Journal of Ovonic Research Vol. 18, No. 4, July - August 2022, p. 491 - 497

Study and modeling of photonic crystal fibers

H. Moughli[*], Y .Mouloudi, A. Merabti
University Tahri Mohammed Béchar, Algeria, Laboratory of semiconductor devices physics, Energetic Department, P.O.Box 417, Béchar, Algeria

Optical fiber is a light guide which today constitutes the preferred medium for the transport of information. But, in order to meet the increasing needs generated by the development of the Internet in particular, it was necessary to always improve the propagation characteristics in the fibers. A new generation of fibers has been designed with the aim of obtaining lower losses and better performance than classical fibers. This work presents a design of hexagonal photonic crystal fiber (PCF) geometry for analyzing different optical properties with respect to wavelength ranging. This geometry has been used for analyzing effective refractive index, dispersion, effective mode area, nonlinear coefficient and birefringence. Silica glass is chosen as background material and the cladding region is made of air hole layers. This work is based on the modeling and analysis of the propagation characteristics of waves in a photonic crystal fiber.

(Received August 12, 2021; Accepted July 5, 2022)

Keywords: Photonic crystals fiber, Finite element, Wave propagation, Light

1. Introduction

Photonic crystals are structures where the refractive index varies periodically in one, two or three dimensions. This periodic medium produces on the light which propagates in the photonic crystals an analogous effect to that of the periodic potential on the electrons in a crystal. Just as there exist gaps in the energy band structure of the crystal, meaning that electrons are forbidden to propagate with certain energies in certain directions, there are photonic band gaps, preventing light from propagating in certain directions with specified frequencies. Also, a photonic crystal can allow propagation in anomalous and useful ways.

Photonic-crystal fibers, also called microstructure optical fibers, can be divided into a few broad classes, according to whether they use index guiding or band gaps for optical confinement, and whether the periodicity of the structure is one-dimensional or two-dimensional. Photonic-band gap fibers confine light using a band gap rather than index guiding. Band-gap confinement is attractive because it allows light to be guided within a hollow core. This minimizes the effects of losses, undesired nonlinearities and offers enormous practical advantages [1].In this work presents a design of hexagonal photonic crystal fiber (PCF) geometry for analyzing different optical properties with respect to wavelength ranging. This geometry has been used for analyzing effective refractive index, dispersion, effective mode area, nonlinear coefficient and birefringence. Silica glass is chosen as background material and the cladding region is made of air hole layer. The main goal here is to ensure that this structure provides the required performance.

2. Digital processing

2.1. Geometry of PCF

A PCF model has been designed having a hexagonal geometry with a periodic triangular lattice arrangement of air holes. So, to simulate this we first draw the PCF. To draw this, at first a large circle is drawn, then many small circles are drawn with the given parameter in line, the space between two air holes is equal to pitch and the radius of air hole is determined from d/Λ ratio, the

---

[*] Corresponding author: moughlihassane@yahoo.fr

https://doi.org/10.15251/JOR.2022.184.491

holes are arranged at the corners in triangular lattice. The properties of the PCF can be controlled to a large extent by varying these parameters. After drawing all circles center air hole is removed to make the fiber index guided. Then a large circle is again drawn. The difference of radius between this large circle and previous large circle is the thickness of PML [2].

Finally, as shown in Fig .1, the core is surrounded by rings of such air holes with Diameter of 1.2 µm for the circular air holes and elliptical ones with a major-axis of 1.44 µm, minor-axis of 0.84 µm, Diameter of the core is 1.4 µm and the pitch is 2µm, finally the Overall Diameter of the geometry is 28.6 µm.

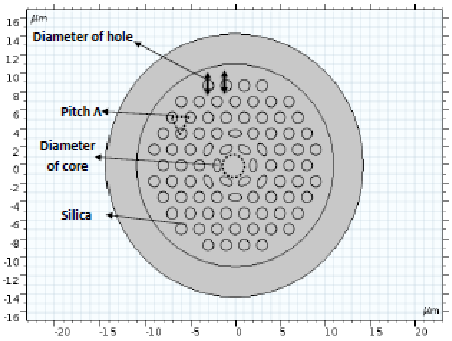


Fig. 1. Geometry of a PCF.

2.2. Material Selection

After drawing geometry next step is to define proper material for each part from material section. In air hole, air is used as material and the refractive index of air is given which is 1. For the first big circle we used silica as a material. The refractive index of silica is a function of wavelength [3].

$$n^2(\lambda)=1+\frac{B_1\,\lambda^2}{\lambda^2-C_1}+\frac{B_2\,\lambda^2}{\lambda^2-C_2}+\frac{B_3\,\lambda^2}{\lambda^2-C_3} \tag{1}$$

2.3. Mesh generation

The Finite Element Method approximates the PDE (Partial Differential Equation) as a system of ordinary differential equations which can be solved separately using various numerical techniques. It sub-divides the object into very small but finite size elements. This process is called ‘meshing’ and is shown in Figure.4 for the solid-core PCF. A set of characteristic equations which describe the physical properties and boundary conditions govern each element of the mesh. These equations are then solved as a set of simultaneous equations to compute the effective index of the modes supported by the fiber (Figure.3) [4].

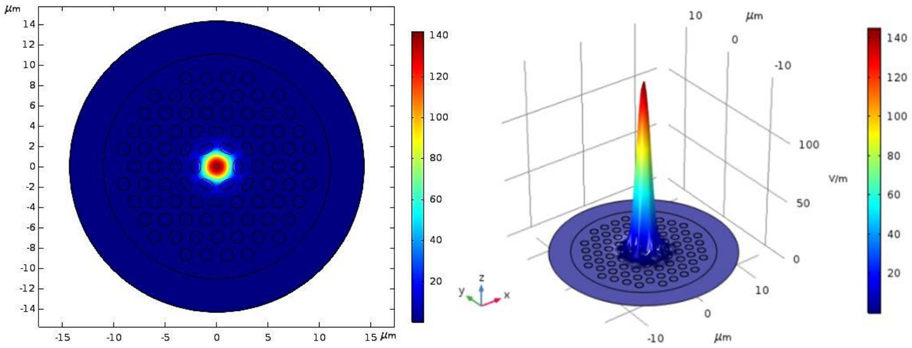


Fig. 3. Light confinement in the PCF.

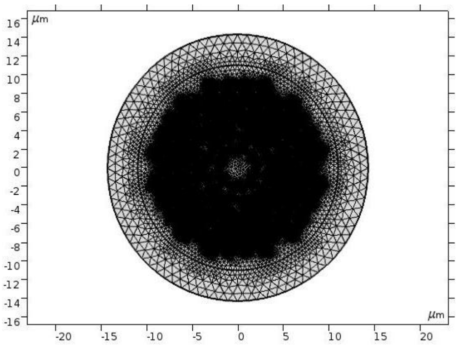


Fig. 4. Solid-core PCF meshing.

3. Modeling equations

Since the guiding properties such as dispersion, modal birefringence, effective area, and nonlinear coefficient of the PCF are investigated, the formulations for the corresponding optical parameters are discussed in this section.

- Chromatic dispersion $D(\lambda)$ of the PCF is wavelength-dependent and can be estimated from the effective refractive index n_{eff} of the fundamental mode using the following expression:
-

$$D = \lambda/c\ (d^2 n_{eff}/d\lambda_2) \tag{2}$$

where the unit of the dispersion in ps/(nm.km), c is the velocity of light in vacuum, is the wavelength in μm . Chromatic dispersion of the PCF can be manipulated by changing the geometrical parameters and distribution of the air holes in the PCF structure [3].

- Birefringence is one of the important properties of PCFs. The mathematical formulation of birefringence can be expressed as:
-

$$(\lambda) = |n_{eff\,x} - n_{eff\,y}\,| \tag{3}$$

Birefringence is a property of a PCF comes from some geometric asymmetry based on air holes position. Highly structural asymmetry of PCF, especially 1st ring of the PCF produces higher order of birefringence and structural symmetry of PCF has no influence to produce birefringence [5].

- Effective area is an important quantity in the nonlinearity's context, but it also has connection to leakage loss. To determine effective area, we used electric field distribution, where λ is the wavelength of light and Aeff is the effective mode area given by the expression [3]:

$$A_{eff} = \frac{[\iint |E^2| dxdy]^2}{\iint |E^4\,| dxdy} \tag{4}$$

The unit of the effective mode area is μm^2.

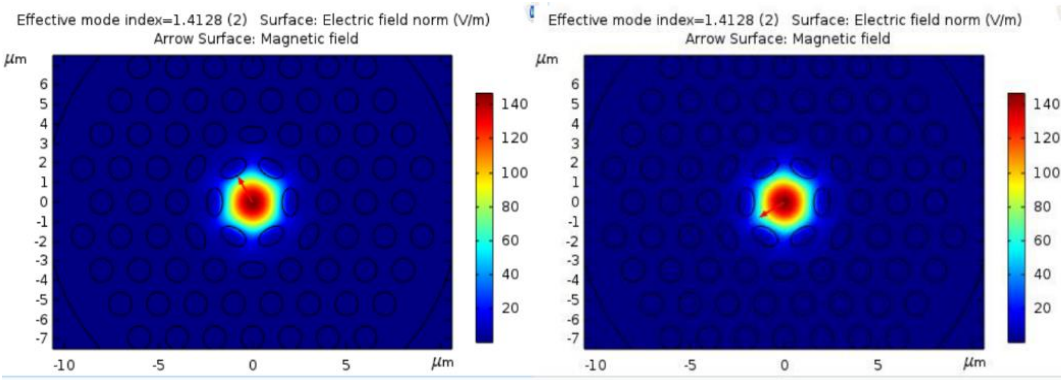
- The non-linearity is inversely proportional to the effective mode area and can be defined as follows:

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \tag{5}$$

where the unit of non-linearity is $W^{-1}Km^{-1}$ and n_2 is the Kerr constant of the material with a unit of $\frac{m^2}{W}$ [6]. Nonlinear effects are very advantageous in different optical devices and optical applications such as broadband amplification, channel de multiplexing, wavelength conversion, solution formation, optical switching and many more applications [5].

4. Results and discussion

In this section, the guiding properties such as dispersion, modal birefringence, effective area, and nonlinear coefficient of the proposed PCF geometry are investigated. Figure .5 shows the field distribution of the fundamental mode of the proposed PCF for both x and y polarization at wavelength of 1550 nm respectively. The simulation results demonstrate that the electric field is strongly confined in the core region of the PCF for two orthogonal polarizations.



(a) *(b)*

Fig.5 (a) Electric field distribution of the fundamental mode at wavelength of 1.550 µm for polarization; (b) electric field distribution of the fundamental mode at wavelength of 1.55 µm for polarization.

4.1. Effective refractive index

The first thing we notice in the plot of Figure.6 is that the effective refractive index is following a general decreasing while the wavelength is increasing. A maximum n_{eff} of 1,4164 was observed at a wavelength 1.45 µm and a minimum n_{eff} of 1,4052 was observed at a wavelength of 1.75 µm. The effective refractive index of the Solid-Core Photonic Crystal Fiber lies between the refractive index of the core and the cladding and it's close to the refractive index of the core. As wavelength increases the effects of diffraction become more important and the light spreads slightly into the cladding so the effective refractive index decreases towards the refractive index of the cladding.

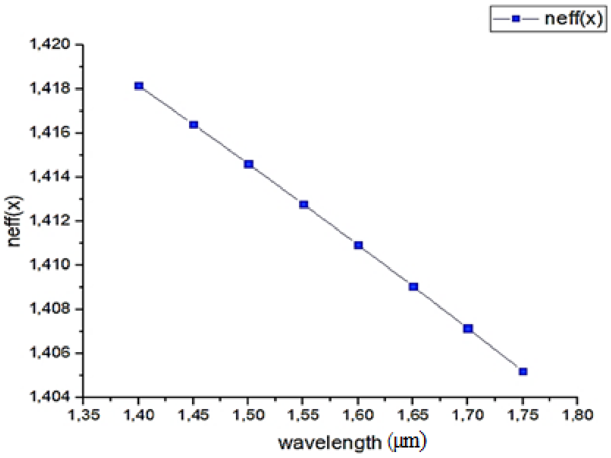


Fig. 6. Plot of the effective refractive index against wavelength for the proposed PCF.

4.2. Dispersion

Figure.7 illustrated the dispersion variation with respect to wavelength for PCF geometry. The dispersion is approximately zero, achieved from 1.4 µm to 1.75 µm. The dispersion is about 5,9133E-11 ps/(nm.km) at the wavelength 1.55 µm. Comparing our results to other research papers we noticed that the most effective parameters that effect the dispersion of PCFs are the pitch and the diameter of the core. So, a suitable cladding design leads to a controlled dispersion of PCF.

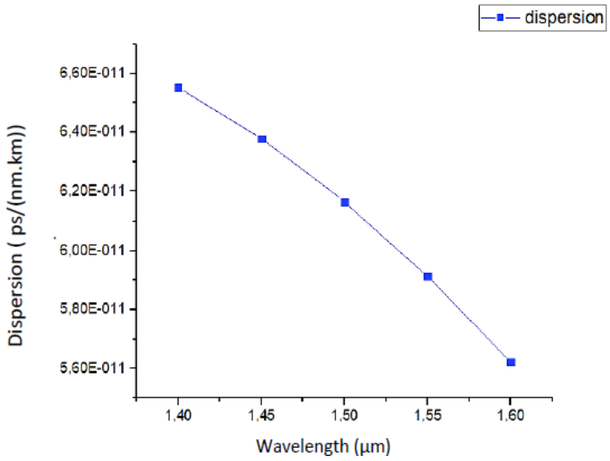


Fig. 7. Dispersion against wavelength for the proposed PCF.

4.3. Birefringence

We notice in the plot of Figure.8**,** the birefringence of the proposed PCF can reach 4,68792E-8 (Δn) at the wavelength 1.75 µm and 4,45497E-8 (Δn) at the wavelength 1.4 µm. The perturbation of the birefringence in the calculated wavelength region is small, which shows that the proposed PCF exhibits uniform birefringence in the large wavelength region. Our calculated results show that this property can be achieved based on our design. And the proposed PCF exhibits a flexible control of the birefringence by designing the structures of the fiber cladding and with suitable parameters.

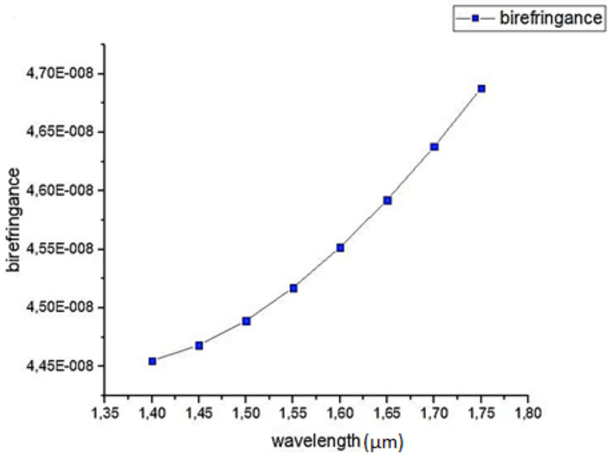


Fig. 8. Plot of the birefringence against wavelength for the proposed PCF.

4.4. Effective Area

Effective area exhibits a generally increasing trend to increasing wavelength. A minimum effective area of 5, 9719E-12 m^2 was obtained at 1.45 µm and a maximum of 6,59265E-12 m^2 was obtained at 1.75 µm. As wavelength increases, power density decreases and hence the effective area increases. It can be seen that Figure.9 does follow this trend.

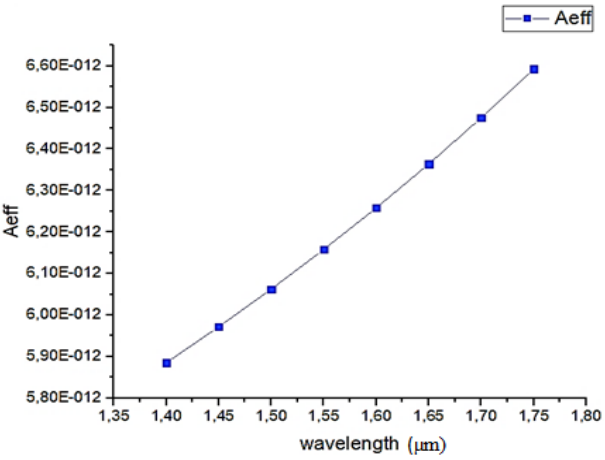


Fig. 9. Plot of the effective area against wavelength for the proposed PCF.

4.5. Nonlinear Coefficient

The relationship between nonlinear coefficient, wavelength and A_{eff} is inversely proportional, where the nonlinear coefficient is decreasing with the increasing of wavelength. A minimum nonlinear coefficient of 1,19813E-8 m^2/watt at 1.75 µm, and the maximum value of the nonlinear coefficient is at the wavelength 1.45 µm as shown in Figure.10. The nonlinear properties of PCF depend on the core diameter which determines the effect of the mode area.

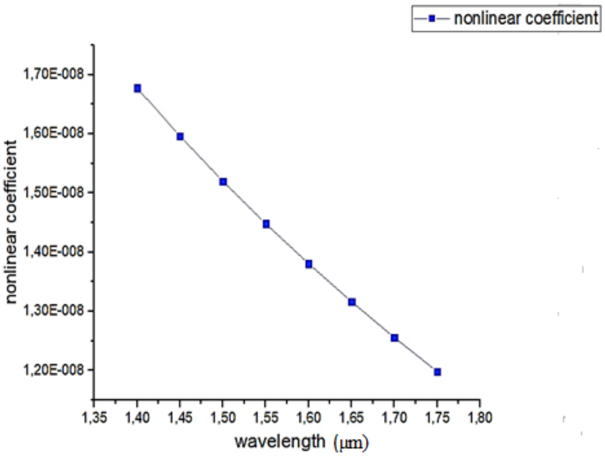


Fig. 10. Nonlinear coefficient against wavelength for the proposed PCF.

5. Conclusion

Les PCF ont fait l'objet d'une intense activité de recherche de la part des groupes les plus importants à travers le monde. En effet, il est intéressant d'étudier les nouveaux mécanismes de guidage de la lumière par les PCF et les propriétés liées à la présence du PBG. De plus, la possibilité de modifier la géométrie des trous d'air dans la section transversale de la fibre n'est limitée que par la faisabilité technologique des PCF conçus. Il est également très intéressant d'étudier comment les propriétés du PCF peuvent être influencées par les changements de caractéristiques géométriques.

In this work using the finite element method which is based on a direct divide and conquer approach, we were able to model a low loss PCF with low dispersion. The motivation for applying finite element techniques in the study of photonic crystal fibers is to allow flexible, efficient and precise modeling of crystal structures. The propagation properties of the proposed PCF were analyzed. The analysis was carried out by the finite element method. The proposed fiber exhibits low birefringence and minimal dispersion for a wide range of wavelengths.

The results obtained it also gives an effective refractive index close to the refractive index of the cladding, a high non-linear coefficient and a low effective surface.

References

[1] John D. Joannopoulos, Steven G. Johnson, Joshua N. Winn, Robert D. Meade, Photonic Crystals: Molding the Flow of Light, Princeton University Press. 2nd edition, 2008.

[2] Kuang-Yu Yang, Yuan-Fong Chau, Yao-Wei Huang, Hsiao-Yu Yeh, Din Ping Tsai, Journal of Applied Physics, 2011.

[3] Anwar, Khushnub, Nowrin Nowsher, Basharat Nahar Islam, Analysis of Various PCF Structures Using Finite Element Method. Diss. department of electrical, electronic and communication engineering, 2017.

[4] Hossain, Md. Bellal et al., Optics and Photonics Journal **7**(11), 235 (2017).

[5] Kumar, Shiva, M. Jamal Deen, Fiber optic communications: fundamentals and applications, John Wiley & Sons, 2014. https://doi.org/10.4236/opj.2017.711021

[6] S. K. Tripathy, J. S. N. Achary, N. Muduli, G. Palai, J Laser Opt Photonics, 2015. https://doi.org/10.1002/9781118684207