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Characterization of Erbium Doped Photonic Crystal Fiber

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Abstract

Photonic crystal fibers (PCFs) are a new emerging research area, and have been undergoing rapid development in recent years due to their unique and excellent optical properties and features. Studies on the characteristics of various types of PCFs have been reported. However, characterization on erbium-doped PCF has not previously been investigated. Therefore, in this paper, we have modeled an erbium-doped core PCF which has 7 rings of hexagonal air holes. The PCF structure, with a perfectly matched layer (PML), is modeled and simulated using Finite Element Method (FEM) via COMSOL software. The PML is optimized by varying the radius and thickness of the layer. Modal properties of the PCF have been investigated in terms of its effective index of the supported fundamental mode, confinement loss and thickness of the perfectly matched layer. This erbium-doped PCF has a confinement loss of 1.0E^{-6} at 1500 nm and a maximum effective refractive index of 1.476. This paper gathers useful data, which could be used for studying the characteristics of a PCF.

Keywords: *Finite element method (FEM), erbium-doped photonic crystal fiber, comsol multiphysics, perfectly matched layer, confinement loss*

1. Introduction

A new class of waveguide, photonic crystal fibers (PCFs), has become an interesting and extensively developed subject in worldwide optical field research, leading to a large variety of designs and applications [1-6]. For example, PCF can be used in fiber sensors similar to those already presented; such as fiber Bragg gratings (FBG) in single mode fiber (SMF) for strain [7] and stress sensors utilizing multimode optical fiber (MMF) [8]. PCFs have unique and excellent optical properties; such as endless single-mode operation, flexible design of air-hole cladding, anomalous dispersion, high non-linearities, ultra-large-mode-area cladding and intrinsic polarization stability [9, 10]. A photonic crystal fiber (also called holey fiber, hole-assisted fiber or microstructure fiber) is an optical fiber which obtains its waveguide properties not from a spatially varying glass composition, but from an arrangement of very tiny and closely spaced air holes which go through the whole length of the fiber. Such air holes can be obtained by using a preform with (larger) holes made. For example, by stacking capillary or solid tubes (stacked tube technique) and then inserting them into a larger tube [11, 12]. There exists an extensive variety of hole arrangements, thus leading to PCFs possessing very different properties.

PCFs are distinguished from standard "step-index" optical fibers by their cladding, formed by low refractive index inclusions; such as air holes that run along the entire fiber core length. PCFs have unique properties and parameters which are frequently superior to traditional fiber parameters; such as lower bending losses, better chromatic dispersion compensation and endlessly single mode light propagation for a very broad wavelength range [13]. Furthermore, by appropriate selection of fiber microstructure, such as the hole size, distance between holes – lattice pitch, geometry and the air holes position, PCFs can be fabricated with specific properties.

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Studies on the characteristics of various types of PCFs, in terms of chromatic dispersion, confinement loss, effective area and nonlinearity have been reported. For example, a solid core PCF has been modeled and the effective index, as well as the dispersion, have been investigated via fundamental space-fill mode (FSM) layer [14]. Besides that, an index-guiding PCF has also been characterized via a new type of circular perfectly matched layer (PML) [15]. Additionally, characterization of a GeO_2-doped PCF has been reported by inserting an extra GeO_2-doped SiO_2 square in the core region, in order to control the waveguide properties of the fiber [9]. However, modeling on erbium-doped PCF has not previously been investigated.

Therefore, in this paper, a PCF containing an erbium-doped core, with seven rings of hexagonal air hole rings, is modeled. A finite element method, with a perfectly matched layer (PML), is used to compute the effective mode index and confinement loss. The PML is optimized by varying the radius and thickness of the layer. The RF physics feature of COMSOL MULTIPHYSICS is used in the simulation.

2. Design of PCF Structures

The cross-section of our model for hexagonal PCF has 7 rings of air holes, and is shown in Figure 1. The central core region is perturbed by erbium doping, and the background material used is silica. The PCF has two parameters to define its geometrical structure; they are the diameter of air hole (d) and the pitch length (Λ) (i.e. periodic length between the holes). The properties of the PCF can be controlled to a large extent by varying these parameters. The parameters used in our modeling are shown in Table 1.

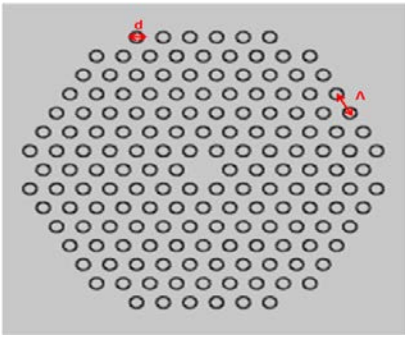

Figure 1. Geometry of Erbium Doped Photonic Crystal Fiber

Table 1. Simulation Parameters

PARAMETER	VALUE (µm)
Cladding diameter	125
Hole diameter (d)	2.0
Pitch of holes (Λ)	4.0
Doped area	4.0
Mode field diameter	4.5

3. Theoretical Background

A Finite element method, with a perfectly matched layer (PML), was used for accurate modeling of the PCF. A circular, perfectly matched layer is created around the PCF structure. PML is an absorbing layer specially studied to absorb the incident radiation, without producing reflection of the electromagnetic waves. The PML can be defined by two parameters, which are the layer thickness (*e*) and internal radius (r_{in}). The PML is schematically shown in Figure 2.

In the PML region, Maxwell's equation can be written as [15]:

$$\nabla \wedge \vec{\mathrm{H}} = j\omega\varepsilon_0 n^2 s.\vec{\mathrm{E}} \tag{1}$$

$$\nabla \wedge \vec{\mathrm{E}} = -j\omega\mu_0 s.\vec{\mathrm{H}} \tag{2}$$

Where,

$$s = 1 - j.\frac{\sigma_e}{\omega\varepsilon_0 n^2} = 1 - j.\frac{\sigma_m}{\omega\mu_0} \tag{3}$$

Where E is the electric field, H is the magnetic field, ω is the angular frequency, ε_0 and μ_0 are the permittivity and permeability of vacuum respectively, n is the refractive index, σ_e and σ_m are the electric and magnetic conductivities of the PML respectively. Based on the m-power profile in Figure 2, a small reflection coefficient, R at the interface between the PML and the pure silica region shows that the absorption of the PML is optimal. To optimize R, electric conductivity can be written as:

$$\sigma_e = \sigma_{\max} \cdot \left(\frac{\rho - r_{in}}{e} \right)^m \quad (4)$$

In this paper, we carry out simulation of Erbium doped silica PCF based on the following theoretical background. The refractive index of silica in the simulation has been calculated using Sellmeier's equation [9] as given below:

$$n^2 = 1 + \sum_{i=1}^{3} \frac{A_i \lambda^2}{\lambda^2 - l_i} \quad (5)$$

Where A_i and l_i are the oscillator strength and oscillator wavelength respectively. The refractive index of erbium doped silica can be computed from the following equation:

$$n^2 = 1 + \sum_{i=1}^{3} \frac{(SA_i + X(EA_i - SA_i))\lambda^2}{\lambda^2 - (Sl_i + X(El_i - Sl_i))^2} \quad (6)$$

Where *SA, Sl, EA, El* are the Sellmeier coefficients for the silica and erbium respectively and X is the doping concentration of erbium. We had also calculated confinement loss which is defined by equation 7 [10]. Confinement loss is a fraction of leaky modes which is calculated from the imaginary part of the effective index of the fundamental mode, ***imag (neff)***. k_0 is defined as the free space wave number and λ is the operating wavelength.

$$L_c = 8.686 k_0 imag(neff)[dB/m] \quad (7)$$

With:

$$k_0 = \frac{2\pi}{\lambda} \quad (8)$$

4. Modeling and Simulation

4.1. COMSOL Multiphysics

COMSOL Multiphysics is a finite element analysis and software package for modeling and solving all kinds of scientific and engineering problems. COMSOL consists of built-in physics interfaces, and has advanced support for material properties by building the models based on the defined relevant physical quantities; such as material properties, loads, constraints, sources and fluxes. COMSOL Multiphysics then internally compiles a set of equations representing the entire model [16].

The software runs the finite element analysis, together with adaptive meshing and error control, using a variety of numerical solvers. In this paper, an RF Module is selected in order to solve problems in the general field of electromagnetic waves.

4.2. Modeling

Figure 3 shows the flowchart for the modeling of the PCF using COMSOL. It consists of 5 steps, and begins with geometry modeling based on the desired fiber structure. The next step is to specify the physical settings, followed by mesh generation. Next, it computes the solution for analysis purpose. Finally, the results are interpreted using post processing and visualization tools.

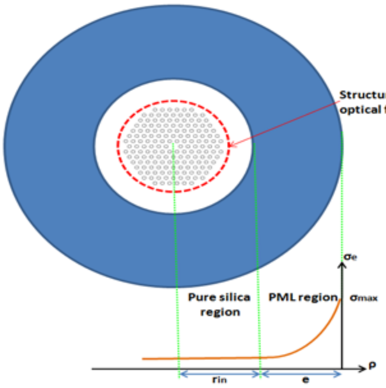

Figure 2. Schematic Diagram of PML

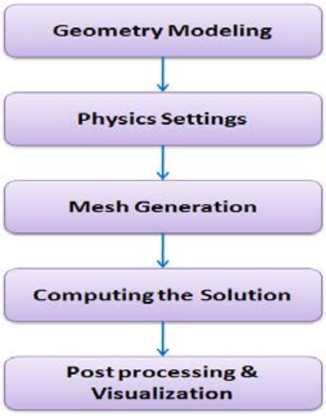

Figure 3. Flowchart for Modeling

In the geometry modeling step, an erbium-doped PCF, having 7 rings of hexagonal air holes, is designed via the COMSOL software, as shown in Figure 4. The PCF is designed and modeled, based on the structure of the scanning electron microscope (SEM) photograph (Figure 5). The SEM photograph is provided by Fiberhome Company. The PCF has a few parameters to define its geometrical structure; these are the diameter of air hole (d) which is 2µm, pitch of holes (Λ) which is 4µm, doped area of 4µm and cladding diameter of 125µm.

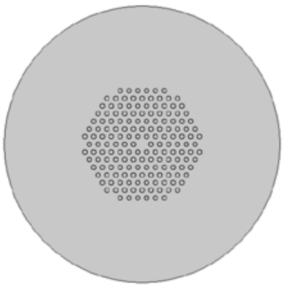

Figure 4. Simulated Profile

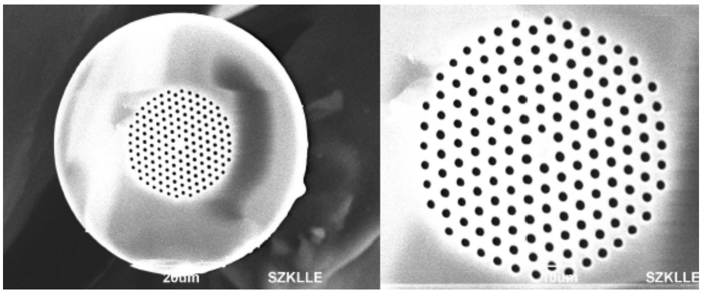

Figure 5. SEM Photograph

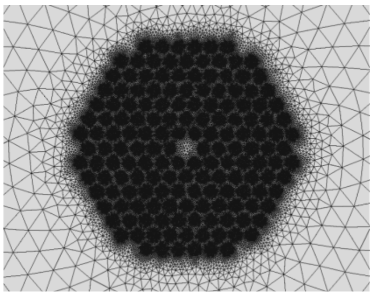

Figure 6. Mesh of the Structure

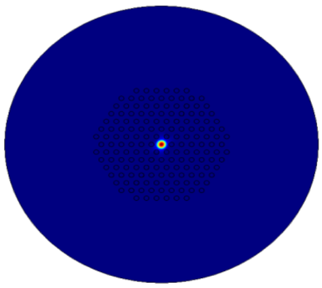

Figure 7. Solution Computed (The Red Portion Indicates the Highest Electric Field)

The next step is to specify the physical settings; which include the material properties, wavelength of light, boundary condition and refractive index of the silica cladding, erbium core and the air holes using equation 5 and 6. This is followed by mesh generation, as shown in Figure 6.

The mesh features enable the discrete characterization of the geometry model into small units of simple shapes referred to as mesh elements. Each element of the mesh is governed by a set of characteristic equations, which describe its physical properties and boundary conditions. These equations are then solved as a set of simultaneous equations to compute the effective index of the modes supported by the fiber [14]. The results are interpreted using post processing and visualization tools, as shown in Figure 7.

5. Results and Discussion

In Figure 8, the variation of effective index as a function of wavelength is plotted. By using Comsol Multiphysics, effective refractive index of the fiber can be found, which are useful for studying the characteristics of the PCF in terms of its chromatic dispersion, confinement loss, effective area and nonlinearity. The effective index result is in good agreement with previous work done [10, 14] - whereby the effective index decreases with wavelength. The maximum effective refractive index of this fiber is observed to be 1.476.

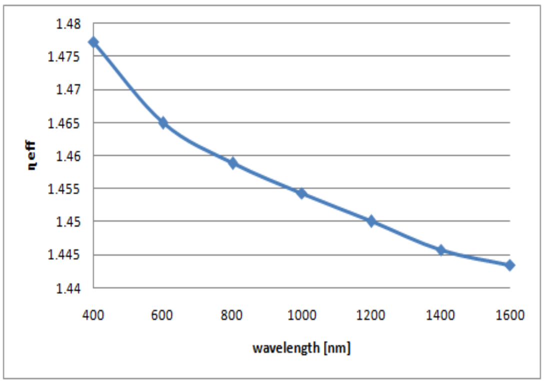

Figure 8. Effective Index of the Fundamental Mode

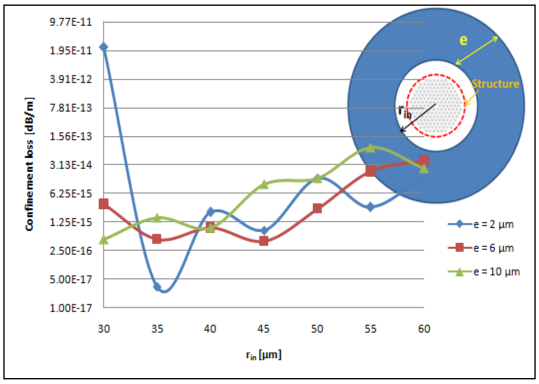

Figure 9. Variation of Confinement Loss in 26 µm Radius Structure

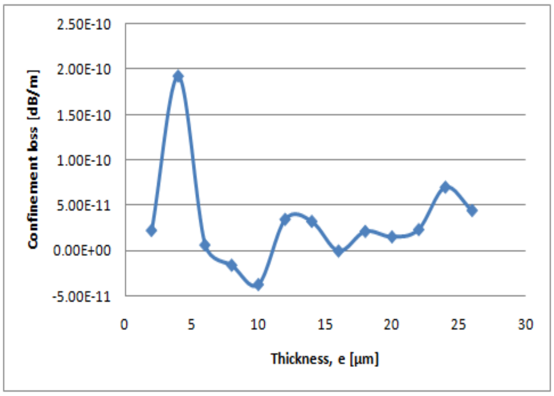

Figure 10. Variation of Confinement Loss for Internal Radius, r_{in} = 30 µm

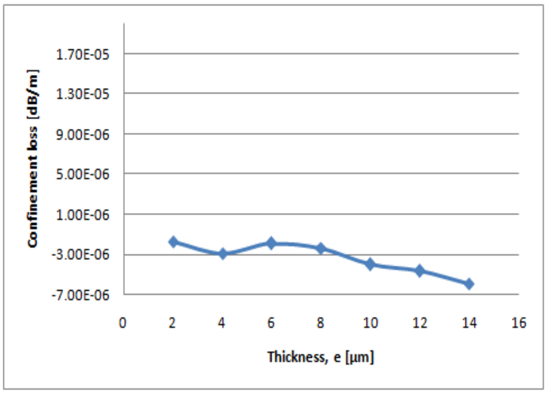

Figure 11. Variation of Confinement Loss for Internal Radius, r_{in} = 50 µm

Figure 9 shows the optimization of the perfectly match layer (PML) by varying the layer thickness (*e*) along the internal radius (r_{in}) at 1550 nm. Based on the principal of PML, the layer should be placed far from the structure of the fiber. It should be large enough to obtain less variation of confinement loss. In the in-set of Figure 9, the structure of the PML is shown. For a thickness of 2 µm, the variation of confinement loss is large, compared to thicknesses of 6 µm and 10 µm. The thickness of 10 µm is adequate to obtain less variation of confinement loss.

Figure 10 and Figure 11 show the variation of confinement for internal radius, r_{in} of 30 µm and 50 µm, respectively, at 1550 nm. For an internal radius of 30 µm, a thickness of more than 12 µm is sufficient to obtain less variation of confinement loss. On the other hand, an internal radius of 50 µm shows less variation of confinement loss along the whole range of thickness. In this case, the thickness of the PML is not a curial parameter, as the internal radius is large enough to evaluate less variation of confinement loss.

The calculation of confinement loss as a function of wavelength for internal radius, r_{in} = 50µm and PML thickness, e = 12.5 µm, is shown in Figure 12. The confinement loss shows an almost linear relationship with wavelength. This erbium doped photonic crystal fiber has a confinement loss of 1.0E^{-6} at 1500 nm. This result is in good agreement with previous work done [9, 10] whereby the confinement loss increases with wavelength.

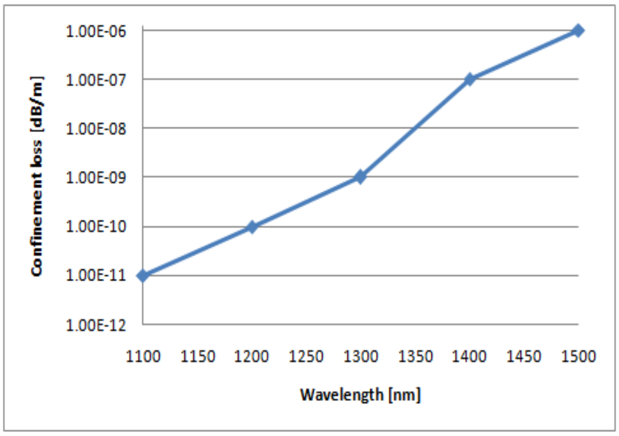

Figure 12: Confinement Loss for Internal Radius, r_{in} Of 50 µm and Thickness, E Of 12.5 µm

6. Conclusion

We have modelled and simulated an Erbium doped PCF core, with 7 rings of hexagonal air holes, using COMSOL Multiphysics. The Finite element method, with a perfectly matched layer (PML), has been used for accurate modeling of the PCF. The geometrical structure and numerical results of the effective index and confinement loss of the fiber have been presented. The PML layer, which is placed far from the structure of the fiber, shows less variation of confinement loss. Internal radius and thickness layer are two crucial parameters needed for optimization of the PML. This paper gathers useful data, which could be used for studying the characteristics of a PCF.

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