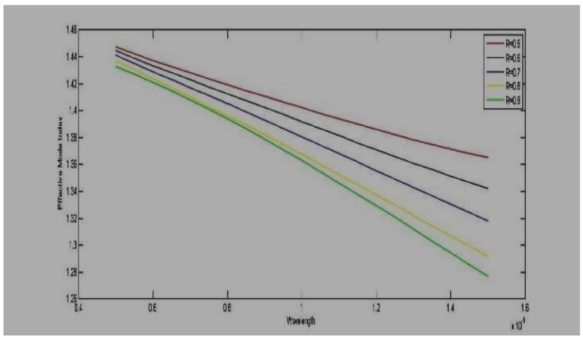


Fig.5 Plot of Effective Mode Index against Wavelength

2. Plot of Confinement Loss:

The confinement loss of PCF has been described by utilizing the imaginary part of the effective mode index. It varies regarding the wavelength as shown in Fig.6. Light is found to be maximally confined to the core at a wavelength of 1350 nm for R=0.8 as shown in graph.

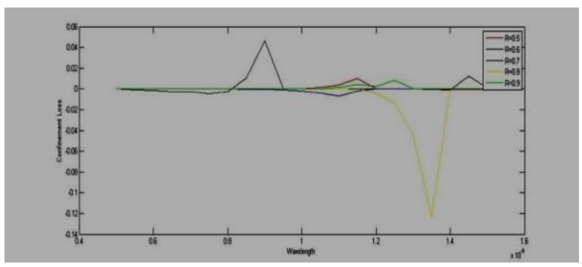


Fig.6. Plot of Confinement Loss against Wavelength

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3. Plot of Chromatic Dispersion:

Dispersion generally increases as the wavelength increases, but, when we take small difference in wavelength, there is fluctuation in dispersion. Due to which we got maximum number of zero dispersion wavelength (ZDW) that is found in R=0.9 at various frequency as shown in Fig.7.

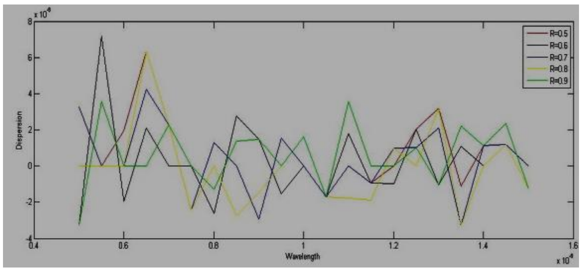

Fig.7 Plot of Dispersion against Wavelength

4. Plot of Effective Mode Area:

Effective area exhibits a generally increasing trend to increasing wavelength. From Fig. 8, we could figure out that the effective mode area decreases with increases ratio R (d/Λ). The minimum effective area of 6.78*10^{-13} m^2 was obtained at 0.5μm for R=0.9 and a maximum of 5.87*10^{-12}m^2 was obtained at 1.5μm for R=0.5.As wavelength increases, power density decreases and so the effective mode area increases.

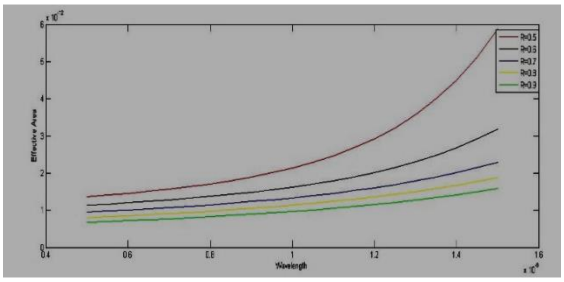

Fig.8. Effective mode area against Wavelength

5. Plot of Nonlinear Coefficient:

The relationship between nonlinear coefficient and wavelength and A_{eff} could be obtained according to eq. (2) where the wavelength through both mode field radius and A_{eff}, a fact that must be taken into account in broadband nonlinear applications.

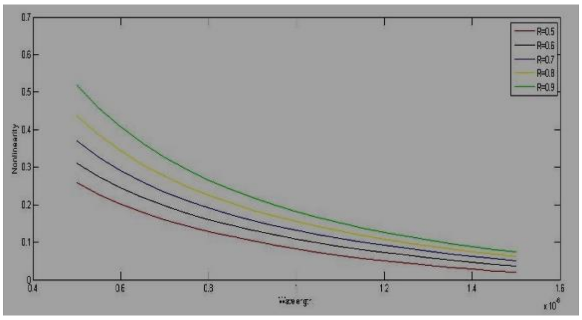

Fig.9. Nonlinearity against Wavelength

VI. CONCLUSION

We have designed simulated solid core PCF with four rings hexagonal structure using FEM. Simulation output of the effective mode index, chromatic dispersion, confinement loss, effective mode area, and nonlinear coefficient of the fiber are presented and compared with various ratio from R(d/Λ) =0.5 to 0.9. We found that the results for R(=0.9) is best as compare to others. It is highly nonlinear which is useful for various applications like supercontinuum generation, biomedical image etc.

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