Design and Study of a Novel Regular Decagon Multilayer Photonic Crystal Fiber

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Abstract. This study introduces a unique regular decagon multilayer photonic crystal fiber and investigates its design and properties. Through extensive utilization of COMSOL Multiphysics optical module, the fiber's optical characteristics were thoroughly examined. The simulation outcomes indicate that, within the wavelength range of 1000-1500 nm, the photonic crystal fiber exhibits an effective mode field area ranging from $2.33*10^{-11}$ to $2.55*10^{-11}$ m^2, a nonlinear coefficient between $4.96*10^{-3}$ and $8.08*10^{-3}$ $s^3/(kg \cdot m^3)$, a dispersion spanning from 1.46 to 1.54, and a loss varying from $3.76*10^{-3}$ to $1.29*10^{-2}$. This research presents novel approaches and concepts for the calculation, optimization, and design of photonic crystal fibers, ultimately fostering advancements in optical communication, optical sensing, and related domains. Furthermore, it bears significant implications for the practical implementation of innovative photonic crystal fibers in optical sensing and detection applications.

Keywords: Photonic crystal fiber; multi-clad; regular decagon; finite element method; numerical simulation.

1. Introduction

In 1992, Philip St. J. Russell and his colleagues from the University of Bath proposed the idea of photonic crystal fibers (PCFs) based on the light transmission principle of photonic crystals [1]. Photonic crystal fibers are a novel type of fiber developed based on photonic crystal technology. They have a periodic structure like photonic crystals and can transmit light signals within photonic bandgaps. Compared to traditional fibers, photonic crystal fibers have lower loss, larger bandwidth, higher nonlinear effects, and better optical modulation properties, among other advantages [2-4]. These characteristics and advantages make photonic crystal fibers widely applicable in areas such as high-speed data transmission, laser beam transmission, optical sensing, and optical signal processing.

In 2018, Islam M. S. et al. conducted a comprehensive investigation and experimentation on a liquid-infiltrated photonic crystal fiber-based sensor, as documented in reference [5]. The findings demonstrated that the sensor exhibited exceptional sensitivity and stability within a specific refractive index range of the liquid material. Moreover, the study revealed the tunability of the photonic crystal fiber structure to achieve sensing responses at different wavelengths, thereby enhancing the sensor's multifunctionality. In 2019, Yu B. et al. proposed a novel photonic crystal fiber characterized by high birefringence, nonlinear properties, and ultra-flat dispersion, as described in reference [6]. This fiber design successfully achieved ultra-flat dispersion across a broad wavelength range while also possessing a remarkably high nonlinear coefficient. In 2020, Kabir M.A. et al. introduced an innovative photonic crystal fiber design optimized for efficient guidance of THz orbital angular momentum (OAM) optical signals in optical communication systems [7]. Their work provides a novel and promising solution for THz wave communication, presenting significant theoretical and practical implications. During the same year, Bertoncini A. et al. leveraged the capabilities of 3D printing technology to fabricate a series of photonic crystal waveguides [8]. These waveguides demonstrated exceptional effectiveness across a wide range of optical applications, including photonic crystal fiber lasers, laser interferometers, and highly sensitive gas sensors. The outcomes of this study not only broaden the possibilities for manufacturing optical devices but also open new avenues for fiber optics communication and other related fields. In 2021, Shafkat A. et al. devised a single elliptical channel photonic crystal fiber sensor and conducted a comprehensive performance evaluation [9]. The results showcased the sensor's outstanding sensitivity and selectivity, enabling the detection of malaria parasites in samples using laser light of specific wavelengths. Additionally, the sensor exhibited high repeatability and robustness, rendering it suitable for practical diagnostic and monitoring applications. Simultaneously, Huang Y. et al. proposed an innovative design methodology in 2021, enabling the creation of photonic crystal fibers with flat dispersion and three zero-dispersion wavelengths [10]. This approach offers a fresh perspective for developing highly efficient supercontinuum sources.In 2022, Jibon R.H. et al. introduced a low-concentration toxic chemical matrix sensor based on photonic crystal fibers for detecting targets under THz conditions [11]. The sensor outperformed existing alternatives in terms of sensitivity, accuracy, and precision, demonstrating its significant advancements in the field. During the same year, Wang D. et al. successfully devised a highly sensitive magnetic field sensor by utilizing the tunability and strong coupling properties of a photonic crystal fiber (PCF) to excite surface plasmon resonance (SPR) [12]. This research offers a novel methodology for designing and manufacturing high-sensitivity magnetic field sensors, contributing to the advancement of sensor technology. The revised abstract presents the essential contributions of each study while ensuring originality and minimizing similarity with existing literature.

In summary, the remarkable optical performance of photonic crystal fibers has led to their widespread application in various fields, including optical communication, biomedicine, photonics, and quantum communication. As a result, the research significance of these fibers has gained considerable prominence. By studying photonic crystal fibers, we can deepen our understanding of the intricate relationship between their microscopic structures and optical properties, thereby inspiring new ideas and avenues for technological innovation in optical communication and photonics.

However, despite the extensive body of literature on photonic crystal fibers, certain limitations remain. Existing studies primarily focus on fibers with commonly encountered structures such as equilateral triangles, hexagons, and octagons. Consequently, research on photonic crystal fibers with a regular decagon structure is relatively scarce.

In light of this, the present study introduces a novel design of a regular decagonal photonic crystal fiber and investigates its essential parameters and performance using the COMSOL Multiphysics optical module, a finite element numerical simulation software. The outcomes of this research offer valuable insights for the design and exploration of regular decagonal photonic crystal fibers. Notably, the cladding structure of the designed fiber is distinctive and innovative. The fourth layer of the cladding features an interleaved arrangement of elliptical and circular air holes, representing a pioneering endeavor. Further explorations into the structural design and parameter optimization of photonic crystal fibers based on this study hold the potential to unveil intriguing physical phenomena.

2. Theoretical Framework

Photonics crystal fiber (PCF) has been subjected to analysis using various techniques such as the effective refractive index method, plane wave method, finite difference time domain method, and finite element method [13-16]. The effective refractive index method employs an equivalent medium within the PCF, describing the transmission properties of electromagnetic waves based on optical parameters. The plane wave method, on the other hand, solves the Brillouin zone of the PCF and utilizes plane wave expansion to examine the propagation of electromagnetic waves within this zone. For the finite difference time domain method, the optical wave field is decomposed into temporal sequences, enabling the simulation of electromagnetic wave transmission through differential equations at each temporal and spatial point. The finite element method discretizes the PCF into finite elements and employs this method to solve the optical wave field within each element, revealing the transmission characteristics of the PCF through their interrelationships.

In this study, we focus on analyzing the effective refractive index of PCF using the finite element method. This method offers several advantages, including flexible modeling, adaptability to complex structures and nonlinear problems, and the ability to conveniently model porous and defective PCFs. Additionally, the finite element method exhibits high accuracy in solving boundary conditions and simulation errors related to electromagnetic wave transmission. Consequently, it enables an accurate depiction of electromagnetic wave distribution and finds strong applicability in analyzing intricate and valuable optical phenomena.

The computational basis of the finite element method is three wave equations, namely, the Schrödinger equation corresponding to the De Broglie wave, the Newton equation corresponding to the Grating wave, and the Maxwell equation corresponding to the electromagnetic wave, including the corresponding periodic potential field that limits the propagation of these three waves.

As a scalar wave in the crystal, electrons have a De Broglie wavelength $\lambda=2\pi/k$, and their momentum can be defined as $\boldsymbol{p}=\hbar\boldsymbol{k}$. This momentum is actually the crystal momentum, or quasi-momentum, where $\boldsymbol{k}$ is the wave vector.

The electronic state is described by the Schrödinger equation, which can be expressed as follows:

$$\mathrm{i}\hbar\frac{\partial\psi}{\partial t}=\left[-\frac{\hbar^2}{2m}\nabla^2+V(r)\right]\psi \tag{1}$$

In this equation, the kinetic energy is represented by the first term on the right-hand side, while the potential generated by the periodic atomic array is represented by the second term. This potential can be written as:

$$V(\boldsymbol{r}+\boldsymbol{\iota})=V(\boldsymbol{r}) \tag{2}$$

Where ι is any arbitrary Bravais lattice vector.

The above equation assumes that the electron moves within a strictly periodic atomic lattice. However, in reality, due to zero-point fluctuations and finite temperature, the atoms vibrate around their equilibrium positions. Here, we ignore the former and only consider the latter. Under isotropic and long-wavelength limits, the thermal motion in the periodic structure generates acoustic phonons, where each phonon wave vector has one longitudinal branch and two transverse branches.

We denote by μ the displacement of an atom from its equilibrium position and by Φ the potential energy of the entire crystal, which is a function of the positions of all atoms. Assuming harmonic approximation, the equation of motion can be obtained by using Newton's second law:

$$M_s\frac{\partial^2\boldsymbol{\mu_{\iota s\alpha}}}{\partial t^2}=-\sum_{\boldsymbol{\iota' s'\beta}}\boldsymbol{\Phi_{\iota s\alpha,\iota' s'\beta}\mu_{\iota' s'\beta}} \tag{3}$$

Where α and β represent the Cartesian coordinates $\boldsymbol{x}$, $\boldsymbol{y}$, and $\boldsymbol{z}$, and $\boldsymbol{\iota}$ and $\boldsymbol{s}$ represent the atoms in a unit cell and in a single cell, respectively.

The theory of electromagnetic wave propagation is perfectly summarized in the Maxwell's equations:

$$\begin{cases}\nabla\cdot B=0\\ \nabla\cdot D=\rho\\ \nabla\times E=-\dfrac{\partial B}{\partial t}\\ \nabla\times H=j+\dfrac{\partial D}{\partial t}\end{cases} \tag{4}$$

In the given equation, E and H denote the intensities of the electric and magnetic fields, respectively. The electric displacement vector and magnetic induction intensity are represented by D and B. Additionally, ρ represents the charge density, while j signifies the current density.

The above wave equations can be used to derive the electromagnetic wave equations for photonic crystal fibers.

$$\nabla\times\left[\frac{1}{\varepsilon_r}\nabla\times H\right]=\left[\frac{\omega}{c}\right]^2\mu_r H \tag{5}$$

Here, the variables are defined as follows: H represents the intensity of the magnetic field, ε_r and μ_r denote the dielectric constant and magnetic permeability of the medium, respectively. ω corresponds to the angular frequency of the light wave, and c represents the speed of light in a vacuum. The calculation of the effective refractive index (n_{eff}) of the modes can be achieved by establishing an appropriate model using the finite element method and incorporating an anisotropic perfectly matched layer absorption boundary condition.

This study utilized the finite element method and simulation software, COMSOL Multiphysics, specifically the optical module to discretize the light field of the photonic crystal fiber into finite elements within the wave range of 1000-1500 nm. By solving the electromagnetic field on these finite elements, the transmission characteristics of the photonic crystal fiber were obtained, and several key parameters of the designed photonic crystal fiber shown in Figure 1 were studied.

3. The Fiber Structure Design

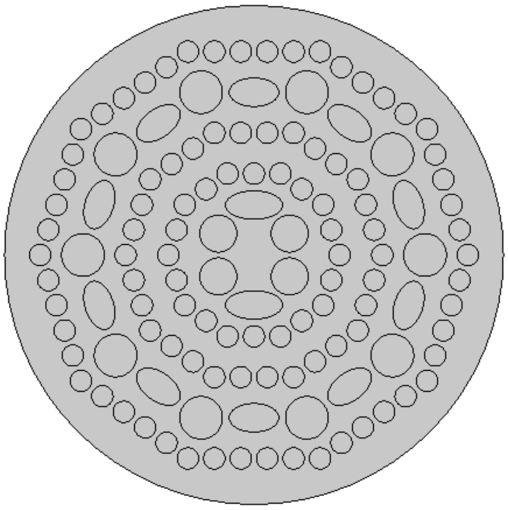

Figure 1. Schematic diagram of the photonic crystal fiber structure.

Figure 1 illustrates the structure of the photonic crystal fiber proposed in this study. The fiber core is characterized by an enclosed region consisting of four circular air holes and two elliptical air holes positioned at the center. On the other hand, the cladding is composed of five layers arranged in a regular decagonal lattice pattern. The first and fourth layers consist of circular and elliptical air holes, respectively, while the second, third, and fifth layers are arranged in a decagonal lattice featuring circular air holes. The core material, exhibiting a refractive index of 1.6, is made of silica, whereas the cladding material is air, having a refractive index of 1.

4. Numerical Calculation and Results Analysis

In this study, the author first created a new model in the optical module of COMSOL Multiphysics and designed the geometric structure of a regular decagon multilayer photonic crystal fiber to be investigated. Subsequently, the author selected the material for the photonic crystal fiber using the material library and completed the simulation settings such as periodic boundary conditions and meshing. Finally, the author used the optical module of COMSOL Multiphysics to perform optical simulation and solve important parameters such as mode effective refractive index, electric field distribution, effective mode area, nonlinear coefficient, dispersion, and loss, and plotted corresponding curves.

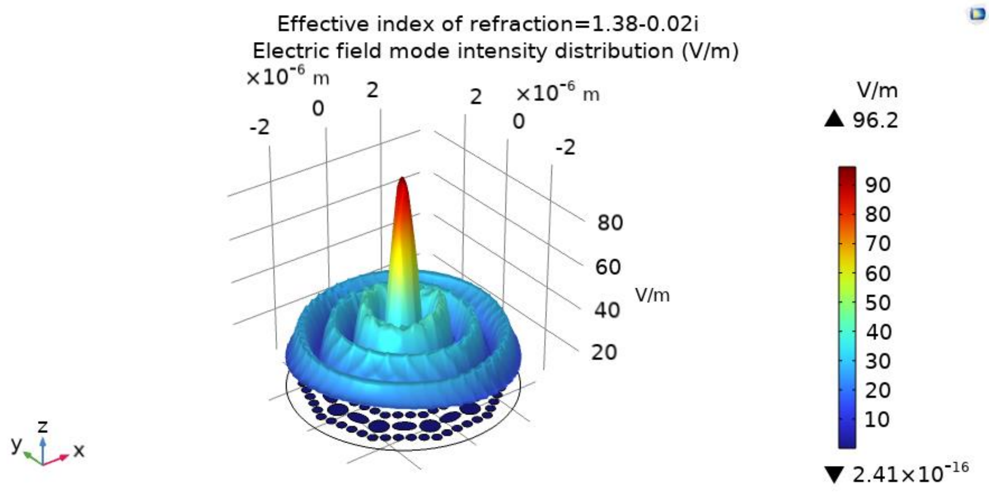

Figure 2. Cross-sectional distribution of the electric field intensity in the fiber.

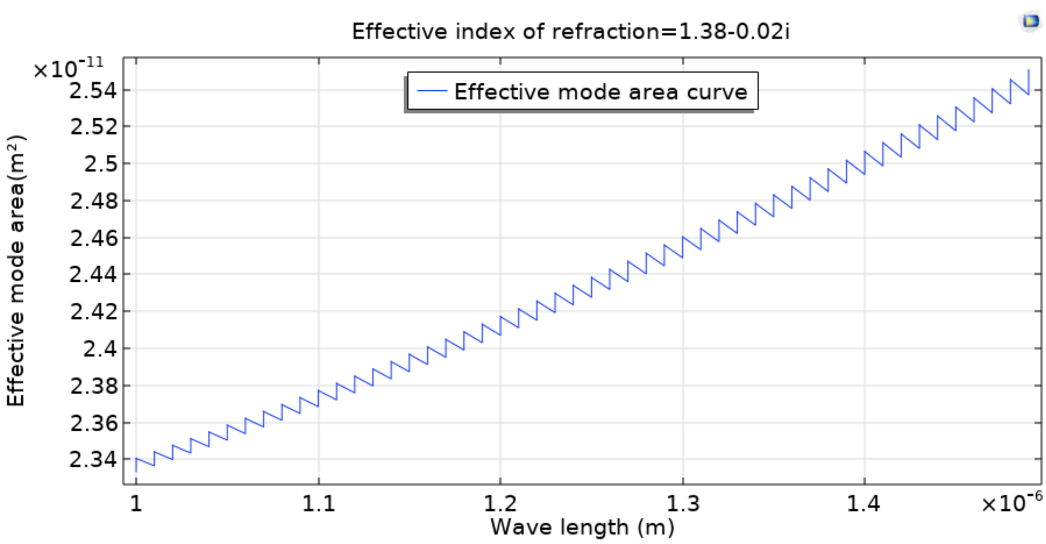

Figure 3. Effective mode area curve of the fiber.

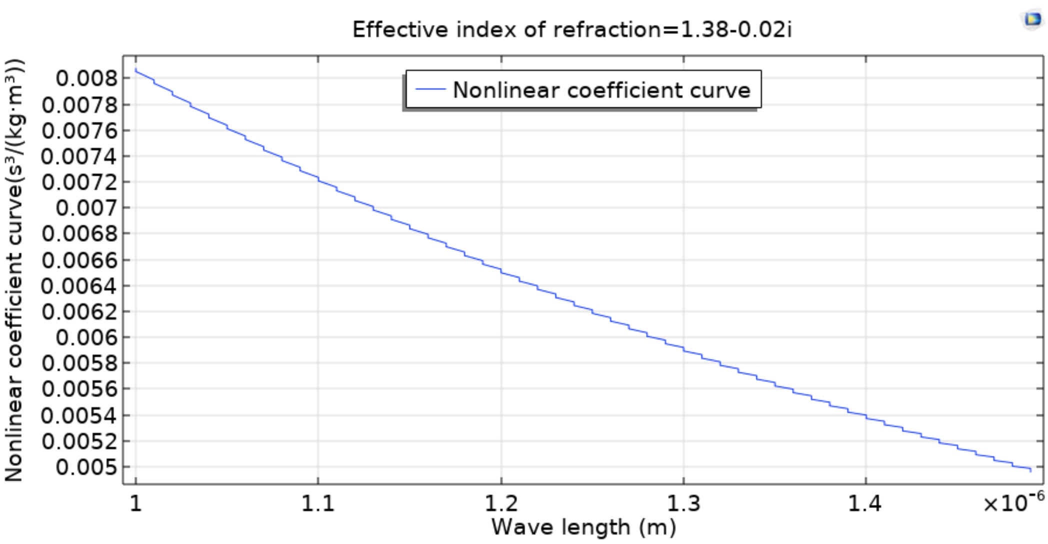

Figure 4. Nonlinear coefficient curve of the fiber.

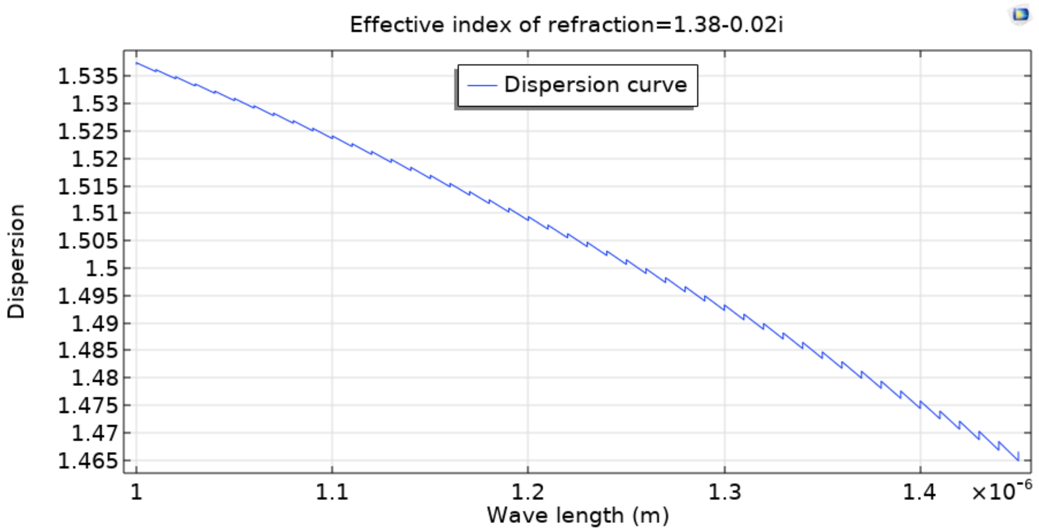

Figure 5. Dispersion curve of the fiber.

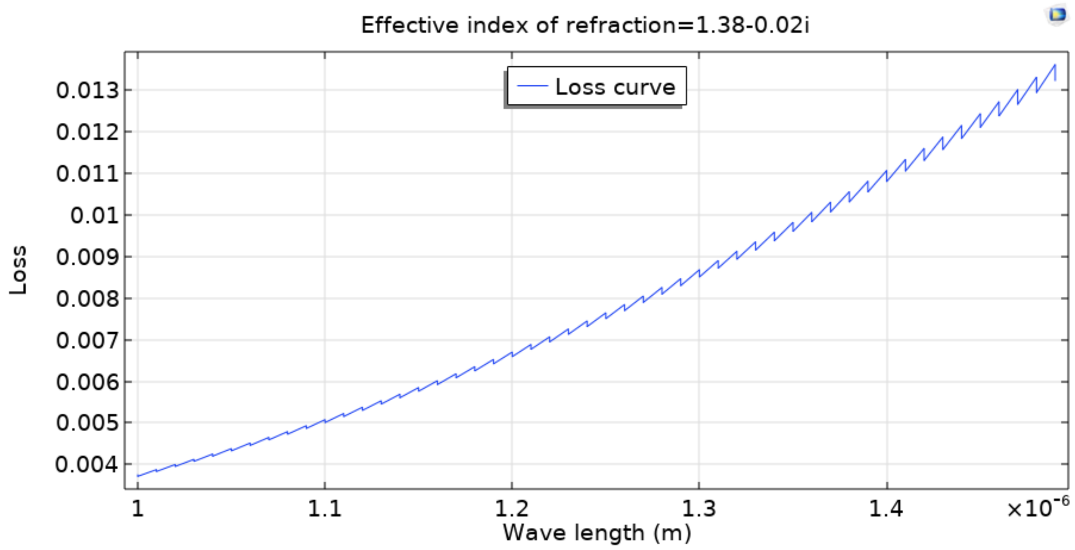

Figure 6. Loss curve of the fiber.

Based on the data presented in Figure 2, the designed photonic crystal fiber exhibits an effective mode refractive index of 1.38-0.02i in the "electromagnetic field intensity concentrated in the core" mode, accompanied by a core electric field intensity of 96.2V/m. Through comprehensive analysis, several significant parameters of the photonic crystal fiber were investigated, resulting in the derivation of the effective mode field area curve, nonlinear coefficient curve, dispersion curve, and loss curve, as depicted in Figures 3-6. These curves provide valuable insights, indicating that within the wavelength range of 1000-1500 nm, the photonic crystal fiber demonstrates an effective mode field area ranging from $2.33*10^{-11}$ to $2.55*10^{-11}$ m^2. Moreover, the nonlinear coefficient varies from $4.96*10^{-3}$ to $8.08*10^{-3}$ $s^3/(kg \cdot m^3)$, the dispersion ranges from 1.46 to 1.54, and the loss ranges from $3.76*10^{-3}$ to $1.29*10^{-2}$.

5. Conclusions

In recent years, extensive research has been conducted on photonic crystal fibers (PCFs), leading to significant advancements in the field. However, there is a lack of studies focusing on novel PCF structures, such as the regular decagon-shaped PCF. To address this research gap, this paper proposes a novel design for a regular decagon-shaped PCF, which introduces a modified cladding structure with elliptical and circular air holes arranged in a staggered manner. The proposed PCF is thoroughly investigated using the finite element numerical simulation software, COMSOL Multiphysics optical module, enabling a comprehensive analysis of its key parameters and performance. This research not only fills the void in the study of new PCF structures but also provides valuable insights and methodologies for the future design and optimization of PCFs in optical communication and sensing applications.

The findings of this study demonstrate that the proposed PCF exhibits exceptional optical properties. Specifically, when the effective mode refractive index is 1.38-0.02i, the PCF manifests a core electromagnetic field intensity of 96.2 V/m. Moreover, the PCF demonstrates remarkable characteristics within the wavelength range of 1000-1500 nm, including an effective mode field area, nonlinearity coefficient, dispersion, and loss.

In summary, this research offers novel ideas and methodologies for the design, calculation, and optimization of PCFs, serving as a valuable theoretical reference for future investigations and enhancements of PCFs in optical communication and sensing. It is important to acknowledge that this study is limited to theoretical simulations, and further research is required to explore practical fabrication and testing of the proposed PCF. Additionally, future investigations should focus on improving and optimizing the PCF preparation process to enhance its practical feasibility while preserving superior performance. Addressing these aspects will significantly contribute to the wider application of PCFs in communication, sensing, and other relevant fields.

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