Simulation of Hexagonal HC-PCF With Circular Holes using COMSOL Multiphysics Software

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Abstract:

Optical fibers are still important in many fields but not as the hollow-core photonic crystal fiber. The HC-PCF has many unique features which paved its way to enter a lot of important fields such as sensing, communications and active optical devices. To employ this type of fibers in the mentioned fields, it is very essential to study them and understand how they work correctly and deeply. In this paper, the seven-cell HC-PCF were simulated with COMSOL Multiphysics 5.5 software utilizing the finite element analysis, a step-by-step simulation were mentioned in section three. Subsequently, the fiber characteristics were analyzed within the wavelength range 1500–1600 nm. The fundamental mode profile, intensity, effective mode index, confinement lose, and the effect of the pitch which is the most important structure parameter were analyzed precisely.

Keywords: hollow core photonic crystal fibers; characteristic analysis; photonic band gap fiber; simulation; COMSOL Multiphysics, sensing applications.

1. Introduction:

Analogously to the conventional fibers; the photonic crystal fiber has a centered core surrounded by a cladding area but it is distinguished with the periodic arrangements of its micro capillary,[1] and being made of photonic crystal materials. This unique structural design with embedded air holes of different shapes and sizes gives this type of fiber a momentous flexibility, consequently manipulating its properties. Regarding optical properties such as low confinement loss, high sensitivity, single-moodiness and high nonlinearity of the fiber can be attained by freely changing its parameters such as the diameter of the core and integrated holes, number of air holes, the design of its core and cladding and lattice pitch as well. [2,3] In addition that the common demerits of the conventional fibers such as high leakage loss and low index contrast can be reduced significantly with PCF. [1] For all previous reasons PCFs can be applied in many optical applications such as industrial, communication and biomedical sensors. [2,4]

Photonic material is a dielectric material comprises from two materials arranged periodically and each material has a particular refractive index different than other material. The opal mineral is an example of natural photonic material, it comprises form silica spheres dispersed in a hydrous matrix. The contrast between refractive indices of these two materials considered low if it is compared with the industrial photonic material for PCFs manufacturing field.

A so-called "photonic energy bands" had been resulting from the contrast in refractive indices of photonic materials. The photon experiences the photonic energy band just like an electron travelling through a crystal lattice and faces its periodic potential. Undoubtedly that photon energy is inversely proportional to its wavelength, consequently the photonic material will allow some wavelengths to pass freely while block other photons with wavelengths in the photonic band gap to pass throw. Figure 1 explains this phenomenon in details. [5]
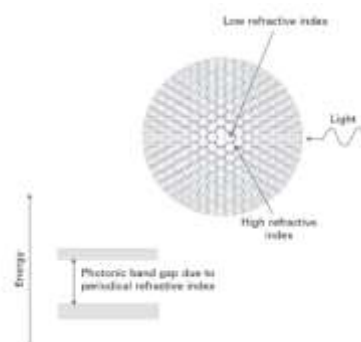

Figure (1) photonic materials with periodic variation of refractive indices [5]

There are two types of the PCF fibers, the solid core and the hollow core. Each type work with a mechanism different than the other. [1,2]

In this paper, we proposed a simple hollow-core photonic crystal fiber (HC-PCF) which consists of cladding area with a specific material such as silicon as a background material embedded with air holes of different shapes and sizes with air filled core. This structure makes this type of fibers different than other fibers by its guiding mechanism named Photonic Bandgap effect (PBG) as explained above. Thus, the electromagnetic wave will propagate longitudinally at a defect region because it cannot propagate in the transverse directions. Due to the PBG effect this fiber named Hollow-core photonic bandgap fiber (HC-PBG) as well.[6] Figure 2 show this type of fiber.
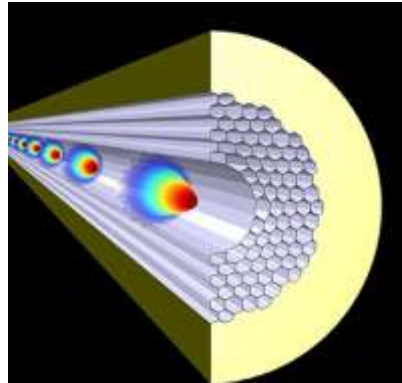

Figure (2) HC-PBG Fiber

The ineffable structure of the PBG fiber pave the way for chemical and biomedical sensing applications, where remarkable characteristics has been offered by this fabulous fiber including high relative sensitivity, endlessly single mode, low confinement loss, high nonlinearity, and large mode area and other characteristics.[3]

Indisputably, any type of optical fibers should be studied, and how it works and analyzed clearly before it is applied in a particular field. This step is important in obtaining useful results in the field in which it will be applied and used. Therefore, in this research, the proposed HC-PCF will be analyzed with the software COMSOL Multiphysics 5.5 which utilizing the finite element method. This work uses Hollow Core PCF (HC-1550) with these optical properties: 1550 nm as the design wavelength, ±10% of design wavelength as an operating bandwidth, 7-cell core offers large continuous operation bandwidth and a small number of core modes and parasitic surface modes. Figure 3 shows the (HC-1550). Regarding the physical properties, the core diameter is 10 ± 1 μm, cladding pitch 3.8 ± 0.1 μm, diameter of PCF region 70 ± 5 μm, cladding diameter 120 ± 2 μm.
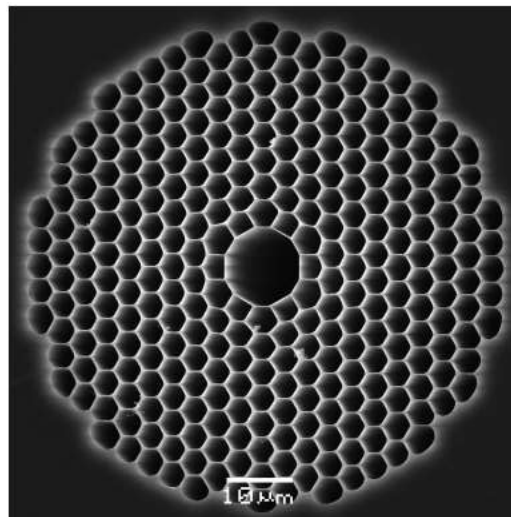

Figure (3) HC-1550

2. Characteristic Analysis of HC-PBG fiber:

2.1 Normalized Frequency and Single-Mode Transmission:

For the conventional step fiber, single-mode transmission is defined by the normalized frequency (V):

$$V = \frac{2\pi r}{\lambda}\sqrt{n_c - n_{cl}} \ \dots\dots\dots\dots \ (1)$$

where n_c and n_{cl} are the refractive indices of the core and cladding, respectively, r is the core radius, and λ is the wavelength of the optical transmission.

The refractive index of this type of fiber is independent of its operational wavelength, its normalized frequency V increases when the wavelength decreases, then its normalized cut-off frequency is 2.405.[7]

In the case of PCF fiber, the normalized frequency (V) defined as follows:

$$V = \frac{2\pi\Lambda}{\lambda}\sqrt{n_{ef} - n_{sf}} \ \dots\dots\dots\dots\dots \ (2)$$

where n_{ef} and n_{sf} represent the effective refractive indices of the fundamental mode and the fundamental space-filling mode, respectively, and Λ is the spacing of adjacent air holes only.

From above equation, it is clear that V depends on the wavelength in addition to the pitch (Λ).[7]

2.2 Effective Mode Field Area:

The effective mode field area (A_{ef}) can be calculated according bellow equation:

$$A_{ef} = \frac{\left\{\iint |E(x,y)^2|\, dxdy\right\}^2}{\iint |E(x,y)^4|dxdy} \dots\dots\dots\dots \ (3)$$

By integrating the electric field distribution of the fundamental mode E(x, y) in the numerator and denominator in equation (3), the effective mode field area (A_{ef}) achieved. This calculation required as some photon energy in HC-PBG fiber transmitted to the cladding, consequently the photon energy will not concentrate completely in the central air hole. [7]

2.3 Confinement Loss:

One of the known losses of HC-PBG fiber is the surface mode which can be allow the core mode to couple with the cladding mode resulting in a coupling loss of the surface mode. Added to the coupling loss of the surface mode, an essential factor which is the confinement loss. This kind of losses can be avoided by increasing the number of air holes layers in the cladding which leads to increasing the percentage of restricted light in the core. The confinement loss can be presented using bellow formula:

$$\alpha_{loss} = 8.686 \times \frac{2\pi \times 10^{-9}}{\lambda[nm]} Im(n_{ef}) \left[\frac{dB}{m}\right] \ \dots\dots\dots \ (4)$$

In order to calculate the confinement loss, an imaginary part of the effective refractive index should be available. Finally, reducing or even neglecting these losses can be executed by changing some parameters of the fiber design. [7]

3. Simulation of HC-PBG Fiber:

This work uses a simulation platform called COMSOL Multiphysics® , which is a software used by engineers and scientists to simulate designs and devices in all fields of engineering, manufacturing, and scientific research.

This software utilizes the finite element method (FEM) which is a numerical method used to compute the partial differential equations (PDEs) after its approximation with numerical model equations. This approximation can be executed using the discretization methods.

3.1 Start up with COMSOL 5.5 :

The new model is selected **New > Model Wizard,** Space dimension is selected to **2D**, from **Select physics** choose **Optics >Wave Optics > Electromagnetic Wave, Frequency Domain (ewfd)** then clicked **Add >Study** then from **Select Study** the **Mode Analysis** chosen > **Done.**

3.2 Parameters:

Parameters entered according the mentioned physical properties of the HC-PCF, in addition to other parameters required for the design.

- Cladding outer diameter 120 µm and referred to be Dcl, the perfectly match layer PML chosen to be (4λ), where the symbol (λ) refer to the operating wavelength of the fiber.
- The pitch between each two air holes is 3.8 µm according the original physical properties of the fiber.
- The cladding air holes diameter (Dhol) is chosen 0.9*pitch.
- The thickness of the air core chosen to be 0.6 µm and referred (T).
- The number of repeated cladding air holes (N) chosen to be 15.

3.3 Geometry:

The **Length unit** in micrometer (µm) is selected.

<u>First: Creating the outer cladding</u>

Right click the **Geometry** and the circle is chosen to create the cladding of the fiber.

- **Object Type** > **Solid**
- **Size and Shape:** Radius: Dcl/2+PML , Sector angle: 360.
- **Position:** Base > Centre, x=0 & y=0
- **Rotation angle** is Zero
- **Layers:** Layer name is Layer 1 and the Thickness is PML.
- **Build Selected** chosen.

Figure (4) show the cladding with PML.

Fig. (4) the cladding with PML of proposed HC-PBG fiber

<u>Second: Creating the air core</u>

The same steps in (First) but with the following changes:

- **Size and Shape:** Radius: 3*Dhol/2+T
- **Layers:** Layer name is Layer 1 and the Thickness is T.
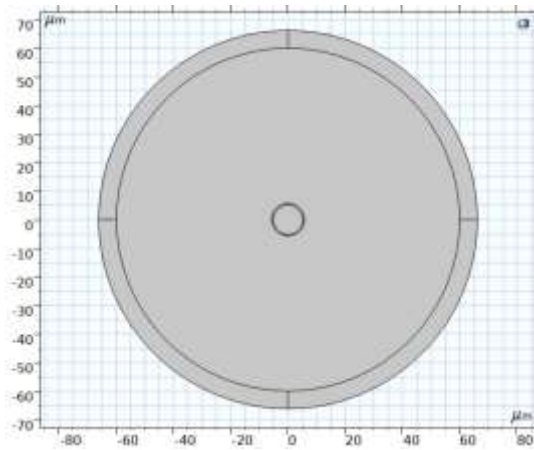
Figure (5) show the cladding with PML

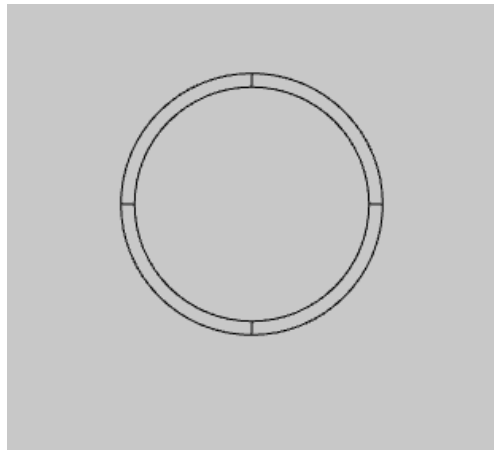Fig. (5) the air core of proposed HC-PBG fiber

Fig (6) zooming picture for the air core

Third: Creating the first cladding air hole

The same steps in (First) but with the following changes:

- **Size and Shape:** Radius: Dhol/2

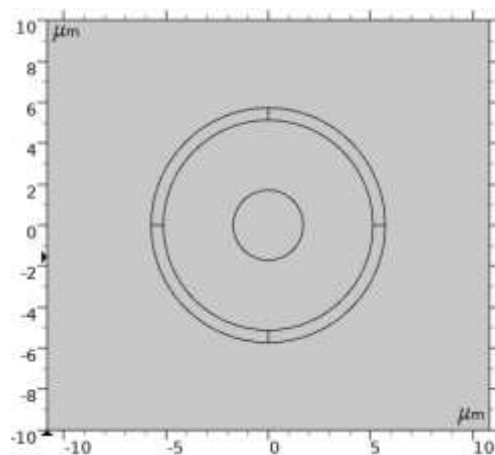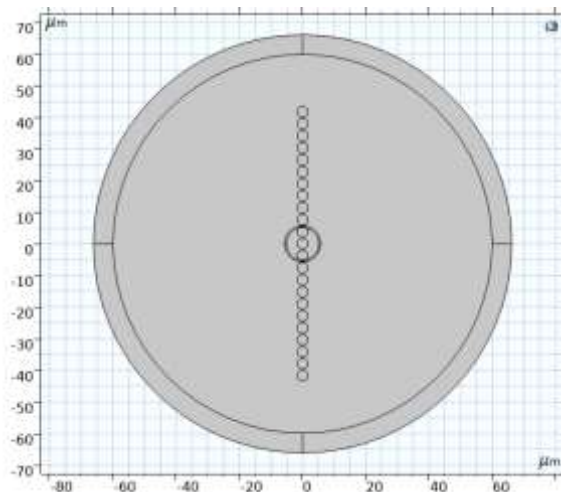Figure (7) show the first cladding air hole

Fig (7) first cladding air hole

Fourth: Creating an array of air holes in the (+Y) direction

Right click the **Geometry** and choose Transforms > Array

- **Input Objects:** click on the cladding air hole which was drawn in previous step.
- **Size:** Array type >Linear, Size is N
- **Displacement:** x=0, Y=pitch
- **Build Selected** chosen.

Figure (8) show the +Y array

Figure (8) show the +Y array

Fifth: Creating an array of air holes in the (-Y) direction

The same steps in fourth but with the following changes:

- **Displacement:** Y= - pitch

Figure (9) show the -Y array

Figure (9) show the -Y array

Sixth: Creating a group of air holes in the (+X) direction

Right click the **Geometry** and choose Transforms > Array

- **Input Objects:** click on the all the air holes which was drawn in array 1 and 2.
- **Size:** Array type >Linear, Size is N
- **Displacement:** x= pitch, Y= 0
- **Build Selected** chosen
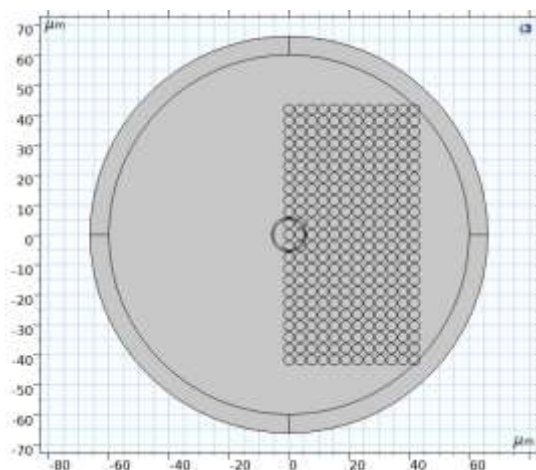
Figure (10) show the +X group of air hole

Figure (10) +X group of air hole

Seventh: Creating a group of air holes in the (-X) direction

The same steps in sixth but with the following changes:

- **Displacement:** x= - pitch, Y= 0
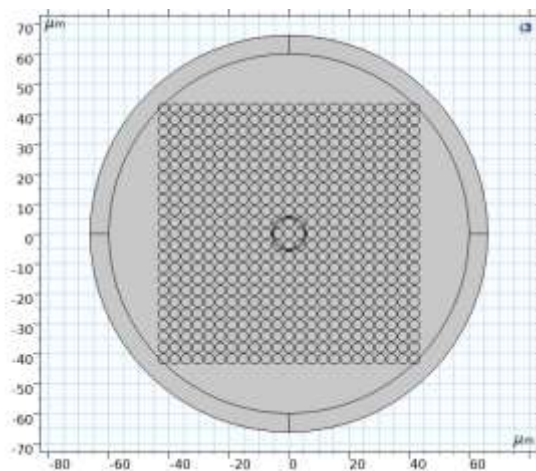
Figure (11) show the -X group of air hole

Figure (11) -X group of air hole

Eighth: Deleting some air holes to match the original structure:

Right click the **Geometry** and choose **Delete Entities**

- **Geometric entity level :** Domain.
- **Selection:** click on un wanted air holes
- **Build Selected** chosen, the original structure got.

This step can be repeated until the user get the original structure.

There are some cases that cannot delete the object with the above mentioned way because there are two or more objects cross each other. In this case it should be use the **Partition Domain** or **Partition Object** before use **Delete Entities**

After above mentioned steps done, the structure got.

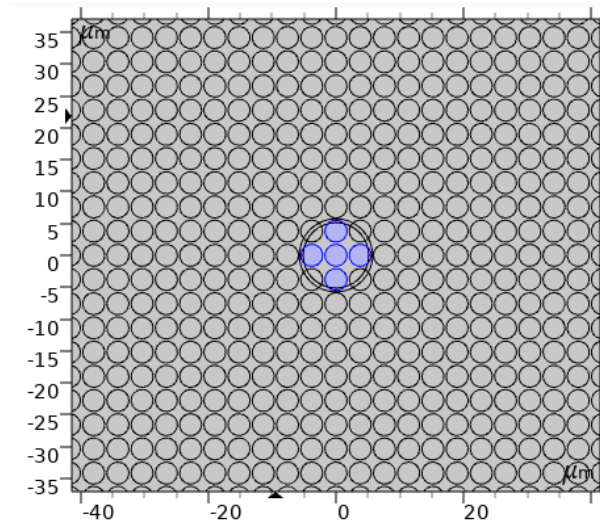Figure (12, 13, 14) show the delete entities process.

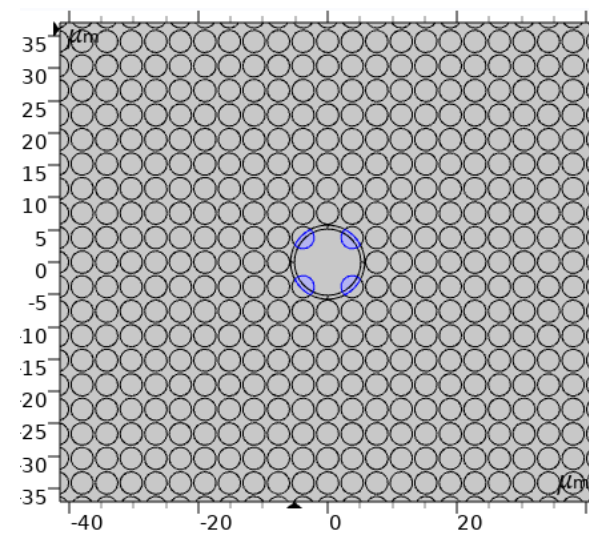Figure (12) deleting central holes
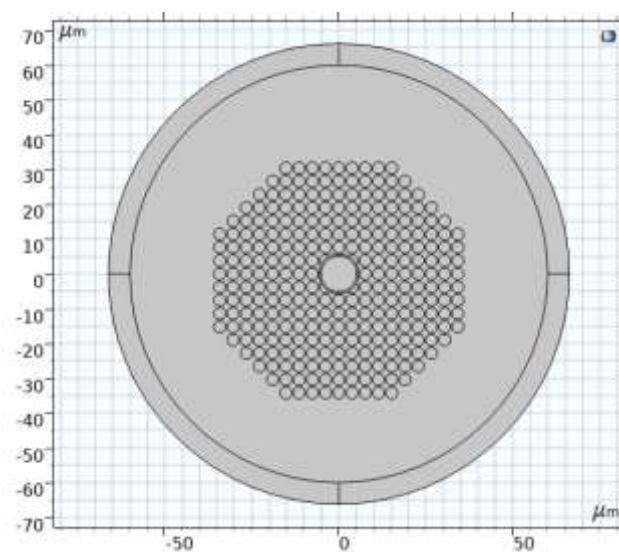

Figure (13) deleting edge-central holes

Figure (14) deleting the extra cladding holes

3.4 Materials

Right click the **Materials** and choose **Add material from library** (if the material known), in this case the software will insert the material parameters such as refractive index, permittivity and permittivity. Here the Sio2 fused silica selected for the background domain of the fiber in addition to the ring which surrounds the core air hole.

- **Geometric entity level :** Domain.
- **Selection:** click on the background and the ring which surrounds the core air hole

While the air selected for the core and the cladding air holes, the same previous steps used with this change

- **Selection:** click on all air holes in addition to the core.

There is another way which is faster, click on the **select box** icon which located up in the **Graphics window** on the right of the main COMSOL window.

For PML layer also right click the **Materials** and choose **Blank material,** in this case the user needs to insert the material parameters. Here the refractive index of value (-1.45) inserted.

- **Geometric entity level:** Domain.
- **Selection:** click on the four pieces of PML layer.

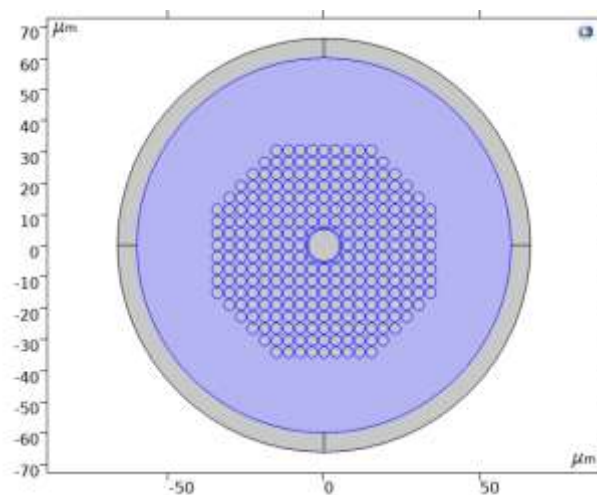Figure (15, 16, 17) show the background material, air holes and PML layer respectively.
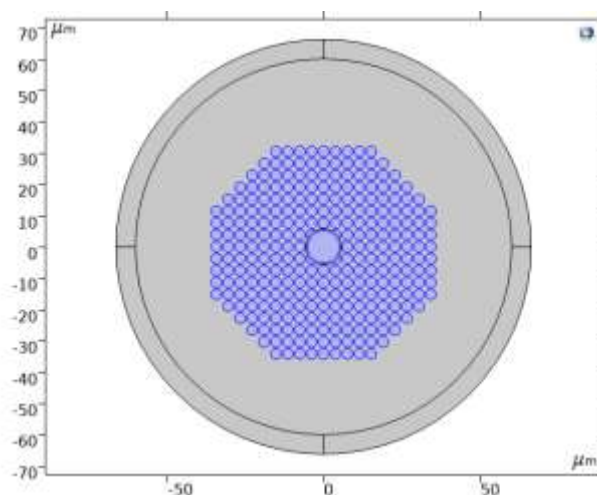

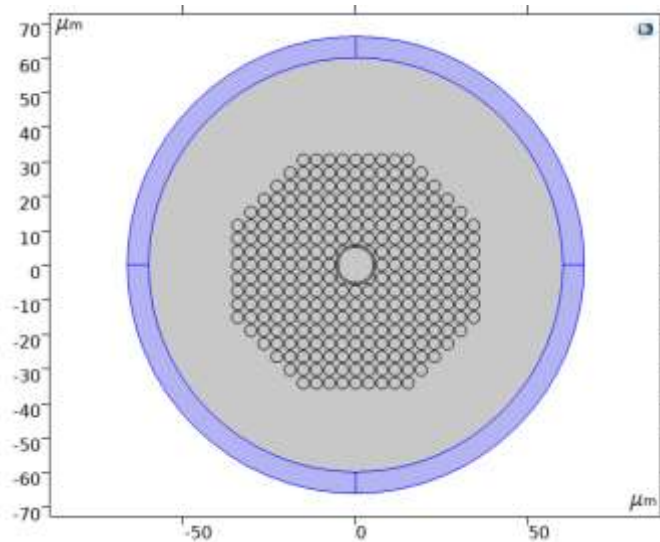Figure (15) Silica material area

Figure (16) Air holes material area

Figure (17) PML material area

3.5.Mesh

The meshing of the active area represents the concept of the finite element method (FEM)

First: Size

Element Size

- Calibrate for: Semiconductor selected.
- Predefined > Extremely coarse
- **Build Selected** chosen

Element Size Parameters

Kept same as the software settings.

Second: Free Triangular1

Domain Selection

- Geometric entity level: Domain.
- Selection: Manual
- All silica area chosen

Scale Geometry

- x-direction scale: 1.
- y-direction scale: 1.

Control Entities

- Smooth across removed control entities chosen.
- Number of iterations: 8.
- Maximum element depth to process: 8.

Build Selected chosen
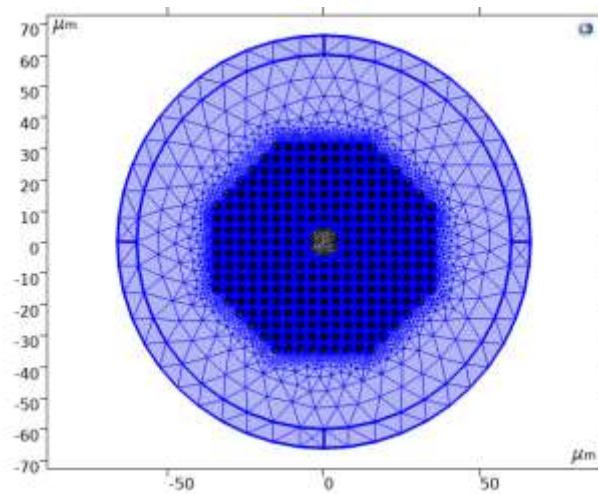
Figure (18) show the background mesh

Figure (18) show the background mesh

Second: Free Triangular2

Same as previous steps with these changes:

Domain Selection

• All air area chosen.

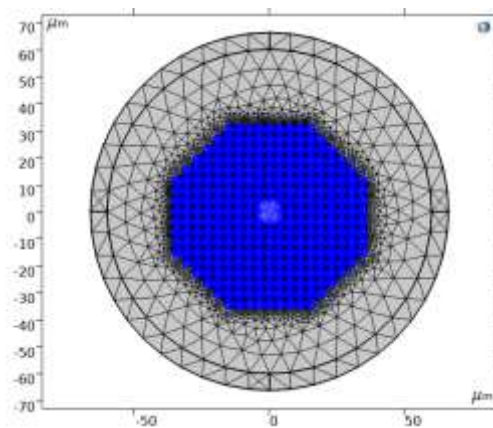Figure (19, 20) show the core and cladding air holes mesh.

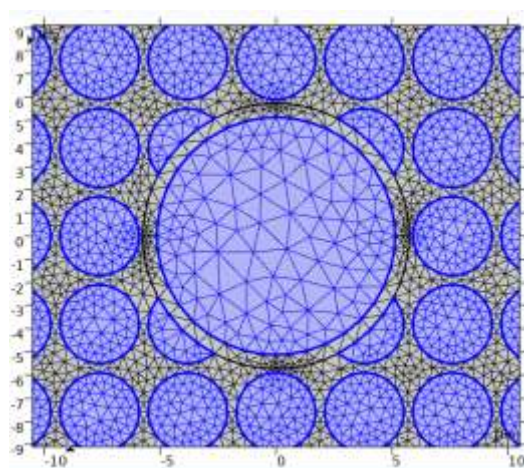Figure (19) core and cladding air holes mesh.

Figure (20) Zooming on core and cladding air holes mesh

3.6 .Study

Step1: Mode Analysis

Study Settings

- Transform: Effective mode index
- Mode analysis frequency: c_const/1550[nm]
- Mode search method: Manual
- Desired number of modes: 100 (also tried more than this value)
- Search for modes around: 0.99
- Mode search method around shift: Closest in absolute value.
- Use real symmetric eigenvalue solver: Automatic

Physics and Variables Selection

Electromagnetic Waves, Frequency Domain (ewfd), (solve for) selected, Discretization> physics setting.

Compute button clicked

3.7.Electric Field (ewfd)

Data

- Dataset: Study 1/Solution 1 chosen
- Effective mode index: 0.99336 (as a result)

Selection

- Geometric entity level: Entire geometry

Plot button clicked and the result below has been got:

4.Results:

4.1 The Fundamental Mode Profile:

In this type of fibers, the energy in the cladding depends strongly on the effective mode index. For more simplification, in the HC-PBG fiber the multiple reflections of light in the photonic crystal led to guide the light in the core and any changing in the field that penetrate the cladding even if this change is very little it will cause a noticeable change in the phase velocity of the mode. [8] Figure (21) show the intensity profiles of the fundamental mode at wavelength 1550 nm.
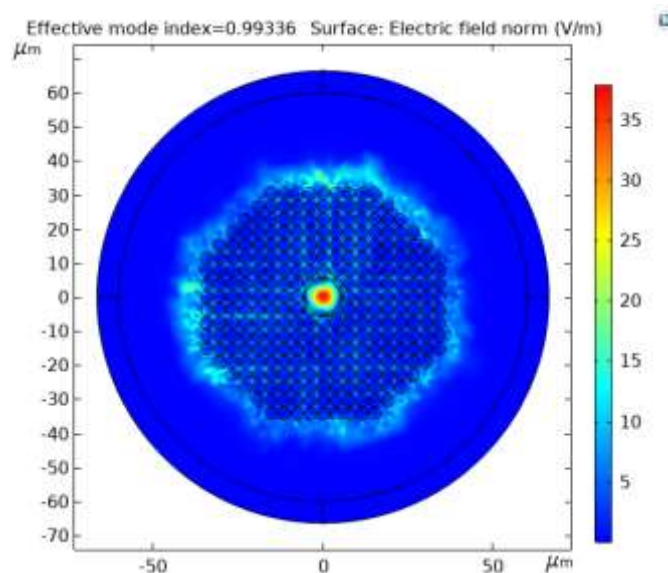

Figure (21) the intensity profiles for the fundamental mode of HC-PBG fiber
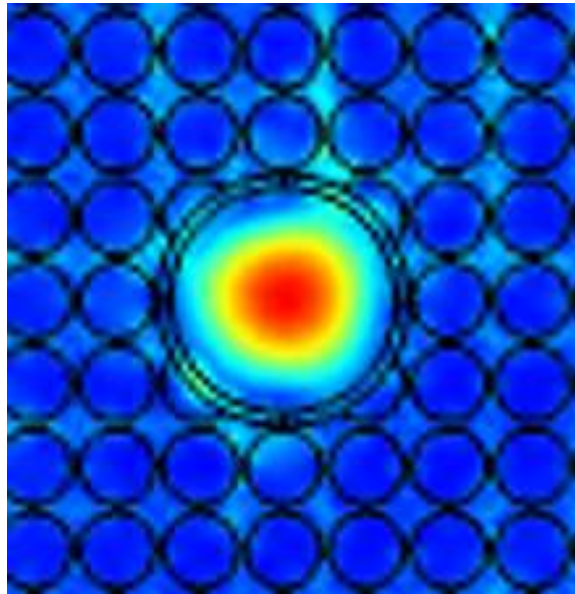
Figure (22) Zooming of the intensity profiles for the fundamental mode of HC-PBG fiber

The intensity profiles show that the modes were well confined in the core region with electric field 35 V/m which is considered very low, in addition the shape of the mode was not a perfect circular shape.

All mentioned defects because of the irregular cladding structure, although the shape of the HC-PBG fiber seems regular for the first glance and consists of hexagonal shape with eight rings of circular air holes, the size of the pitch is not uniform between each adjacent air holes.

4.2 Effective Mode Index:

The hollow fiber had an air filling core with refractive index 1 and a silica of refractive index 1.45 as background material for the cladding region which included holes filled with air. [9] This fiber resulted with an effective refractive index value of <1, [3] and it is clear in this work as shown in figure (23), the effective mode index between 0.993 and 0.994 with response to changes in wavelength from 1500 nm to 1600 nm.

This value considered a good result for this type of fibers as long as less than 1, but this does not mean that the lower effective mode index lead to better results. In fact, the higher reduction of effective mode index led to deteriorates its guidance along the core. [10]
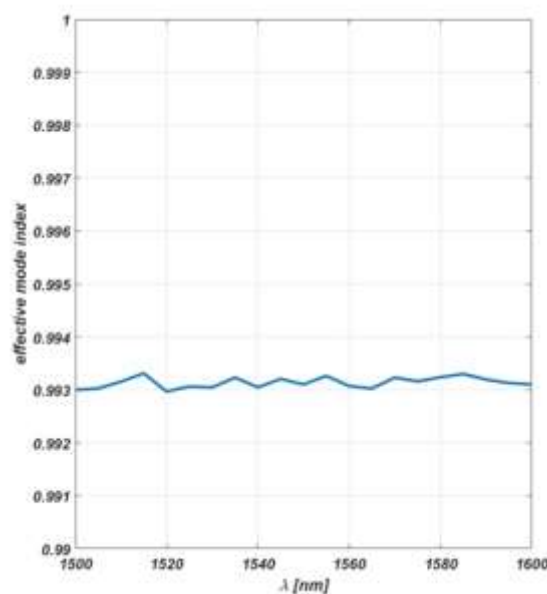

Figure (23) Effective mode index in response to changes in wavelength.

4.3 The Confinement Lose

As denoted before to the confinement lose equation, it depends on the imaginary part of the effective refractive index, this resulted from the high index contrast between air and glass. [3,11] Figure (24) show this important parameter in response to the changes in wavelength.
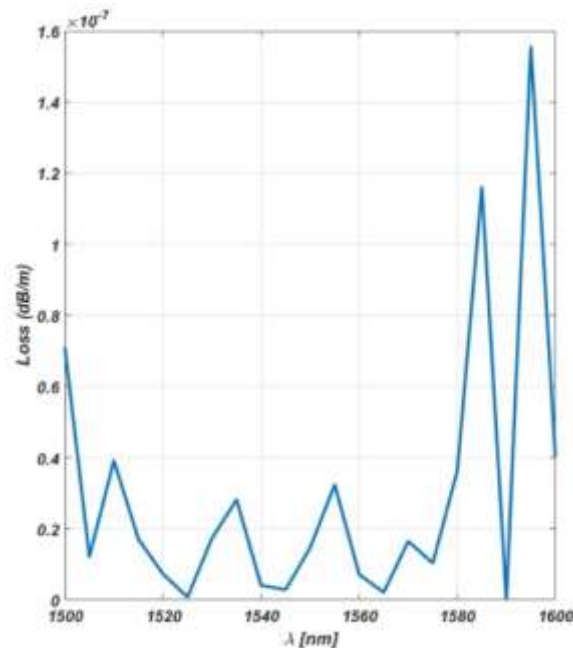

Figure (24) the confinement loses in response to changes in wavelength.

The lowest confinement loss of the proposed optical fiber starts at 1505 nm ending with 1580 nm, out of these wavelengths also considered very low, the reason behind these values was the leak of light from the core to the cladding of the PCF.

Precisely it was noticed that the lowest losses achieved at the wavelengths 1525, 1545 and 1565 nm. The X- polarization and Y-polarization mode belongs to the mentioned wavelengths were extracted in figures (25-a , 25-b, 26-a , 26-b, 27-a , 27-b) respectively.

It is clear from figure (24) there was a low loss in the wavelength1590 nm but could not find its clear mode because there was a high loss before 1590 nm and sharply drop to zero losses -which is an ideal mode- then again get rise to a very high loss. Because of this reason the mode of wavelength 1590 nm excluded.
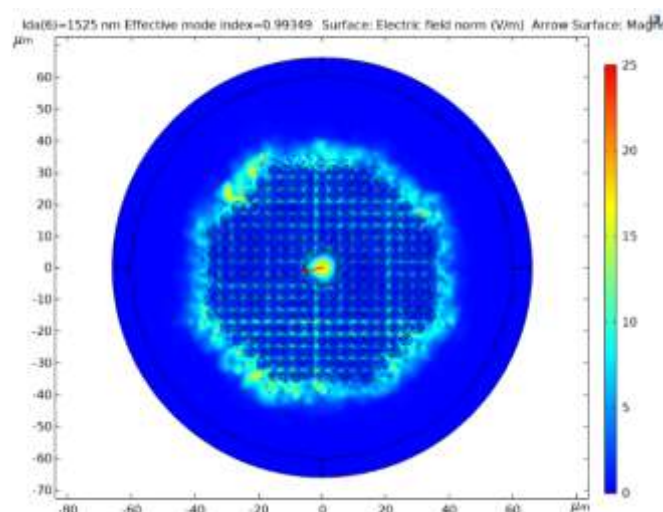

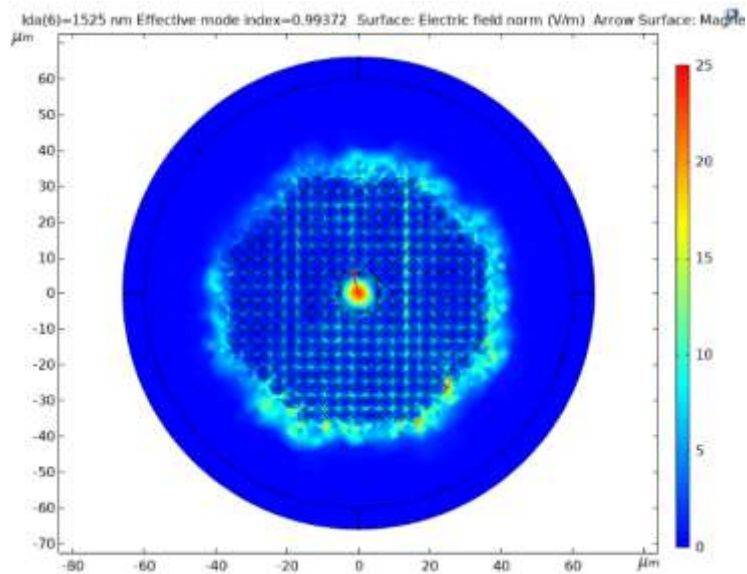Figure (25-a) the X-Polarized mode of 1525 nm

Ida(6)=1525 nm Effective mode index=0.99372 Surface: Electric field norm (V/m) Arrow Surface: Magne...

Figure (25-b) the Y-Polarized mode of 1525 nm

Ida(10)=1545 nm Effective mode index=0.99332 Surface: Electric field norm (V/m) Arrow Surface: Magn...

Figure (26-a) the X-Polarized mode of 1545 nm

Ida(10)=1545 nm Effective mode index=0.99335 Surface: Electric field norm (V/m) Arrow Surface: Magn...
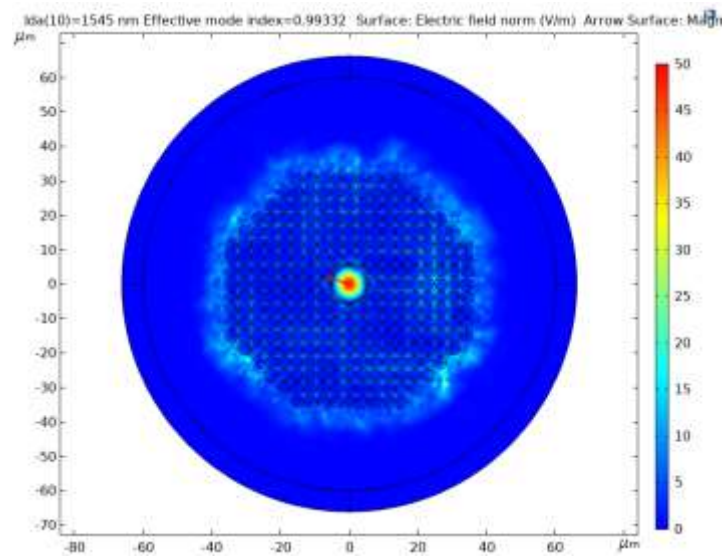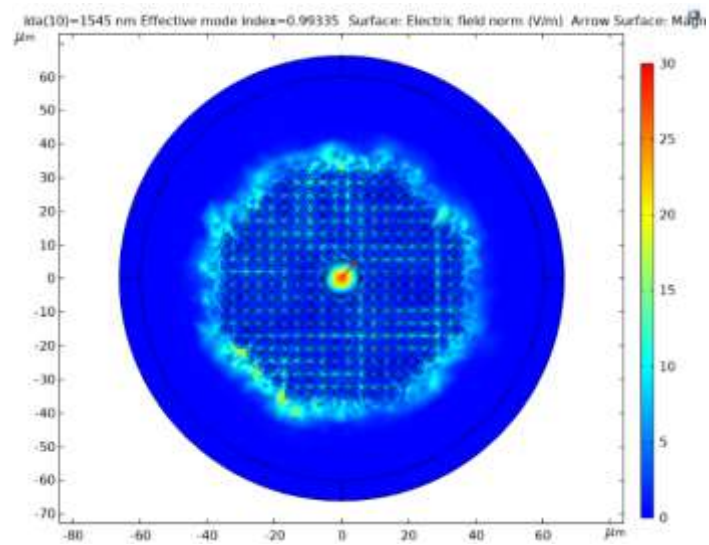
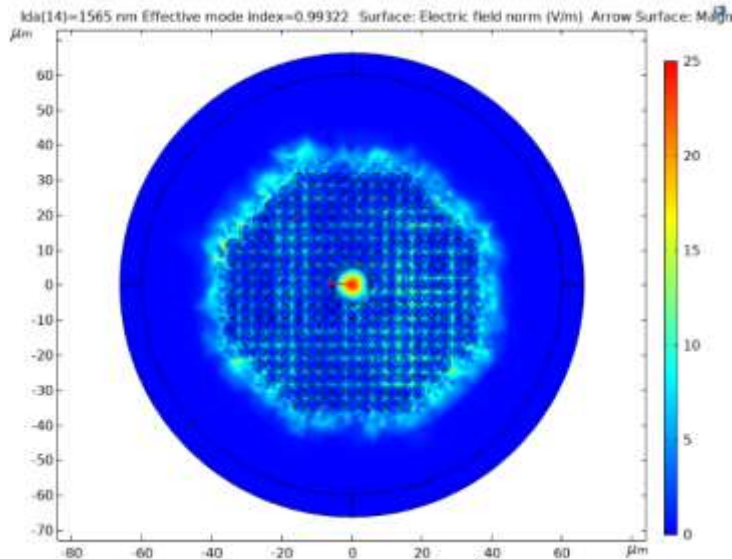Figure (26-b) the Y-Polarized mode of 1545 nm
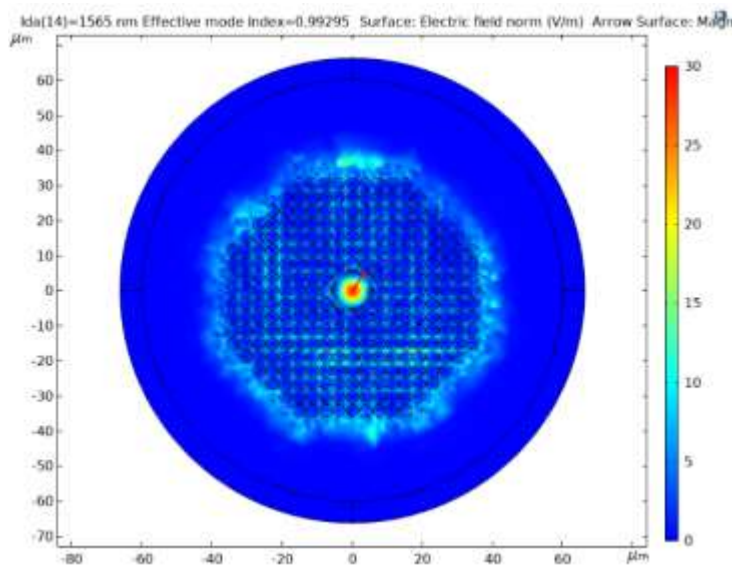
Figure (27-a) the X-Polarized mode of 1565 nm

Figure (27-b) the Y-Polarized mode of 1565 nm

5. Conclusions

In this paper, the fiber characteristics were analyzed within the wavelength range 1500–1600 nm. The fundamental mode profile, intensity, effective mode index, confinement lose, and the effect of the pitch which is the most important structure parameter were analyzed precisely then from this research the following conclusions can be drawn:

1.The pitch is one of the most important structure parameters, [11] chosen to be non-uniform to see its effect on the fiber performance. To achieve this non uniformities we arranged the circular air holes using the rectangular array instruction in COMSOL.

In spite of this selection, the mode was confined in the core with electric field 35 V/m in the wavelength 1550 nm, it was noticeable that the shape of the mode was not a perfect circular shape.

It is required to adjust the pitch and other structure parameters such as the core diameter and the air holes diameters as well.

2. check the effect of these parameters on the effective mode index which is expected to deviate to higher values, at that time some other parameters need to adjust in order to achieve the best result.

3.It is expected after adjustment the parameters, the loss will be lower in the wavelength lower than 1500 nm and higher than 1580 nm as well.

6. Applications:

The unique characteristics including the strong confinement make this fiber to be ideal for liquid and gas sensing applications where a strong interaction with light will be executed in the confined mode. [12]

Resources:

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