Numerical Study of Solid Core Photonic Crystal Fibres with Endlessly Single Mode

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Abstract

In this work, a solid core photonic crystal fibre (SC-PCF) has been designed with endlessly single mode of which both centred core and holes in the cladding are organized by circles. The designed SC-PCF has a single solid centred core which is ringed by a six rings hexagonal cladding. The computation of SC-PCF is achieved by using the finite element method (FEM) with perfectly matched layer (PML) boundary condition. All the designed factors like dimensions and distance of both core and cladding areas have varied with an optimized structure. After ending the numerical calculation, the results show that there is a link between the air_holes in the cladding, and the different normalized air hole size.

Keyword: Numerical Study, photonic crystal fiber, endlessly single mode.

1. Introduction

The very magnificent features of Photonic Crystal Fibers (PCFs) such as the micron size, sensing, and electrical inviolability among others, make them an excellent choice for many applications [1]. The development technology of PCFs. permits the researchers to have very good features by choosing the suitable design parameters. Light speared characteristic and enhancement “structural flexibility” of the PCFs allow us to have outstanding property by regulate the air_holes in the core and cladding area [2].

The photonic crystal fibers could be designed due to the dimension of the air_ holes of the cladding, the air hole dimension, (d), and the hole to hole spacing (Λ), as shown in **Figure 1.** The relative hole size, (d/ Λ) is defined as the ratio of the air_hole size to the pitch spacing is also a commonly used factor. Another measurement is used to depict PCFs is the Air. Filling. Fraction. (AFF), is defined as the portion of the area of the air_holes to the area of the silica in “the cladding” area. the core diameter of hexagonal PCFs with one air hole defect is often counted for as (2 Λ -d), also shown in **Figure 1**. [3].

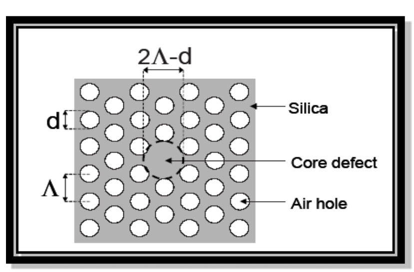

Figure 1. Cross section of photonic crystal fiber [3].

2. Simulation Part

This type of PCFs is made of a patrol system of air_holes rings with a centered solid core, which is prolonged over fiber length. They are made of pure silica and it is the lowering effective refractive index of the cladding, to obtain the mechanism of guidance to be total internal reflection. The cross section of the solid core is presented in **Figure 2a.** and its refractive index variation with the radial distance in **Figure 2b.**

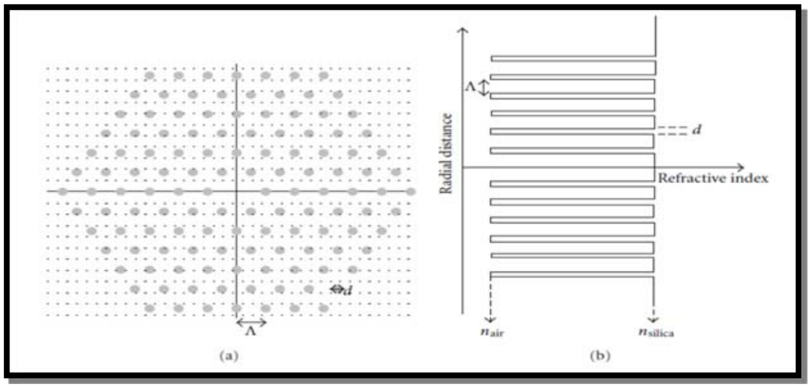

Figure 2. (a) The cross-section of solid core fiber and (b) respective refractive index profile [4].

One of the charming properties of (PCFs) is their prospect to be single-moded through a beamy wavelength ranges, outstanding the ordinary single-mode fibers which become multi-moded for wavelength under their single-mode cut-off wavelength. PCFs, which are in particular designed with this advantage are called the Endlessly Single-Mode (ESM) - PCFs [5]. The small air-filling-fraction of the cladding, to have a low index-contrast equivalent waveguide, which is needed for single-mode operation. At lower wavelengths, the effective index of the cladding will be close to the refractive index of the silica. This property will be decreasing the wavelength and keep the single-mode through a wide wavelength range [6].

COMSOL MULTIPHYSICS is a commercial application which depending on the Finite Elements Methods FEM. This software includes many physical models and a design window using Computer Aided Draw (CAD) for construction design, mesh builder, interior matrix assembler, different numerical solvers for matrices, and several post-processing features. The main steps simulate an ESM-PCF are shown in **Figure 3**.

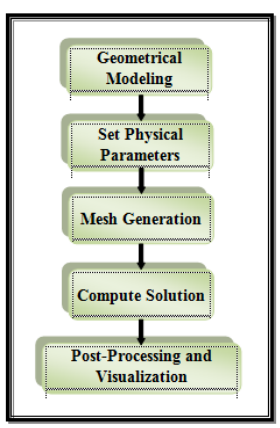

Figure 3. Block Diagram of the modeling ESM-PCF with Comsol Multiphysics.

In geometrical modeling, an ESM- PCF having hexagonal geometry with desirable parameters is designed. The model consist of circular with desirable diameter also specify holes diameter (d), shape, rings number, spacing between two adjacent holes (pitch (Λ)), core diameter (ρ), and positioning them on the required lattice. The cladding structure includes rings of circular formed the air_holes with a hexagonal lattice arrangement along the full length of the fiber surrounding. **Figure 4.** a simulation of the real ESM-PCF (ESM-12-02).

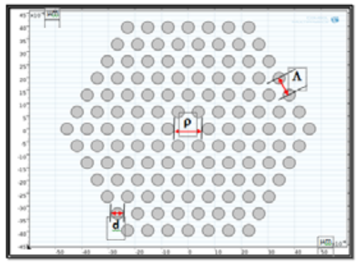

Figure 4. Geometrical sketch for cladding region of ESM-PCF, with six rings, the fiber formed by removing one air hole from the center of the fiber.

The physical parameters include the properties of the material in each domain as shown in **Figure 5.**

Perfectly Matched Layer (PML) is an average absorbing material; this merit makes the PML to be highly absorb outgoing waves from the whole of the calculation region without reflecting them back into the interior. The PML in the proposed model in circular; and it is important to note that there is no ideal PML, for each structure of fiber, there is a different optimized PML.

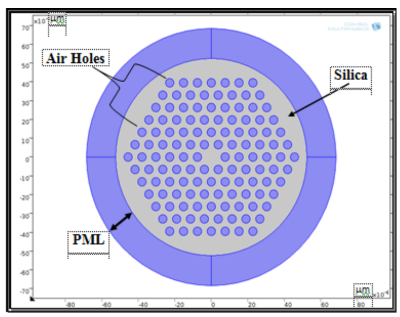

Figure 5. The designed ESM-PCF with six air_holes ring, d/Λ= 0.6.

The mash generation is made a triangular mesh. The effective refractive index of the (PCFs) is calculated by solving the eigenvalue equation for each of triangular meshes using COMSOL's (FEM) by increasing these triangles the accuracy of solution and calculation time is increased. The mesh generation is shown in **Figure 6.** is a finer mesh.

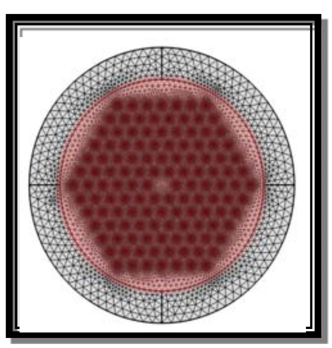

Figure 6. Finer meshing for the modeled ESM-PCF.

In this work an ESM-PCF model is designed. The first design is studying the effect of variation of ring's number with three different models. These models are done by deleting air_holes from the center. The 1st model is made by deleting one air_hole from the center; the

2nd model is made via taking off air hole in the center and the 1st ring of air_holes and the 3rd model is made by deleting the air_hole of the center and the 1st ring of air_holes and the 2nd ring of air holes. As shown in **Figure 7.** The second design is studying the effect of varying of diameter of the core by modeling three different designs. The air normalized which effected the size of air_holes of the cladding. The three models have air normalized (d/Λ) [0.4, 0.6, and 0.8] respectively. As shown in **Figure 8**.

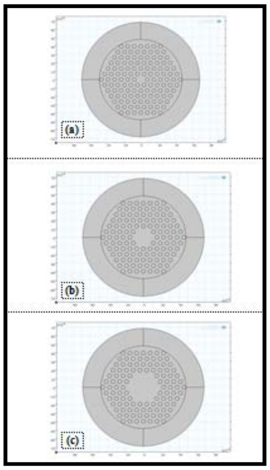

Figure 7. The cross section of designed ESM-PCF with d/Λ=0.6(a) six rings,(b)five rings(c)four rings.

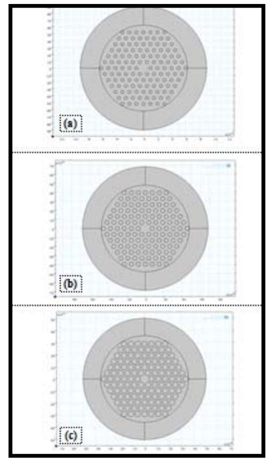

Figure 8. The cross section of designed ESM - PCF with (a) d/Λ=0.4 and Λ=10μm, (b) d/Λ=0.6 and Λ=7.6μm, (c) d/Λ=0.4 and Λ=5.6μm.

3. Modulation Part

The better optical guiding properties to ensure that PCFs is suitable for the wanted application through the following properties:

3.1. Effective Area

Effective mode area is generally considered as the light carrying region. For fundamental propagating mode, electric-field (E) distribution occurs inside the core, as a result, effective mode area (EMA) of a PCF can be determined by the following Equation (1) [7]:

$$A_{eff} = \frac{\left(\iint_s |E_t|^2 \, dx \, dy\right)^2}{\iint_s |E_t|^4 \, dx \, dy} \tag{1}$$

3.2.Non Linear Coefficient (γ)

High optical power density is supplied by a small effective area for which the nonlinear effects would be worthy. The nonlinear effective or nonlinearity is closely related with the effective area and also nonlinear coefficient of the PCF background material in associated with the operating wavelength λ. The nonlinear coefficient can be examined by the Equation (2) [7]:

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

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Where (n_2) is the nonlinear-index coefficient in the nonlinear part of the refractive index δn=n_2 |E|^2 and for pure silica its equal to2.2×〖10〗^(-20) m^2⁄watt , c speed of light, ω angular frequency of the signal, and λ its wavelength.

3.3.Chromatic dispersion:

Chromatic dispersion in light wave system is concerning to the diversity of group velocity of optical signals in fiber, its limit the maximum distance, to which a signal can be transmitted without the necessity of regeneration of its shape, timing, and amplitude. It's straight effects the pulse width and the phase-matching conditions which is important for most telecommunication applications [8]. Chromatic dispersion consists of two components:

4. Material Dispersion (Dmat)

The material dispersion (in the core region) of the step index fiber model can be approximated by Sellmeier expression since pure silica glass is used in fabricating this PCF. It's refer to the wavelength dependence of the refractive index of material caused by the interaction between the optical mode and ions, molecules or electrons in the material. The material dispersion is given by

$$D_{mat} = -\frac{\lambda}{c}\frac{d^2 n_M}{d\lambda^2} \quad (3)$$

Where (λ) is the wavelength, (c) is the speed of light, and (n_M) is the cladding air-holes index.

4.1. Waveguid Dispersion (Dw):

The group velocity of guided optical pulses depends on the wavelength even if material dispersion is negligible. This type of dispersion known as the waveguide dispersion. The contribution of waveguide dispersion DW to the dispersion parameter D is given by:

$$D_W = -\frac{\lambda}{c}\frac{\partial^2\left[\mathrm{Re}(n_{eff})\right]}{\partial\lambda^2} \quad (4)$$

By gathering Eq. (10) and Equation (11), we will get the total dispersion and is given by [8]:

Dt = Dmat + Dw (5)

5. Result and Discussion

Endlessly single-mode photonic crystal fiber has been designed with different core diameter and ring's number. The cores of ESM-PCF are formed by removing one, six, and twelve air_holes from the center, the designed fiber have pitch (hole to hole spacing (Λ)) about 7.6 µm, air hole diameter (d) 4.5 µm, and the outer diameter (D) 130 µm. Each iteration has been done within range of wavelengths 0.9 µm to 2 µm with step 0.05. The result of the pulse propagation through the ESM-PCF which is represented by the single mode Gaussian distribution for the selective data has been shown in **Figure 9**.

The numerically simulation results showed the following:

The imaginary part of effective refractive index (neff) doesn't appear because it is too small for COMSOL software to calculate. In COMSOL software any number under (10-9) doesn't appear. The imaginary part of effective refractive index (n_{eff}), is too small because of the high confinement so the light will distribute just in the core area since the imaginary part related to losses of PCFs

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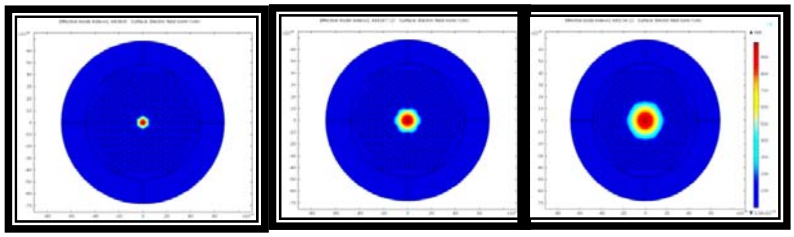

Figure 9. Single mode Gaussian distribution output of wavelength 1.55 µm, six, five, and four air hole rings

The real part of (n_{eff}) is decreasing and following a general trend to the increasing of wavelength and decreasing of the core diameter and that shown in **Figure 10**. For ESM-PCF designs, the refractive index of cladding depends on wavelength and it defined by the cladding structure. The (n_{eff}) of the ESM-PCF. lies between the refractive index of both core and cladding refractive index and it's very close to the one in the core. The effects of diffraction take an important role with the increases of wavelength and the light spreads slightly into the cladding so the (n_{eff}) decreases towards the refractive index of the cladding. We notes that when the core diameter (ρ) increasing the (n_{eff}) increasing too because (n_{eff}) of the fundamental mode began to reach to refractive index of pure silica propagation and became parallel to ESM-PCF axis so the interaction with holly structure will be minimized.

The effective mode areas (A_{eff}) are calculated from Eq. (1). The (A_{eff}) for fundamental mode were taken as a function.of.wavelength. for.different.core .diameter and that shown in **Figure 11**. It is noticed that the (A_{eff}) increasing with the increasing of core diameter because when the core area increased the laser field distribution extended more in silica and the field confined in the core and there is no overlapping with cladding air hole.

The nonlinear coefficient (γ) calculated from Equation (2) as it clears from the equation that the (γ) inversely proportion with (A_{eff}), and it is decreased by the increasing of wavelength, and increased with the increasing of core diameter and increasing of air hole rings as it shown in **Figure 12**. An important value to know the strength of nonlinear effects, is the ratio between the nonlinear-index. coefficient, n_2), and the effective area for a given wavelength" for the optical field. The (Aeff) depending on the spot size (w) and direct proportion with (A_{eff}) and as we noticed from Eq. (1-9) the (γ) inversely proportion with (A_{eff}) so the (γ) inversely proportion with (w).

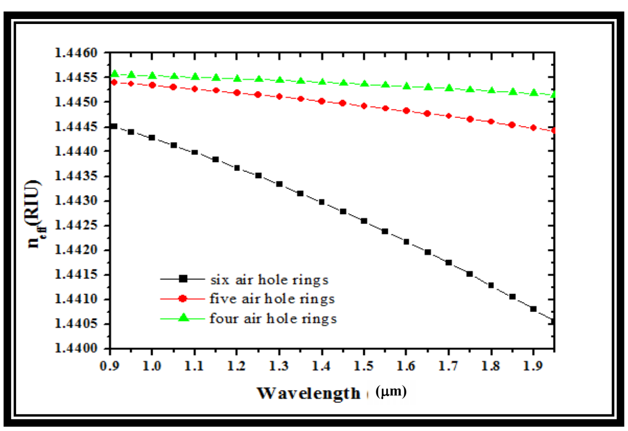

Figure 10. The (n_{eff}) versus wavelength for ESM-PCFs with six, five, and four air hole rings.

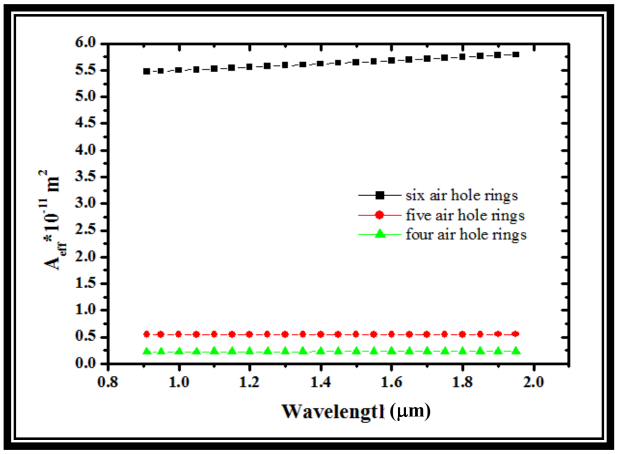

Figure 11. The (A_{eff}) versus wavelength for ESM-PCFs

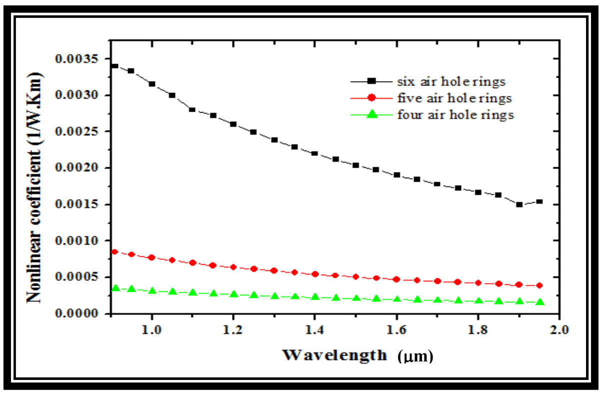

Figure 12. The (γ) versus wavelength for ESM-PCFs**.**

The most effective parameters that influence the dispersion properties of PCFs are the space between two hole (Λ) and. "diameter. of the core (ρ)". The total dispersion can be calculated through Eq. (5). The total dispersion as it mentioned before is consist of two parts. The first part is the waveguide dispersion which has been figure out from the real part value of the effective refractive, index as a function of wavelength as it clears from Eq. (1-11), while the second part is the material dispersion which was calculated according to Equation (1-10). The dispersion for various frames of PCF is calculated and shown in **Figure 12**. From these figures one can chose which design of. PCFs is desired by collecting an appropriate core diameter to have a desired dispersion wavelength.

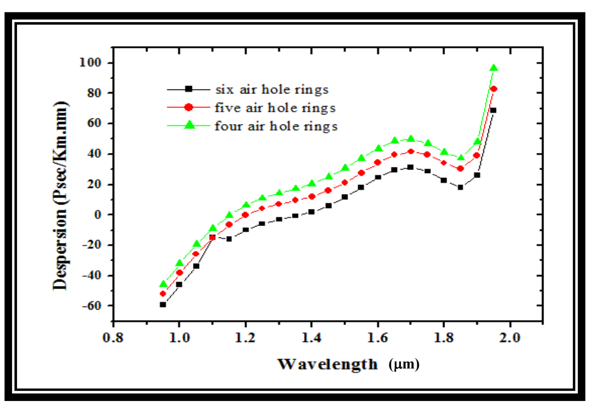

Figure 13. The dispersion versus wavelength for ESM-PCFs**.**

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ESM-PCFs have been designed with various normalized air_holes size (d/Λ) of 0.4, 0.6 and 0.8 with six air hole rings, air hole diameter (d) 4.5 μm, core diameter (ρ) 12 μm. The result of the pulse propagation through the ESM-PCF which is represented by the single mode Gaussian distribution for the selective data has been shown in Figure 13.

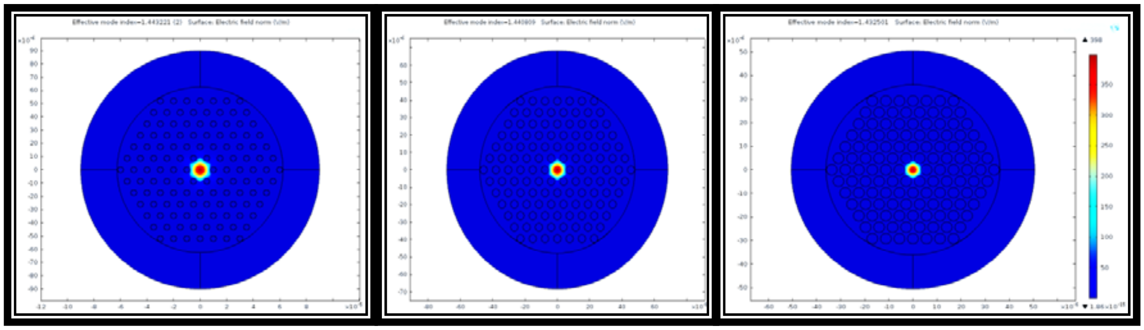

Figure 14. Single mode Gaussian distribution output of wavelength 1.55 pm, (d/A) = 0.4, (d/A) = 0.6, and (d/A) = 0.8.

The outcomes of numerical simulation showed that:

The effective refractive index (n_{eff}) are decreasing by increasing the wavelength with different normalized air holes' size (d/Λ) as shown in **Figure 14**. because the (n_{eff}) of the ESM-PCF lies between the refractive index of the core and the cladding and it's very close to the one of the core as we said, and it changes with the change of holes' size in the cladding and with the distance between them and the plane wave will travel through these air holes.

The effective mode areas (A_{eff}) are calculated from Equations (1-7). The effective mode area (A_{eff}) are increasing by increasing of the wavelength for different normalized air hole size (d/Λ) as shown in **Figure 15**. From obtained results one can notice that the mode will be more restricted – lower effective area – for increasing of normalized air hole size. The increasing of (d/Λ) made up by a changing the diameter of air_holes and (Λ). By increasing the (d/Λ) decreasing the (Λ) so the air_holes will be close to each other with the decreasing of (Λ) lead to lowering the (A_{eff}) and so the light will by more confined. From **Figure 16**. the nonlinear coefficient (γ) is decreasing with the increasing of (d/Λ) respectively to the increasing of hole – to - hole distance (Λ). As we it mentioned before that the nonlinear coefficient (γ) inversely proportion with effective mode area (A_{eff}).

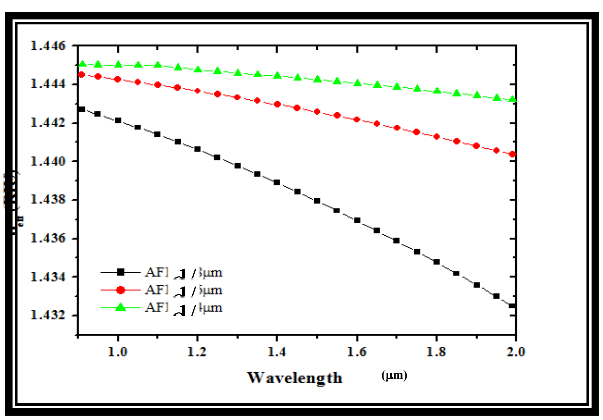

Figure 15. The (n_{eff}) verses wavelength.

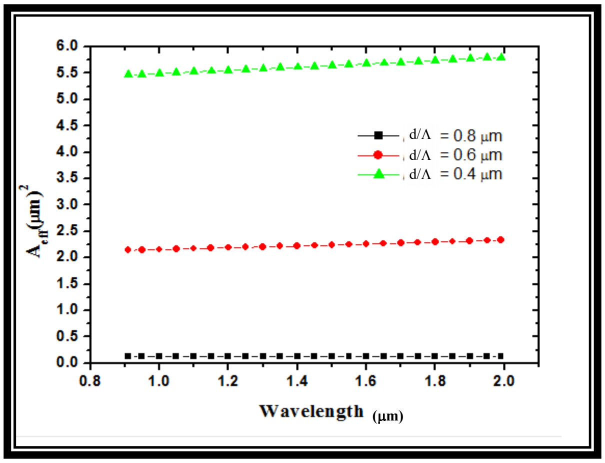

Figure 16. The (A_{eff}) verses wavelength.

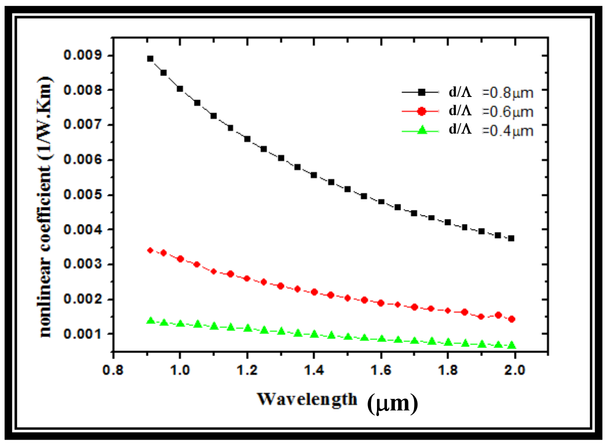

Figure 17. The(γ) verses wavelength.

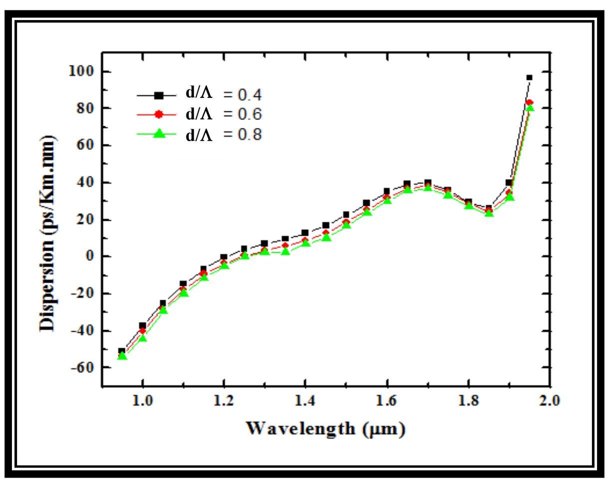

Figure 18. The dispersion verses wavelength.

Figure 17. is shown the total dispersion for a range of wavelength. One can have noticed that the dispersion is decreasing with the increasing of (d/Λ). The chromatic dispersion follows the design of the photonic crystal fiber, in this work it made by different (d/Λ) which effect the dispersion of ESM-PCF

6. Conclusion

Solid -Core Photonic Crystal Fibers (SC-PCFs) have been designed with FEM through COMSOL MULTIPHYSICS 4.4, the pulse propagation properties are decided by the size and arrangement of cladding region which is containing the air holes. The arrangement of cladding of SC-PCF is taken with two arrangements the first one is with different core diameters and different ring numbers and the second one is Different Normalized Air Hole Size. The outcome of the numerical simulations of the finite element method is very good approval with these in the literature.

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