Novel Butterfly Photonic Crystal Fiber Structure with Negative Dispersion and High Non-Linearity

Sabrina Abedin,[a]* Avijit Hira,[a] Sayeb Mohammad Tadvin,[b]
[a]Department of Electronics and Telecommunication Engineering, Chittagong University of Engineering & Technology, Chittagong, Bangladesh.
[b]Department of Electrical and Electronic Engineering, Chittagong University of Engineering & Technology, Chittagong, Bangladesh.

Abstract. Design flexibility and enormous optical properties of Photonic Crystal Fiber (PCF) suited for different types of applications have influenced researchers and engineers in enhancing present drawbacks. Photonic crystal fiber is based on periodic morphological microstructure of air-holes where different arrangement of air holes led to different types of structures. Several types of structures with different shapes like Hexagonal, Octagonal, Honeycomb, Circular etc. have been proposed earlier. In this research, a novel PCF structure is proposed with butterfly geometry being inspired by natural form of PCF. To validate the performance of the new design, optical properties like dispersion, confinement loss and high nonlinearity are extracted with satisfactory results. COMSOL Multiphysics is used as modelling and simulation environment. To achieve negative dispersion -1.56x10^4 ps/km.nm at 1550nm, holes diameter and their spacing are considered accordingly. Multiple defect holes as well as elliptical core make the structure asymmetric which exhibits high nonlinearity of $42.7W^{-1}Km^{-1}$ at the operating wavelength 1550nm. High nonlinearity with negative dispersion makes the proposed structure suitable for telecommunication applications also in long distance data transmission, super-continuum generation, fiber sensor design and as Dispersion Compensating Fiber (DCF) etc.

Keywords: optics, photonics, light, lasers, templates, journals.

***** Correspondence Author**,** E-mail: sabrina@cuet.ac.bd

1 Introduction

In worldwide optical field research, Photonic Crystal Fibers (PCFs) are a new up-and-comer in this line of research, which have the potential to revolutionize optical fiber technology. From lenses to optic wires, one always seeks to further improve both our understanding and control of photonic phenomena. The Photonic Crystal fiber (PCF) which is also known as micro-structured or holey fiber, exhibits enormous unique properties due to its unprecedented degrees of freedom for choosing design parameters [1]. Design parameters like variety of hole arrangements, holes diameter, pitch distance (^), geometry and the air holes position etc. give the PCF structures flexibility to design for a required application [2]. Unrivalled properties of PCF such as dispersion control, less confinement loss, Endless Single Mode (ESM) operation, controllable birefringence, a high degree of nonlinearity, controlled effective area etc. are liable to be used in many applications of communication field for secured and high data transfer, in high power fiber lasers, fiber amplifiers, non-linear devices, optical sensors which is useful in biomedical applications, Wavelength Division Multiplexing (WDM) and in Super-continuum generation [3,4].These promising features of PCF attract the researchers attention to work on many PCF structure for different application with different strategy like solid core PCF [5], circular PCF supporting 26 OAM modes [6], hexagonal and spiral lattice PCF [7], honeycomb lattice structure and triangular cladding structure [8], dispersion compensating fiber [9]etc.

Light guiding mechanism inside the PCF is either modified total internal reflection (TIR) or photonic band-gap guidance. PCF design with a core material of higher refractive index than the cladding effective refractive index is known as index-guiding PCFs, where light is guided through a form of total internal reflection (TIR). In contrast to traditional ones, photonic crystal fiber having greater cladding refractive index than the core is known as Photonic Band Gap Fiber (PBGF) where a PC will exhibit a band of prohibited frequencies in which no electromagnetic waves can propagate [3]. Several researches have been done to design PCF based optical filters either broad band pass or narrow band pass filter using line defect or point defect[10,11].

Increasing interest of designing different PCF structures due to its unprecedented design flexibility, led the researchers to propose various kinds of PCF structure for versatile applications with regular or irregular structure [11, 12], hexagonal, octagonal, spiral shape structure[7,10,13], using different defect as core or holes [14-16]. In terms of optical properties, numerous works are done highlighting the properties such as flattened dispersion [17], ultra- flattened near zero dispersion with liquid infiltration[18,19], low dispersion PCF using smoothing filter coefficients[20],highly birefringence residual dispersion compensating PCF [13].

Photonic crystal also exists in nature in the peacock tail and the wings of butterfly [1]. Being inspired from this, a novel structure with butterfly geometry is analysed. To validate the workability of proposed structure for practical application, optical characteristics like dispersion, confinement loss and non-linearity are extracted where satisfactory results obtained. Moreover, effects on cladding holes filled with air and another one is filled with water is also analysed. For the design and simulation purpose COMSOL Multiphysics is used where to analyse the optical characteristics of designed novel butterfly structure MATLAB is used. In this work, a full vectorial Finite Element Method (FEM) is used to analyse the designed PCF structure as it is suitable for complicated structure geometries which works by dividing the fiber cross section into elements [7]. A Perfectly Matched Layer (PML) is introduced which is a boundary condition used as a perfect absorber and to analyse light confinement [7].

2 Study of Optical Properties

2.1 Chromatic Dispersion

Chromatic dispersion is a phenomenon that is an important factor in fiber optic communications as it is 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 resulting errors or Inter Symbol Interference (ISI) and a loss of information [9]. The chromatic dispersion, D of a PCF is calculated from the real part of effective index of the fundamental mode ηeff versus the wavelength using [7]:

$$D = -\frac{\lambda}{c}\frac{d^2 Re[\eta_{eff}]}{d\lambda^2} \quad (1)$$

Where, $Re[n_{eff}]$ is the real part of n_{eff}, λ is the wavelength and c is the velocity of light in vacuum.

For secured long distance data transmission, dispersion should be kept as small as possible. For this reason some research have been proposed for low dispersion using smoothing filter coefficients [20], near zero ultra-flat dispersion PCF with one layer of air hole infiltrated with liquid [19], for flattened dispersion using triangular lattice [17] etc.

2.2 Confinement loss

Confinement loss which is occurred due to the leakage of light from core to cladding can be calculated from the following mathematical representation [3]:

$$\text{Confinement loss} = 8.686 * k_0 * \mathrm{Im}(\eta_{eff}) \quad (\mathrm{dB/m}) \tag{2}$$

where $k_o = \frac{2\pi}{\lambda}$ and $\mathrm{Im}(\eta_{eff})$ is the imaginary part of effective refractive index

This loss can be minimized by selecting proper value of pitch constant (∧), air holes diameter (d) and number of air holes surrounding the core [3].

2.3 Effective Modal Area

The effective mode area, A_{eff}, is related to the effectiveness of the confined segment of fiber, can be computed using transverse field vector of the whole cross-sectional area of the fiber. The effective modal area of the fiber core, A_{eff} is mathematically related as [7]:

$$A_{eff} = \left(\iint |E_t|^2 \, dxdy\right)^2 / \iint |E_t|^4 \, dxdy \tag{3}$$

where E_t is the transverse electric field vector and the integration is done through the whole cross-sectional area of the fiber. This identical property of PCF is essential to calculate nonlinearity of the structure.

2.4 Nonliner Coefficient

Nonlinear effects like Four Wave Mixing (FWM), Soliton affects, Self Phase Modulation (SPM) and Cross Phase Modulation (XPM) etc. where most of them are originate from nonlinear refraction due to the third order susceptibility $\chi^{(3)}$. PCF structure can be designed for achieving both low and high non-linearity [6,21,22]. The non-linear coefficient, γ can be calculated from the following equation:

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \tag{4}$$

Where n_2 is the nonlinear refractive index of silica (2.66x10^{-20} m^2/W) and A_{eff} is the effective area calculated from equation 3 [3].

3 Design of the Proposed Fiber Structure

A novel butterfly shaped structure is proposed in this work and to validate the proposed structure optical properties like dispersion, confinement loss and nonlinear coefficient are analysed. Silica is considered as background material and in order to pass light through specific region and at specific frequencies of optical windows, four air holes are perturbed by copper material at four different positions.

The second layer among two consecutive layers is designed with air filling ratio, d/∧ = 0.21μm where pitch constant, ∧ = 2.1μm and d is the radius of air holes for this layer. For the first layer, radius of the air holes is d/2 with pitch constant, ∧ = 2.1μm. Two large holes radius at two wings of butterfly are 2*d and 1.5*d. In this geometry, different sizes of holes diameter are used by manipulating the original one, d. The major and minor axis of central elliptical core is 1.1μm and 0.5μm respectively. For the purpose of obtaining asymmetric structure and perfect shape of butterfly, different air holes diameter is used as asymmetric shape provides high nonlinearity. Cylindrical PML layer available in COMSOL Multiphysics is used for better confinement. Sellmeier's equation is used to find out the refractive index of silica as it is varied with wavelength [23]:

$$n^2(\lambda) = 1 + \sum_{j=1}^{m}(B_j\lambda^2 \; /(\lambda^2 - \lambda_j^2)) \quad (5)$$

where λ_j is the *j*-th resonant wavelength and B_j is the strength of the *j*-th resonant wavelength. Parameters in Sellmeier's equations are: $B_1 = 0.6961663$, $B_2 = 0.4079426$, $B_3 = 0.8974794$, $\lambda_1 = 0.0684043\mu m$, $\lambda_2 = 0.1162414\mu m$, $\lambda_3 = 9.0896161\mu m$

As there exists different sizes of holes in the proposed PCF structure, sol-gel technique can be used to fabricate the fiber where holes size, shape and spacing may all be adjusted independently[12].

The optical properties of PCF can be controlled to a large extent by varying two design parameters; air hole diameter (d) and pitch distance (∧) which is the distance between holes. Besides the variation of other parameters like number of air holes, number of defected holes, material used, defected holes position etc. also play significant role. The cross section of the designed novel butterfly PCF structure is delineated in Figure 1. The simulation is carried out within the wavelength range of 0.85µm-1.8µm. After simulation, corresponding mesh formation obtained from the subdivision of structure into small and finite elements is displayed in Figure 2.

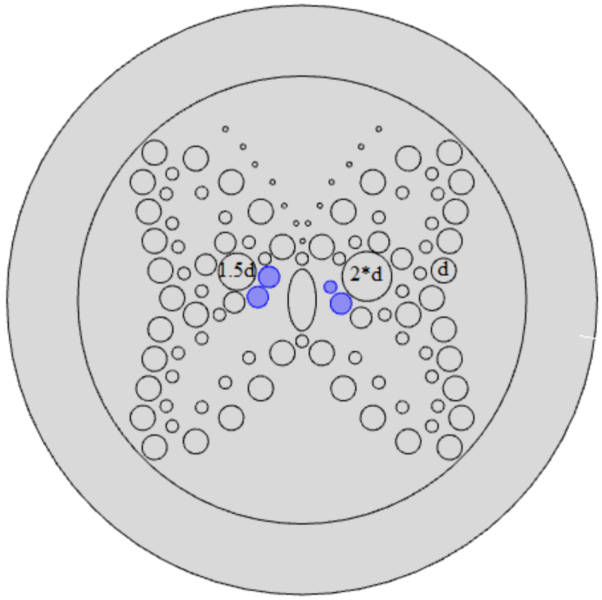


Figure 1. Cross section view of designed butterfly structure with four defected holes

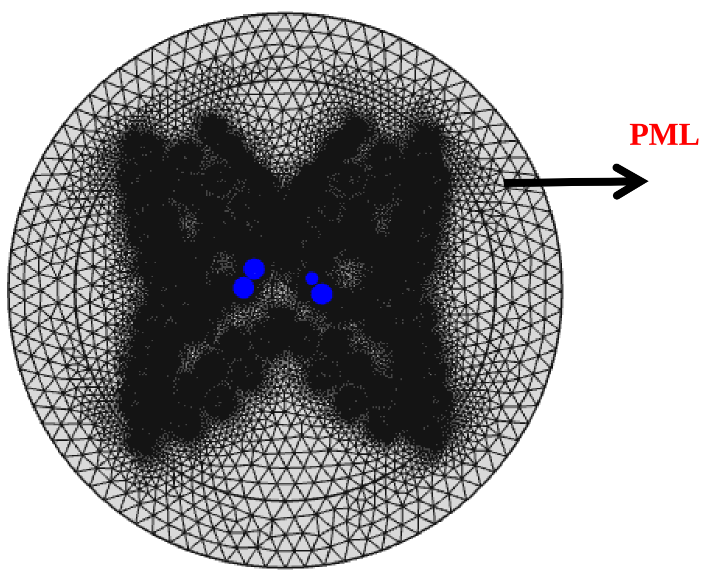
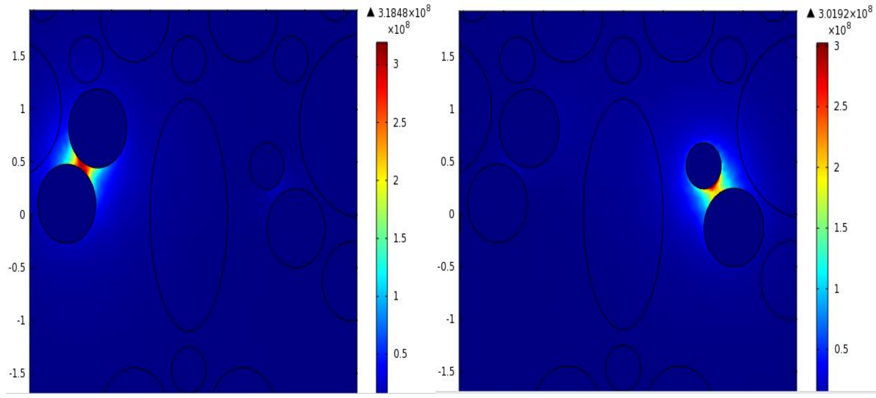


Figure 2. Mesh analysis of proposed butterfly structure indicating four defected holes (blue)

Confinement of light through the defected holes is visualized in Figure 3 at the desired wavelength 1.55μm with color indicator scale (red for maximum, blue for minimum power).



(a) (b)

Figure 3. Light confinement at 1.55μm for defected holes of (a) Left wing (b) Right wing of butterfly

4 Results Analysis

For the analysis of optical characteristics like dispersion, confinement loss and nonlinear coefficient of proposed butterfly shaped PCF structure, equations 1, 2 & 4 are used respectively. Figure 4 displays the dispersion characteristics curves where it is visualized that it exhibits negative dispersion and at 1.55μm the value is -1.56x10^4 ps/km.nm.

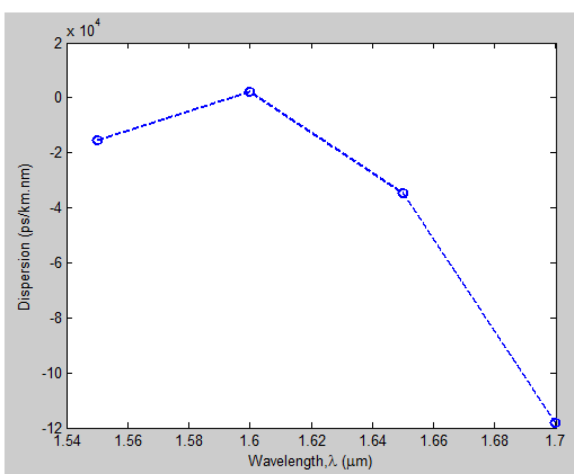


Figure 4. Dispersion characteristics of proposed structure

By varying the pitch constant, air holes diameter, confinement loss can be minimized. It should be kept minimum as possible to increase the data transmission efficiency. Figure 5 depicts the confinement loss characteristics of the proposed butterfly structure. It is observed that confinement loss is decreasing with the increase of wavelength, from 1.45 μm to 1.7 μm it reduces about 1.1times.

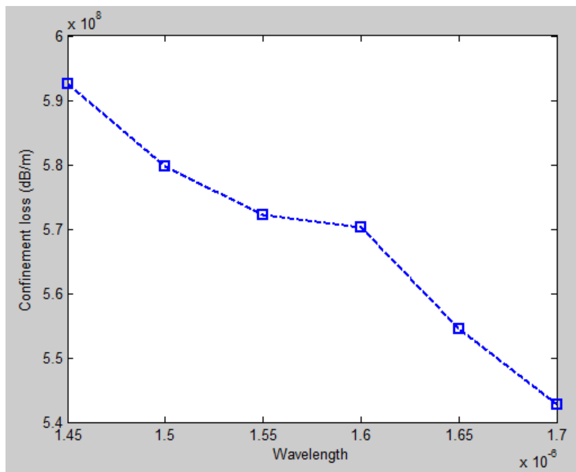


Figure 5. Confinement loss versus wavelength curve for butterfly structure

PCF can exhibit both low and high nonlinearity by varying its design parameters to optimize the desired result. This proposed novel butterfly structure exhibits high nonlinearity. Figure 6 illustrates the nonlinear coefficient of the proposed butterfly structure with the effect of pitch constant on it.

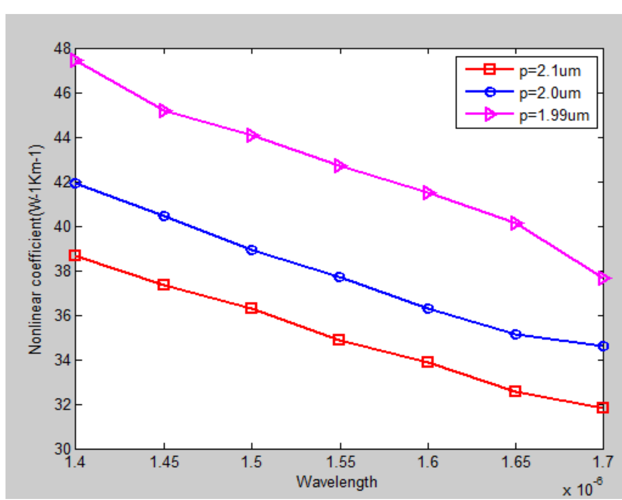


Figure 6. Variation of nonlinear coefficient with pitch constant

From figure 6 it is observed that nonlinear coefficient increases with the decreasing of pitch constant. The reason is as nonlinear coefficient is inversely proportional to effective area, A_{eff}, when pitch constant decreases the effective area also decreases and thus increases the nonlinear coefficient value. At the operating wavelength 1.55μm, the values of nonlinear coefficient for pitch constant 2.1μm, 2.0μm and 1.99μm are 34.9 $W^{-1}Km^{-1}$, 37.7 $W^{-1}Km^{-1}$ and 42.7$W^{-1}Km^{-1}$ respectively.

In this work, another approach is investigated which is instead of air holes cladding, liquid (ex. water) is used as material of cladding holes and the optical properties are extracted for this. Figure 7 displays the dispersion characteristics after water infiltration. It is observed that it also exhibits negative dispersion like air hole cladding.

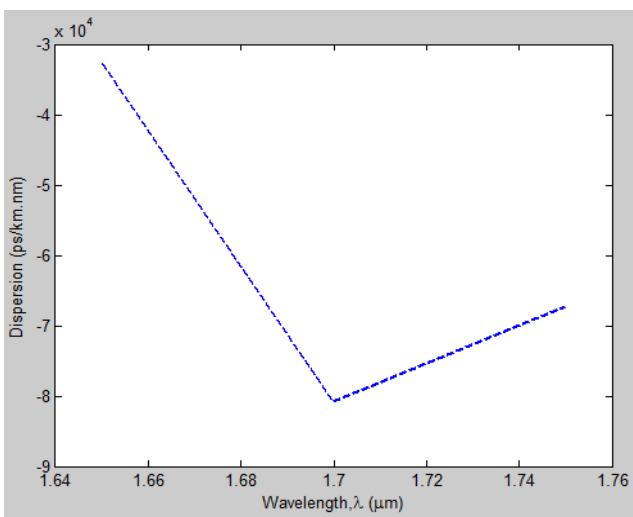


Figure 7. Dispersion characteristics curve for water infiltrated cladding holes

Figure 8 reveals the performance of confinement loss for water infiltration which also expresses the decreasing of confinement loss with the increasing of wavelength as in air cladding holes performance over C+L+U wavelength bands. Moreover, water infiltration reduces the confinement loss of 1.05times than the air cladding holes at the operating wavelength 1.55 μm.

In water infiltrated cladding holes, nonlinear coefficient increases with the decreases of pitch constant as like as air cladding holes performance illustrated at figure 9. For pitch constant 1.99 μm air cladding holes exhibits more nonlinearity than the water one which is in value $42.7 W^{-1}Km^{-1}$ and $38.6\ W^{-1}Km^{-1}$ respectively. For two others pitch constant, the performance is almost same for both.

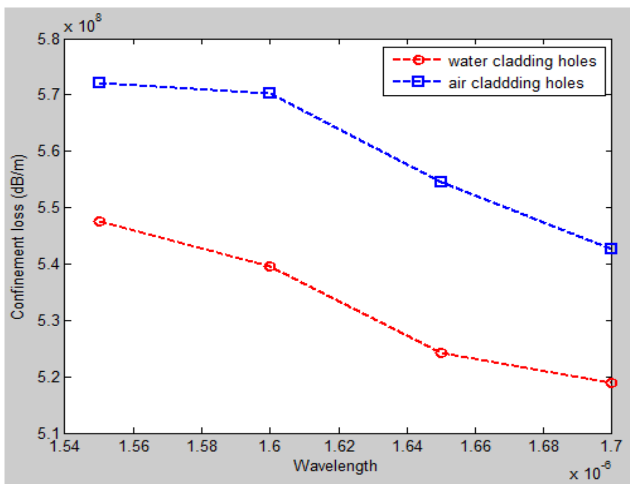


Figure 8. Confinement loss versus wavelength curves for water and air cladding holes

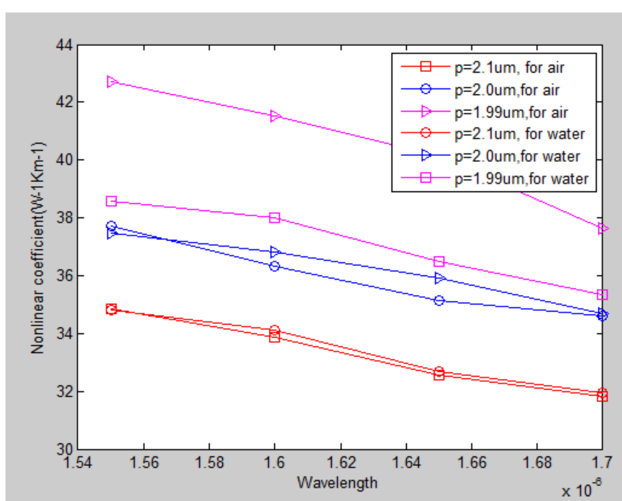


Figure 9. Variation of nonlinear coefficient with pitch constant for water and air cladding holes

4.1 Comparison between proposed and existing structure

In this research, a novel butterfly shaped PCF structure is proposed which has not been done in any previous work and to validate the structure optical properties like dispersion, confinement loss and nonlinear coefficient are extracted with satisfactory result. Moreover, an investigation has also been performed to analysis the behavior of air and water cladding holes. A comparison is tabulated in Table 1 between the existing structures and the proposed one.

Table 1. Comparison of proposed and existing structures

PCF structures	Dispersion (ps/km.nm)	Confinement loss (dB/m)	Nonlinear coefficient $(W^{-1}Km^{-1})$
Dodecagonal[24]	-396.9	10.56 x 10^-3	39.02
Spiral[22]	-355.898	------	39.9333
Octagonal[13]	–562.52[fast axis] –369.10[slow axis]	11 [fast axis] 5.4×10^2[slow axis]	------
Spiral[7]	-855	7x10^7	------
Butterfly [Proposed]	-1.56x10^4	5.72x10^8	42.7

5 Conclusions

In this research, a novel butterfly shaped PCF structure with multiple defects is proposed where negative dispersion and high nonlinearity are obtained and an analysis is also presented on the effect of water infiltrated cladding holes. Confinement loss of the proposed structure is extracted which requires further modification to minimize it more. It is believed that the proposed PCF structure will have promising future in telecommunication field, sensing applications, super-continuum generation, in WDM system as DCF fiber due to its novel behaviour like negative dispersion and high nonlinearity. Another approach to design a butterfly shaped optical filter, waveguide design is currently under investigation for further enhancement of this proposed novel structure.

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