Design and analysis of non-linear properties of photonic crystal fiber with Various Doping Concentration

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Abstract. With exceptional light guiding mechanism and deliver significantly improved performance compared to conventional optical fibers, Photonic Crystal Fibers (PCFs) are a new class of optical waveguide. In this work, a solid core photonic crystal fiber (PCF) is designed using Comsol Multiphysics software based on finite element method. In our analysis the structure introduced is a structure formed by a doped core surrounded by a cladding which is composed by elliptical air holes in silica arranged in a hexagonal array. The important optical properties like effective area and nonlinear coefficient has been studied. Each characteristic has been investigated under different doping concentration within range of wavelength 800-1600 [nm].

1. Introduction
Crystal fibers (PCFs)[1] are a new class of optical fibers which have the potential to revolutionize optical fiber technology. These fibers are essentially low-loss waveguides and consist of a core which is surrounded by a periodic array of air holes in the cladding region. This configuration has led to a number of novel properties like endless single mode (ESM) operation[2], controllable birefringence and dispersion characteristics[3,4] and a high degree of nonlinearity. The cladding of a photonic crystal fiber can be constructed with a structure similar to that found in photonic crystal. This is where the term ‘photonic crystal fiber’ originates.

There are two classes of photonic crystal fibers. solid core PCF (SC-PCF) and hollow-core PCF (HC-PCF). The term solid-core photonic crystal fiber refers to those structures that have a solid core which is usually made of silica. These fibers guide light by the phenomenon of total internal reflection. On the other hand, hollow-core photonic crystal fiber has an air hole in the core region and transmits light by photonic band gap type guidance[5]. In this work, a solid core photonic crystal fiber (PCF) is designed using Comsol Multiphysics software based on finite element method. In our analysis the structure introduced is a structure formed by a doped core surrounded by a cladding which is composed by elliptical air holes in silica arranged in a hexagonal array. The important optical properties like effective area and nonlinear coefficient has been studied. Each characteristic has been investigated under different doping concentration within range of wavelength 800-1600 [nm].

2. Fiber Design
The cross section of the proposed (PCF) structure is shown in Fig(1). It is composed of elliptical air holes in the cladding arranged in a hexagonal array with lattice constant Λ, The ellipse have a major radius and a minor radius. The central core region is perturbed by a GeO2 doped SiO2. The properties of the (PCF) can be controlled to a large extent by varying these parameters.
3. Simulation Method
The finite element method (FEM) is used to analyze the various properties of (PCFs). Once the effective refractive index \( n_{\text{eff}} \) is obtained by solving an eigenvalue problem drawn from the Maxwell’s equations using the (FEM), the parameter like effective area \( (A_{\text{eff}}) \) and nonlinear coefficient \( (\gamma) \) can be obtained.

The effective area of (PCF) is the quantitative measure of the area which a waveguide or fiber mode effectively covers in transverse dimensions. The effective area is calculated by \([6]\):

\[
A_{\text{eff}} = \frac{\left(\int |E|^2 \, dx \, dy\right)^2}{\int |E|^4 \, dx \, dy} \, [m^2]
\]

where \( E \) is the transverse component of the electric field.

The nonlinearity of (PCF) can be measured using the parameter \( (\gamma) \) termed as nonlinear coefficient. (PCFs) can have high nonlinearity because of its ability to confine high intensity light \([8]\). The nonlinear coefficient of (PCF) can be calculated by \([7]\):

\[
\gamma = \frac{2\pi n_2}{\lambda A_{\text{eff}}} \, [W^{-1}m^{-1}]
\]

where \( n_2 \) is the nonlinear refractive index of silica material, \( \lambda \) is the wavelength of the light and \( (A_{\text{eff}}) \) is the effective mode area of (PCF).

4. Results and Discussions
The results obtained after the graphical modeling and simulation of proposed (PCF) are presented here.

4.1. Simulation Results
The COMSOL simulated output for the proposed design is given in Fig(2), which represents a highly confined light beam. The graphs of various (PCF) parameters are plotted within a wavelength range of 800 nm to 1600 nm.
4.2. Graphical Results

The variation of different parameters of proposed PCF like effective index, effective area and nonlinearity with respect to wavelength and doping concentration are analysed and plotted:

4.2.1. Effective refractive index. The variation of effective index with respect to wavelength is shown in figure(3). It shows that effective index decreases with wavelength[8,9] and increases with increases of doping concentration[10].

![Effective mode index=1.5106 (2) Surface: Electric field norm (V/m)](image)

Figure 3. Plot of Effective index vs. Wavelength

4.2.2. Effective Mode Area. The variation of effective area with respect to wavelength is shown in figure (4). It shows that effective area increases with wavelength[11] and increases with the decreases of doping concentration[10]. This is because as the wavelength increases the propagating mode leaks in to cladding and so the area covered by propagating mode also increases.
4.2.3. **Nonlinear Coefficient.** The variation of nonlinear coefficient with respect to wavelength is shown in figure (5). It can be seen that nonlinearity decreases with wavelength and increases with the increases of doping concentration[10]. This is because of increase in effective area. At lower wavelength, mode is well confined, reducing its effective area and as the energy is concentrated in small area, nonlinearity increases.

5. **Conclusion.** In this paper, we have modeled a solid-core photonic crystal fiber (PCF) by using full vectorial finite element method (FEM). Modal properties of the (PCF) have been investigated by calculating the effective index of the supported mode. Results for effective index, effective area and non linear parameter are presented. COMSOL Multiphysics software has been used to calculate the effective index of the supported mode of the fiber, with Various Doping Concentration in the core of fiber.

6. **References**
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