

Design and Simulation of Fiber Bragg Grating by Comsol Multiphysics Software

Shaymaa Riyadh Aal Tahhan¹, Ayat Falih²

^{1,2}Nahrain University, College of Engineering, Laser and Optoelectronics Engineering Department, Abo-Noas street, Jadriyah, Baghdad, Iraq

Abstract: In this research, new software Comsol Multiphysics v.5.2 was used to study the mode distribution at the ends of step index optical fiber. Single mode Optical Fiber (SMF) and Multimode Optical Fiber (MMF) intensity distributions were presented in 2D Design. The modes in SMF were confined perfectly. Then, a 3D model of FBG was built on SMF with the same parameters of core and clad radius, refractive index of core and refractive index of clad. The most confined modes were appeared at 1550nm since this wave length is lossless in optical fiber. Increasing the periods of the grating inside the core will confined the modes at the transmission mode in the case of uniform Bragg grating.

Keywords: Fiber Bragg Grating, Comsol Multiphysics, 3D simulation, step index fiber, single mode fiber, multi-mode fiber

1. Introduction

A fiber Bragg grating (FBG) is a periodic change of the refractive index across the fiber length which is made by exposure of the core to an intense optical interference pattern. Permanent grating formulation in an optical fiber was first demonstrated by Hill ET align 1978 at the Canadian Communications Research Centre (CRC), Ottawa, Ont., Canada [1].

Recently, however, all this has changed with the ability to alter the core index of refraction in a single mode optical fiber by optical absorption of UV light. The photosensitivity of optical fibers allows the fabrication of phase structures directly into the fiber core, called FBG, [2].

The length of the grating increased due to increasing the number of grating. Further increments in the grating length seem to have an insignificant impact on the spectrum [3].

In the last years, mid-infrared radiation emitted by CO₂ lasers has become increasing popular as a tool in the development of long-period fiber gratings. 3D finite element model is presented to simulate the interaction between laser radiation and an optical fiber and to determine the resulting refractive index change. Dependence with temperature of the main parameters of the optical fiber materials (with special focus on the absorption of incident laser radiation) is considered, as well as convection and radiation losses [4].

Studying the 2D model of a fiber was illustrated under different wavelength EM radiation (530 nm, 1310 nm, and 1530 nm), also they introduced a novel 3D model of FBG. The 3D model of the FBG is used to study the modes of the fiber under varying grating period (1310 nm, 908.62 nm, and 454.31 nm) and with varying number of slabs in the grating (10, 50, and 100)[5].

Thus, in this work, the values of the grating period, grating length, and number of periods are changed in three stages to examine our proposed FBG.

Many studies had been performed on the step index and

graded index optical fiber showing the mode distribution in the transmission end. Here we suggest a study of the mode distribution on single mode fiber Bragg grating. Comsol Multiphysics V5.2 was used for the first time in our department for undergraduate project to perform this simulation study. The reflection tangential mode of electric field for 1550.9 nm was recorded for the fiber Bragg grating.

As follows the structural of this research paper was represented. Section two displayed the general introduction on the FBG. The basic structure of optical fiber was briefly described in section two, where it was included the ray theory in fiber Bragg grating. The modes distribution in single mode optical fiber was demonstrated in section two also.

Simulation steps of the two dimensional Single Mode (SMF) and Multimode Optical fiber (MMF) were recorded in details Section three. The simulation steps of the 3D fiber Bragg grating were presented in section 3.2. The resultant modes were displayed in section four for both 2D and 3D structure. Finally the conclusion was presented in section 5.

2. Theoretical Background

FBG in its simplest structure consists of a periodic change in the refractive index in the core of single mode optical fiber [6]. This is the uniform FBG and it is the main building block for most FBG structure, Fig. (1).

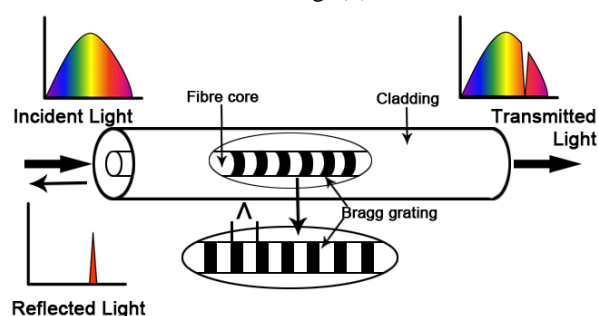


Figure 1: Structure of a uniform Bragg grating with constant pitch[7]

The Bragg grating condition satisfies both energy momentum conversations. Energy conversation requires that that the frequency of the incident radiation and the reflected radiation to be equal. Momentum conversation requires that the wave vector of the scattered radiation to be equal the incident wave vector plus the grating wave vector, k as follows [6]

$$k_i + k = k_f \quad (1)$$

Where the grating wave vector, k , has a direction normal to the grating planes with a magnitude (Λ is the grating spacing). The diffracted wave is equal in magnitude but opposite in direction to the incident wave vector. Thus, the momentum conversation condition becomes [7]

$$2 \left[\frac{2\pi n_{\text{eff}}}{\lambda_B} \right] = \frac{2\pi}{\Lambda} \quad (2)$$

It is explicitly a Bragg condition,

$$\lambda_B = 2n_{\text{eff}}\Lambda \quad (3)$$

Where λ_B is the back reflected Bragg grating wavelength which is, the free space center wavelength of the light from the Bragg grating, and n_{eff} is the effective refractive index of the fiber core at the Bragg grating wavelength [8].

2.1 Induced refractive index change

The simplest uniform fiber Bragg grating structure in optical fiber is an axial (x) and periodic change of the refractive index of the core with a refractive index profile given by [9]

$$n_{\text{eff}}(x) = n_o + \Delta n \cos\left(\frac{2\pi x}{\Lambda}\right) \quad (4)$$

Where Δn is the amplitude of the induced refractive index perturbation, n_o is the average index of the fiber core, x is the distance along the fiber's longitudinal axis and Λ is the grating period. The typical value of Δn varies in the range 10^{-5} to 10^{-2} .

2.2. Modes in Step Index Optical Fiber

"Optical fibers can easily support hundreds of spatial modes, but today's commercial systems - single mode or multimode - make no attempt to use these as parallel channels," notes Prof. David Richardson, deputy director of the Optoelectronics Research Centre at the University of Southampton in the U.K [10].

Fig. (1) for step index profile type, shows the dependence of the normalized propagation constant

$$B = (n_{\text{eff}}^2 - n_{\text{cl}}^2) / (n_{\text{co}}^2 - n_{\text{cl}}^2) \quad (5)$$

on the normalized frequency

$$V = 2\pi a / \lambda (n_{\text{co}}^2 - n_{\text{cl}}^2)^{0.5}, \quad (6)$$

where n_{eff} is the effective index of the LP mode, n_{co} and n_{cl} are the indexes of the core and of the cladding, respectively, a is the core radius, and λ is the wavelength, [11]. For any p -LP-mode fiber, one simply chooses V to be close to the highest possible value that allows for the first

p LP modes to propagate while cutting off the next higher-order LP modes. This way, the p LP modes have B close to their highest possible values and are thus less bend sensitive [11].

Intensity distributions of linearly polarized modes for a step index optical fiber was shown in Fig.(2), [12]. These experimental modes were used with to be comparing with our simulation results.

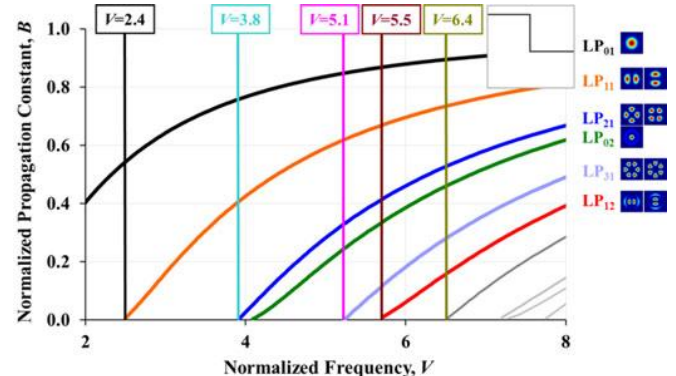


Figure 1: Normalized propagation constant, B , versus normalized frequency, V , for step index core profiles, [11].

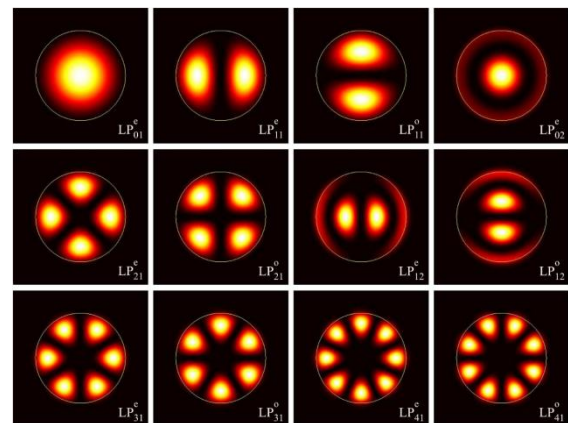


Figure 2: Intensity distributions of linearly polarized modes for a step index optical fiber [12].

3. Simulation Using COMSOL

The design and physically analysis of optical fiber was performed using the Comsol Multiphysics software package V.5.2. The optical fiber design is simulated to produce multi technical specification of optical fiber such as Frequency Domain, Mode Analysis for 2D optical fiber and Boundary Mode Analysis for 3D fiber Bragg grating.

The Wave Optics, Electromagnetic Waves, Frequency Domain interface are used to study, analysis and solve for time-harmonic electromagnetic field distributions.

The design limitation for this physics interface, the maximum mesh element size should be limited to a fraction of the wavelength. The domain size that can be simulated thus scales with the amount of available computer memory and the wavelength.

The physics interface supports the study types Frequency Domain, Eigen frequency, Mode Analysis, and Boundary Mode Analysis. The Frequency Domain study type is used

for source driven simulations for a single frequency or a sequence of frequencies. The Eigen frequency study type is used to find resonance frequencies and their associated eigen modes in resonant cavities. This physics interface solves the time-harmonic wave equation for the electric field.

3.1. Two Dimension Simulation steps of SMF and MMF

3.1.1 2D simulation for Single Mode Fiber (SMF)

As a first consideration the two dimensional single mode optical fiber design was performed. The simulation steps were stated below:

(a) MODEL WIZARD

- 1) In the MODEL WIZARD window, 2D was clicked.
- 2) In the Select Physics tree, Wave Optics>Electromagnetic Waves, Frequency Domain (emw) were selected.
- 3) Add was clicked.
- 4) Study was clicked.
- 5) In the Select Study tree, Present Studies>Mode Analysis was selected.
- 6) Done was clicked.

(b) Global Definitions

- 1) Right Click global definition to add parameters, as shown in Table 1.

Table 1: Parameter values for 2D single mode optical fiber.

Name	Expression	Value	Description
r_core	4.6[um]	4.6E-6m	The radius of core
r_clad	62.5[um]	6.25-5m	The radius of clad
n_core	1.4457	1.4457	The refractive index of core
n_clad	1.4378	1.4378	The refractive index of clad
n_eff	1.4417	1.4417	The effective index
lambda	1.55[um]	1.5509E-6m	The incident wave length
f0	c_const/lambda	1.9331E14 1/s	The frequency domain

(c) Geometry 1

- 1) In the Model Builder window, under Component 1 (comp1) Geometry 1 was clicked.
- 2) In the Setting window for Geometry, The Units section was located.
- 3) From the Length unit list, μm was chosen.

Circle 1 (c1) (clad)

- 1) On the Geometry toolbar, primitives were clicked and size was chosen.
- 2) 2. In the settings window for circle, the size and shape sections were located.
- 3) In the radius text field, r_clad was typed.

Circle 2 (c2) (core)

- 1) Circle 1(c1) was right clicked and build selected was chosen.
- 2) On the geometry toolbar, primitives were clicked and circle was chosen.
- 3) In the settings window for circle, the size and shape section were located.
- 4) In the radius text field, r_core was typed.
- 5) Circle2 (c2) was right clicked and build selected was chosen.

(d) MATERIALS

In the model builder window, under component I(comp) materials were clicked and blank material was chosen.

Material 1(mat1) (core)

- 1) In the settings window for material, doped silica Glass was typed.
- 2) Domian2 only was selected.
- 3) The Material Properties section was expanded. The Material Properties section was located.
- 4) In the Material properties tree, Electromagnetic Mode>Refractive index>Refractive index, real part (n) was selected.
- 5) Add to Material was clicked.
- 6) The Material contents section was clicked. The n_core for the refractive index real part was entered.

Material 2 (mat2) (clad)

- 1) Material was right clicked and Blank Material was chosen.
- 2) In the Setting window for Material, silica Glass in the Label text field was typed.
- 3) Domain 1 only was selected.
- 4) The Material Properties section was clicked to expand. The Material Properties section was located.
- 5) In the Material Properties tree, Electromagnetic Models>Refractive index>Refractive index, real part (n) was selected.
- 6) Add to Material was clicked.
- 7) The Material contents section was located. The n_core for the refractive index real part was entered.

(e) Electromagnetic Wave, Frequency Domian (EMW)

Wave Equation Electric 1

- 1) In the Model Builder window, the component 1 (comp1)>Electromagnetic waves, Frequency Domain (emw) node were expanded, and then Wave Equation, Electric 1 was clicked.
- 2) In the setting window for Wave Equation, Electric, the Electric Displacement Field section was located.
- 3) From the Electric displacement field model list, Refractive index was chosen.

(f) MESH 1

- 1) In the Model Builder window, under component 1(com1) Mesh1 was clicked.
- 2) In the setting window for mesh, the mesh setting section was located.
- 3) From the Element size list, finer was chosen.
- 4) Build All was clicked.

(g) Study 1

Step 1: Mode Analysis

- 1) In the setting window for Mode Analysis, the Study Setting section was located.
- 2) The Search modes around check box was selected.
- 3) In the associated text field n_eff was typed.
The modes of interest have an effective mode index somewhere between the refractive indices of the two materials .The fundamental mode has the highest index .Therefore, setting the mode index to search around to some think just above the core index guarantees that the

solver will find the fundamental mode.

- 4) In the mode analysis frequency text field, type **f0**.
(This frequency corresponds to a free space wave length of 1.55 μm)
- 5) On the Home toolbar, Compute was clicked.

Step2: Frequency Domain

- 1) In the setting window for Frequency Domain, the Study Setting section was located.
- 2) In the frequencies text field, **f0** was typed.
- 3) On the Home toolbar, Compute was clicked

3.1.2 2D Simulation for Multi-Mode Fiber (MMF)

In the second consideration the two dimensional multi-mode optical fiber design was performed. The simulation steps were stated below:

(a) Global Definitions

- 1) Right Click global definition to add parameters, as shown in Table 2.

Table 2: Parameter values for 2D Single mode optical fiber.

Name	Expression	Value	Description
r_core	20[um]	20E-6m	The radius of core
r_clad	62.5[um]	6.25E-5m	The radius of clad
n_core	1.4457	1.4457	The refractive index of core
n_clad	1.4378	1.4378	The refractive index of clad
n_eff	1.446	1.446	The effective index
lambda	1.5509E-6 m	1.55	The incident wave length
f0	c_const/lambda	1.9331E14 1/s	The frequency of light

(b) MODEL WIZARD

- 1) In the MODEL WIZARD window, 2D was clicked.
- 2) In the Select Physics tree, Wave>Electromagnetic Waves, Frequency Domain (emw) was selected.
- 3) Add was clicked.
- 4) Study was clicked.
- 5) In the Select Study tree, Present Studies>Mode Analysis was selected.
- 6) Done was clicked.

(c) GEOMETRY 1

- 1) In the Model Builder window, under Component 1 (comp1) Geometry 1 was clicked.
- 2) In the Setting window for Geometry, The Units section was located.
- 3) From the Length unit list, μm was chosen.

Circle 1 (c1) (clad)

- 1) On the Geometry toolbar, primitives were clicked and circle was chosen.
- 2) In the settings window for circle, the size and shape sections was located.
- 3) In the radius text field, **r_clad** was typed.
- 4) Circle 1 was right clicked and Build selected was chosen.

Circle 2 (c2) (core)

- 1) On the Geometry toolbar, primitives were clicked and circle was chosen.
- 2) In the settings window for circle, the size and shape sections was located.
- 3) In the radius text field, **r_core** was typed.
- 4) Circle2 (c2) was right clicked and build selected was chosen.

(d) Materials

In the model builder window, under component I(comp) materials were right clicked and blank material was chosen.

Material 1(mat1)

- 1) In the settings window for material, doped silica Glass was typed.
- 2) Domain 2 only was selected.
- 3) The Material Properties section were expanded .The Material Properties section were located.
- 4) In the Material properties tree, Electromagnetic Mode>Refractive index>Refractive index, real part (n) were selected.
- 5) Add to Material was clicked.
- 6) The Material contents section was located. The **n_core** for the refractive index real part was entered.

Material 2 (mat2)

- 1) Material was right clicked and Blank Material was chosen.
- 2) In the Setting window for Material, silica Glass in the Label text field was typed.
- 3) Domain 1 only was selected.
- 4) The Material Properties section was expanded. The Material Properties section was located.
- 5) In the Material Properties tree, Electromagnetic Models>Refractive index>Refractive index, real part (n) were selected.
- 6) Add to Material was clicked.
- 7) The Material contents section was located. The **n_clad** for the refractive index real part was entered.

(e) Electromagnetic Wave, Frequency Domian (EMW)

Wave Equation Electric 1

- 1) In the Model Builder window, the component 1 (comp1)>Electromagnetic waves, Frequency Domain (emw) node, then Click Wave Equation, Electric 1 were expanded.
- 2) In the setting window for Wave Equation, Electric, the Electric Displacement Field section was located.
- 3) From the Electric displacement field model list, Refractive index was chosen.

(f) MESH 1

- 1) In the Model Builder window, under component 1(com1) was Mesh1.
- 2) In the setting window for mesh , the mesh setting section was located.
- 3) From the Element size list, Finer was chosen.
- 4) Build All was clicked.

(g) STUDY 1

Step 1: Mode Analysis

- 1) In the setting window for Mode Analysis, the Study Setting section was located.

- 2) The Search modes around check box was selected.
- 3) In the associated text field **n_eff** was typed.
- 4) The modes of interest have an effective mode index somewhere between the refractive indices of the two materials .The fundamental mode has the highest index .Therefore, setting the mode index to search around to some think just above the core index guarantees that the solver will find the fundamental mode.
- 5) In the mode analysis frequency text field, type **f0**.
- 6) On the Home toolbar, Compute was clicked.

3.2. 3D Model for Fiber Bragg Grating

The “Kevin P. Chen et.al , at the University of Pittsburgh ” team resultant experimental fabrication of Fiber Bragg Grating was used to build the 3D model from [8], expect we used the single mode tradition shape.

In the first step, we built the fiber without grating and then with grating. The fiber without grating was considered as a reference point. The list of parameters was shown in table 3. The incident wave lengths that were chosen based on the availability of light sources transmitting/absorbing materials (fibers) and detectors. The wavelength of 1550 nm(C-band) was chosen.

The grating periods are inversely proportional to the effective refractive index. In the other hand the effective refractive index is proportional to the incident wavelength as shown in the eq.(3).

The method is to assign the best effective refractive index according to the incident wave length by using the reference optical fiber in C-band.

The physics module of the 3D simulation was wave optic>electromagnetic wave>frequency domain. The 3D wave equation was

$$\nabla \times (\nabla \times E) - K_0^2 \epsilon_r E = 0 \quad (7)$$

The Eigen values calculated by Comsol were in the form:

$$\lambda = -i\beta - \delta \quad (8)$$

$$\epsilon_r = (n - ik)^2 \quad (9)$$

$$k_0 = \frac{\omega}{c_0} \sqrt{\epsilon_0 \mu_0} = \frac{\omega}{c_0} \quad (10)$$

Where E is the incident electric field; δ is the real part of the solution responsible for damping; β is the Eigen frequency n is the refractive index (real part); k is the imaginary part of the refractive index; k_0 is the wave number of the free space; μ_0 is the permeability of free space, and c_0 is the speed of light in vacuum.

The geometry of the optical fiber was built by using two cylinders. The first cylinder represents the core with a radius of r-core. The other outer cylinder represented the clad with a radius of r-clad. The material was chosen as doped silica with refractive of n_{core} for core material and a silica glass with refractive index of n_{clad} for cladding cylinder.

A perfectly matched layer (PML) was used to confine the light inside the core. PML type was chosen to be cylindrical. This layer is added to the second cylinder (cladding) by 20

um thickness.

To study the modes of the scattered wave and transmitted one, a boundary mode analysis was used for both faces (boundary) of the optical fiber.

A scattering boundary condition was used. The scattering boundary made the boundary transparent for both incident and scattered light. The incident wave was an electric light field and has a plane propagation wave toward z-direction, the incident wave is set to (-1, 1, 0) in (x ,y, z) . The model equation for this boundary was

$$n \times (\nabla \times E) - i k n \times (E \times n) = -n \left(E_0 \times \left(i k (n - k_{air}) \right) \right) e^{i k \cdot k_{air} \cdot r} \quad (11)$$

$$E_{sc} = E_{sc} e^{-i k (n \cdot r)} \quad (12)$$

$$E_{sc} = E_{sc} e^{-i k (n \cdot r)} + E_0 e^{-i k (k_{air} \cdot r)} \quad (13)$$

Where k is the directional vector of the wave; k is the wave number; E is the incident plane wave.

Two ports added at both ends of the optical fiber where the light enters and leave. The type of both ports was set to numeric. The port where light enters was set as an excitation port. The incident light set to on, with an input power of 1 watt.

The periods of the gratings were set to 527[nm] according the reference [8]. The length of the FBG was calculated to be in form:

$$\text{Length} = 2NP \quad (14)$$

Where N ; is the number of grating periods, and P ; is the grating periods.

The study was performance using the boundary mode analysis for both ports and frequency domain to perform the propagation. The number of grating periods was chanced for each wavelength by 1, 3, and 5.

(a) GLOBAL DEFINITIONS

- 1) Right Click global definition to add parameters, as shown in Table 3.

Table 3: Parameter values of 3D Optical Fiber.

Name	Expression	Value	Description
n1	1.4457	1.4457	core refractive index
n2	1.4378	1.4378	cladding refractive index
n3	1.446	1.446	step index grating refractive index
dn	1e-3	0.001	the amplitude of the induced refractive index perturbation
N	5	5	Number of periods
L	N*2*P	5.36E-6 m	fiber length
n_eff	n1 + (dn*cos((2*pi*L)/(P)))	1.4467	effective refractive index
lambda	2*n_eff*P	1.5509E-6 m	incident light wavelength
f0	c_const/lambda	1.9331E14 1/s	frequency of the light
r_core	4.6[um]	4.6E-6 m	core radius
r_cladding	62.5[um]	6.2E-5 m	cladding radius
P	536[nm]	5.36E-7 m	grating period

(b)MODEL WIZARD

GEOMETRY 1

Cylinder 1 (c1) (clad)

- 1) On the Geometry toolbar, primitives were clicked and circle was chosen.
- 2) In the settings window for circle, the size and shape sections was located.
- 3) In the radius text field, **r_clad was typed.**
- 4) In the height text field, L was typed.
- 5) Circle2 (c2) was right clicked and build selected was chosen.

Cylinder 2 (c2) (core)

- 1) On the Geometry toolbar, primitives were clicked and circle was chosen.
- 2) In the settings window for circle, the size and shape sections was located.
- 3) In the radius text field, **r_core was type.**
- 4) In the height text field, L was typed
- 5) Circle2 (c2) was right clicked and build selected was chosen.

Cylinder 3 (c3) (one slab)

- 1) On the Geometry toolbar, primitives were clicked and circle was chosen.
- 2) In the settings window for circle, the size and shape sections was located.
- 3) In the radius text field, **r_core was type.**
- 4) In the height text field, p was typed
- 5) Circle3 (c3) was right clicked and build selected was chosen.

Array1 (arr1)

- 1) Geometry was right clicked, from Transforms Array was selected.
- 2) In the setting window for Array, from Array type Linear was chosen.
- 3) In the Displacement section, in the text field of z, 2π was typed.
- 4) Build selected was chosen.

(c) Materials

In the model builder window, under component I(comp1) materials were right clicked and blank material was chosen.

Material (mat1)

- 1) In the settings window for material, doped silica Glass was typed.
- 2) Domain 2 only was selected.
- 3) The Material Properties section were expanded .The Material Properties section were located.
- 4) In the Material properties tree, Electromagnetic Mode>Refractive index>Refractive index, real part (n) were selected.
- 5) Add to Material was clicked.
- 6) The Material contents section was located. The **n_core** for the refractive index real part was entered.

Material 2 (mat2)

- 1) Material was right clicked and Blank Material was chosen.
- 2) In the Setting window for Material, silica Glass in the Label text field was typed.
- 3) Domain 1 only was selected.

- 4) The Material Properties section was expanded. The Material Properties section was located.
- 5) In the Material Properties tree, Electromagnetic Models>Refractive index>Refractive index, real part (n) were selected.
- 6) Add to Material was clicked.
- 7) The Material contents section was located. The **n_clad** for the refractive index real part was entered.

Material 3 (mat3) of grating

- 1) In the settings window for material, doped silica Glass was typed.
- 2) Domain 2 only was selected.
- 3) The Material Properties section were expanded .The Material Properties section were located.
- 4) In the Material properties tree, Electromagnetic Mode>Refractive index>Refractive index, real part (n) were selected.
- 5) Add to Material was clicked.
- 6) The Material contents section was located. The **n_core** for the refractive index real part was entered.

(d) Electromagnetic Wave, Frequency Domain (EMW) Wave Equation Electric 1

- 1) In the Model Builder window, the component 1 (comp1)>Electromagnetic waves, Frequency Domain (emw) node, then Click Wave Equation, Electric 1 were expanded.
- 2) In the setting window for Wave Equation, Electric, the Electric Displacement Field section was located.
- 3) From the Electric displacement field model list, Refractive index was chosen.

Port1

- 1) Electromagnetic wave, Frequency domain was right clicked, port was chosen.
- 2) In the port properties section 1 was typed in the port name text field, Numeric was chosen from Type of port.
- 3) From wave excitation port off was chosen.
- 4) In the port input power 1[W] was typed in the P_{in} text field, and 0 was typed in θ_{in} .

Port2

- 1) Electromagnetic wave, Frequency domain was right clicked, port was chosen.
- 2) In the port properties section 1 was typed in the port name text field, Numeric was chosen from Type of port.
- 3) From wave excitation port off was chosen.
- 4) In the port input power 1[W] was typed in the P_{in} text field, and 0 was typed in θ_{in} .

(e) MESH 1

- 1) In the Model Builder window, under component 1(com1) was Mesh1.
- 2) In the setting window for mesh, the mesh setting section was located.
- 3) From the Element size list, Finer was chosen.
- 4) Build All was clicked.

(f) STUDY 1

Step 1: Boundary mode analysis

- 1) In the setting window for Boundary Mode Analysis, the Study Setting section was located.
- 2) In the port name text field 1 was typed.
- 3) The Search modes around check box selected.
- 4) In the associated text field **n_eff** was typed.
 The modes of interest have an effective mode index somewhere between the refractive indices of the two materials. The fundamental mode has the highest index. Therefore, setting the mode index to search around to some think just above the core index guarantees that the solver will find the fundamental mode.
- 5) In the mode analysis frequency text field, **f0** was typed.

Step 2: Boundary mode analysis

- 1) In the setting window for Boundary Mode Analysis, the Study Setting section was located.
- 2) In the port name text field 2 was typed.
- 3) The Search modes around check box selected.
- 4) In the associated text field **n_eff** was typed.
 The modes of interest have an effective mode index somewhere between the refractive indices of the two materials. The fundamental mode has the highest index. Therefore, setting the mode index to search around to some think just above the core index guarantees that the solver will find the fundamental mode.
- 5) In the mode analysis frequency text field, type **f0**.

Step3: Frequency Domain

- 1) In the setting window for Frequency Domain, the Study Setting section was located.
- 2) In the frequencies text field, **f0** was typed.
- 3) On the Home toolbar, Compute was clicked.
- ...

Results

In this section the results of transmission mode for both design of two dimensional single mode fiber and multimode fiber were displayed in section 4.1, whereas section 4.2 showed the transmission modes of the three dimensional (3D) single mode fiber with Bragg grating. In the first case the Bragg grating was illustrated with 3 periods and in the second case with 10 periods.

4.1. Two Dimensional Step Index Optical Fiber Results

4.1.1 Single Mode Optical Fiber

For single mode fiber, the parameters were as shown in chapter two, section 2.1.1. The resultant Meshing was shown in Fig. (3).

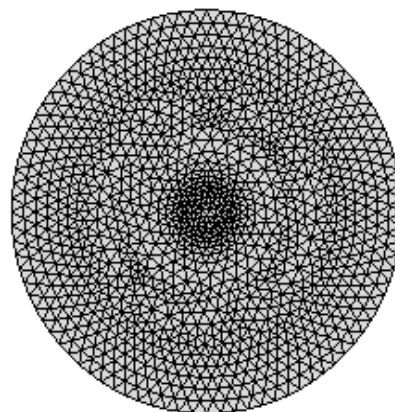


Figure 3: The resultant meshing for the two dimensional single mode optical fiber.

The study was implemented for three different wavelengths 850nm 1330nm, and 1550nm as shown in Fig.(4), (5) and (6), respectively. The number of the modes searching was set to 6 modes. The electric field (EMW) was shown in the graphic toolbar. The default plot shows the distribution of the normal electric field for the highest effective index of the 6 computed modes (the one with the lowest effective mode index). The expression was changed to Component1>Electromagnetic Wave, Frequency Domian>Electric>Electric field>emw.Ez-Electric field, z component.

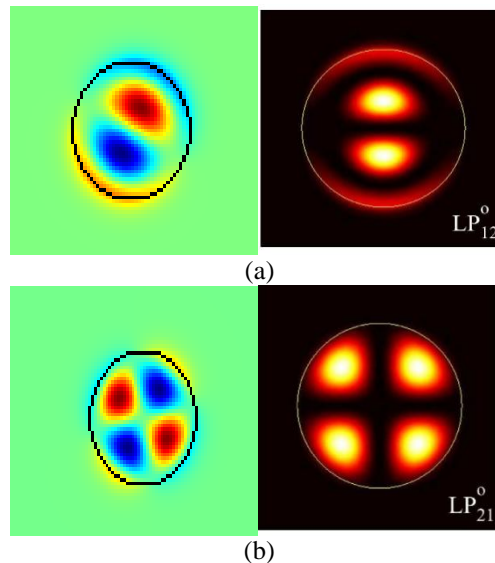
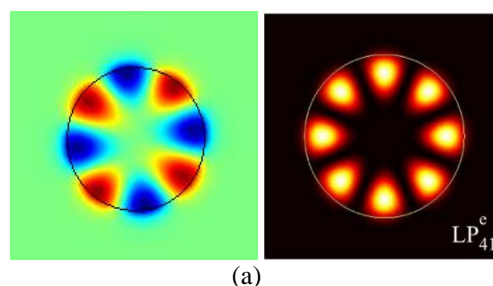


Figure 4: (a) LP_{12}^o mode, (b) LP_{21}^o mode for SMF at 850nm; experimental from ref. [16] on the right compared to simulated result on the left.



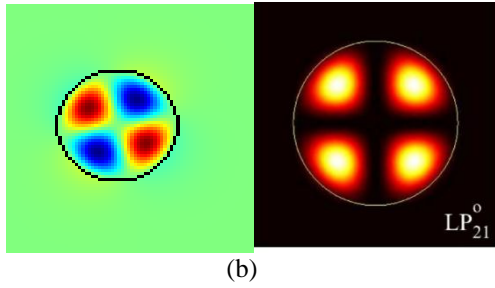


Figure 5: (a) LP_{41} mode, (b) LP_{21} mode for SMF at 1330nm; experimental from ref. [16] on the right compared to simulated result on the left.

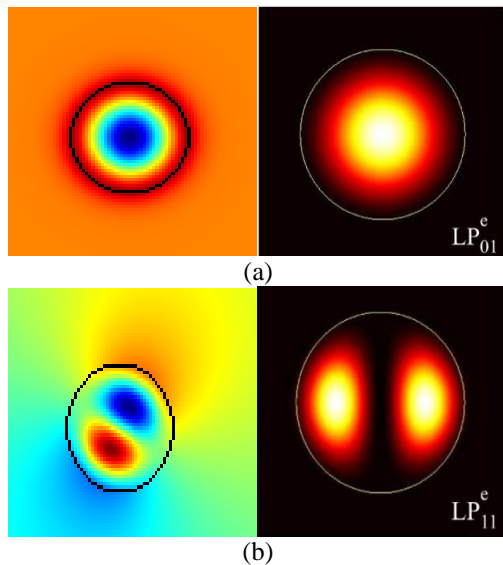


Figure 6: (a) LP_{01} mode, (b) LP_{11} mode for SMF at 1550nm; experimental from ref. [12] on the right compared to simulated result on the left.

1.1.2 Multi-Mode Optical Fiber

For multimode optical fiber, the parameters were shown in chapter two, section 2.1.2. The resultant meshing was shown in Fig. (7). The study was implemented for three different wavelengths 850nm 1330nm, and 1550nm as shown in Fig.(8), (9) and (10), respectively. The number of the modes searching was set to 6 modes. The electric field (EMW) was shown in the graphic toolbar. The default plot shows the distribution of the normal electric field for the highest effective index of the 6 computed modes (the one with the lowest effective mode index). The expression was changed to Component1> Electromagnetic Wave, Frequency Domain>Electric>Electric field>emw.Ez-Electric field, z component.

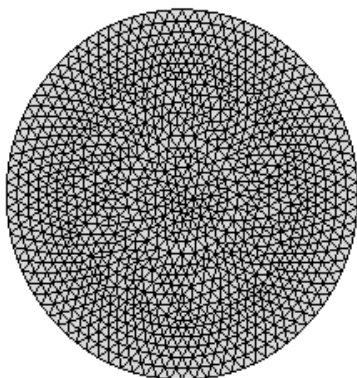


Figure 7: The resultant meshing for the two dimensional multi-mode optical fiber.

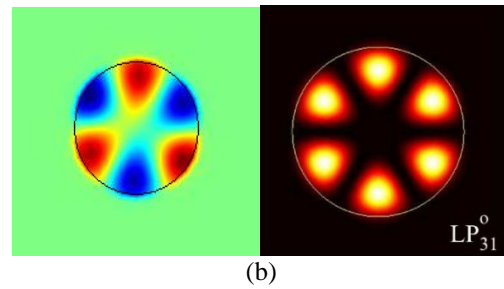
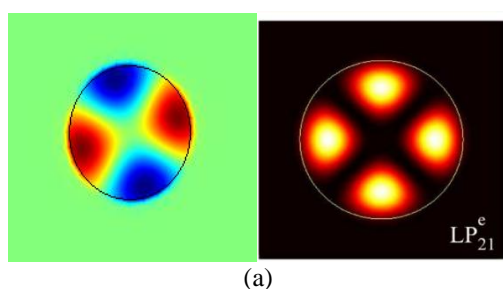


Figure 8: (a) LP_{21} mode, (b) LP_{31} mode for MMF at 850nm; experimental from ref. [12] on the right compared to simulated result on the left.

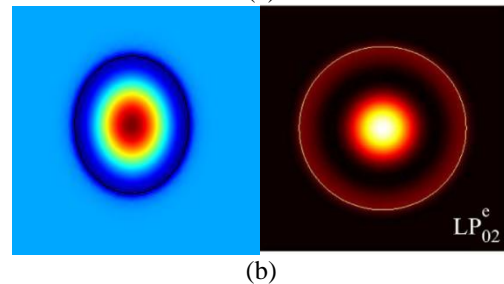
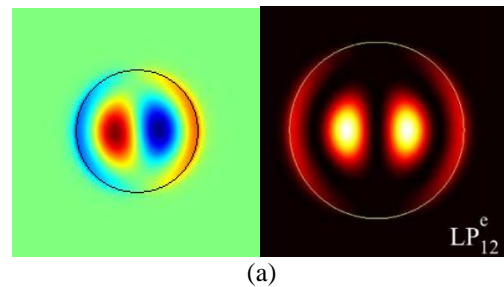


Figure 9: (a) LP_{12} mode, (b) LP_{02} mode for MMF at 1330nm; experimental from ref. [12] on the right compared to simulated result on the left.

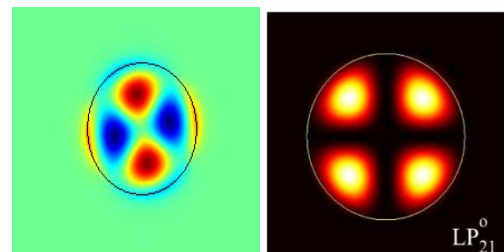


Figure 10: (a) LP_{21} mode for MMF at 1550nm; experimental from ref. [12] on the right compared to simulated result on the left.

4.2. Three Dimensional Optical Fiber with Bragg Grating Results

The three dimensional design of the fiber Bragg grating was illustrated as shown previously in chapter two with the parameters stated in section 2.2. Two designs were considered the first with 3 periods in the core and the other with 10 periods. The resultant geometry was shown in Fig.(11). In the same manner the resultant tangential electric field for the transmitted signal was displayed by take into account the boundary mode analysis study. The electric field distribution of the transmitted wave for 3 Bragg periods was shown in Fig. (12), while for 10 periods was shown in Fig. (13) at 1550.9nm. This wavelength was considered because it is the window of optical fiber.

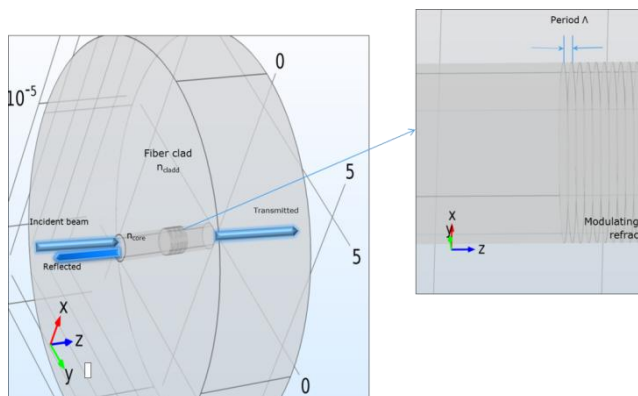


Figure 11: The resultant three dimensional geometry of fiber Bragg grating with 10 periods.

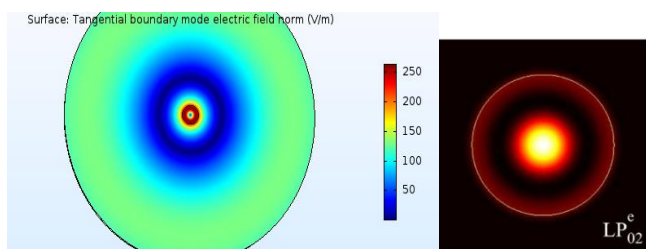


Figure 12: LP_{02} mode for FBG with 3 periods at 1550.9nm; experimental from ref. [12] on the right compared to simulated result on the left.

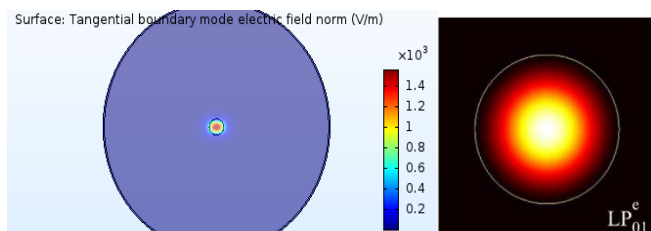


Figure 13: LP_{01} mode for FBG with 10 periods at 1550.9nm; experimental from ref. [12] on the right compared to simulated result on the left.

Conclusion

In this project, new software Comsol Multiphysics v.5.2 was used to study and analysis the mode distribution at the ends of step index optical fiber. As a reference study the two dimensional design of single mode and a multimode optical fiber were built. Here the mode analysis study was used to draw the electromagnetic field of the optical fiber in both cases. The study was performed for three different wavelength 850nm, 1330nm, and 1550 nm. The resultant modes were compared with ref. [16]. The most confined modes were appeared at 1550nm as shown in Fig.(6). Based this point the three dimensional design of the optical fiber was based the cut off frequency ($c/1550\text{nm}$). Other 3D FBG parameters were chosen based on experimental data from ref.[8]. Two different designs were considered by changing the number of periods. In the first consideration the number of periods was chosen to be 3 periods. Boundary mode analysis was the study case on the transmission end of the FBG. The resultant mode was shown in Fig.(12). It shows the spatial distribution of the electric field (V/m) with mode number LP_{02} . In the second consideration, a 10 periods were created inside the core. The resultant spatial distribution of

the electric field (V/m) with mode number LP_{01} was shown in Fig.(13). So increasing the number of periods the most confined modes was appeared. The resultant mode of LP_{02} has a tangential mode electric field of 450 V/m while the LP_{01} has a tangential mode electric field of 1400 V/m.

References

- [1] Kenneth O. Hill and Gerald Meltz, Member, IEEE, Fiber Bragg Grating Technology Fundamentals and Overview, JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 15, NO. 8, AUGUST 1997
- [2] Herbert Venghaus, "Wave Length Filters In Fibre Optics", Springer Series in Optical Sciences, Volume 123, 2006.
- [3] Akram Saad, Yonghyun Cho, Farid Ahmed and Martin Byung-Guk Jun, "Numerical Approach to Modeling and Characterization of Refractive Index Changes for a Long-Period Fiber Grating Fabricated by Femtosecond Laser", Materials, 9, 941, 2016.
- [4] João M. P. Coelho, Marta Nespereira, Manuel Abreu and José Rebordão, "3D Finite Element Model for Writing Long-Period Fiber Gratings by CO2 Laser Radiation", Sensors, 13, 10333-10347, 2013.
- [5] Rasika Dahanayake, "Simulations Of Step-Like Bragg Gratings In Silica Fibers Using Comsol", Master of science thesis, The University of Akron, 2016.
- [6] Andreas Othonos, Kyriacos Kallia, "Fiber Bragg Gratings: Fundamentals and Applications in Telecommunication and Sensing", ARTECH HOUSE, INC. 1999.
- [7] Libish T. M., "Design and Development of Fiber Grating Based Chemical and Bio-Sensors", PhD Thesis submitted to Cochin University of Science and Technology, India, 2015.
- [8] Shaymaa R. Mohammed, Rong Z.Chen, Khalil I. Hajim, and Kevin P. Chen, "Writing of a Bragg Grating on a D-shaped Optical Fiber Using the KrF Excimer Laser", Iraqi J. Laser, Part A, Vol. 13, pp. 37-42(2014).
- [9] Andreas Othonos, D.K.W. Lam and B.K. Garside, "Characterization of single-mode optical fiber filters", Applied Optics, 20, pp. 440-445, 1981.
- [10] Pauline Rigby, "The Fifth Dimension", Light Wave Technology, volume 31, issue 6, 2014.
- [11] Pierre Sillard, Marianne Bigot-Astruc, and Denis Molin, "Few-Mode Fibers for Mode-Division-Multiplexed Systems", Journal Of Lightwave Technology, Vol. 32, No. 16, 2014.
- [12] Ivan Gómez-Castellanos, Ramón M. Rodríguez-Dagnino, "Intensity distributions and cutoff frequencies of linearly polarized modes for a step-index elliptical optical fiber", Optical Engineering, 46, 4, 045003, 2007.

Author Profile



Shaymaa Aal Tahhan received the B.S. and M.S. degrees in Laser and Optoelectronics Engineering from Nahrain University in 2003 and 2007, respectively. From 2007 to 2009 she worked in the many placing as a lecturer as in Babylon University an Nahrain university. During 2009-2016, she stayed in Higher Committee for Education Development in Iraq, Prime Minister Office as a student advisor in the placement, monitoring and financial departments. During this period she finished her PhD studies from Baghdad University and made her research at the university of Pittsburgh, USA in 2014. Now she is a lecturer at college of Engineering, Nahrain University.

Ayat Falih, BSc student at Laser and Optoelectronics Engineering, Nahrain University. She will get her BSc. Degree on July, 2017.