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The Influence of Core Diameter on Endlessly Single Mode Properties for Index Guiding Photonic Crystal Fiber

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ABSTRACT: In this study Endlessly Single Mode properties of index guiding Photonic Crystal Fiber for different core radii had been studied. This work is done by using Finite Element Analysis by using COMSOL MULTIPHYSICS simulation software, which is used to designed two index guiding photonic crystal fiber with six air holes rings one by omitting single air hole and the other by omitting five air holes to form fiber core. Each iteration has been done within range of pitch from 1µm to 10 µm and fixed wavelength of 1.55 µm. The influence of core diameter of photonic crystal fiber on endlessly single mode properties is done by calculation of V-parameter, the simulation results showed that core diameter limiting the endlessly single mode regime ;single mode operation can be extended to higher core diameter which is be very useful in different applications like polarization - maintaing , amplifiers, beam delivery and fiber laser.

KEYWORDS: Photonic Crystal Fiber, Endlessly Single Mode, Finite Element Method, Normalized Frequency Parameter, Optical fiber sensor.

I. INTRODUCTION

Photonic crystal fibers (PCFs), a kind of two dimension photonic crystals, consisting of a central defect region surrounded by multiple air holes that run along the fiber length are attracting much attention in recent years because of unique properties which are not realized in conventional optical fibers. PCFs are divided into two different kinds of fibers. The first one is index guiding PCF, guiding light by total internal reflection between a solid core and a cladding region with multiple air-holes. Index-guiding PCFs, also called holey fibers or microstructure optical fibers, possess especially attractive property of great controllability in chromatic dispersion by varying the hole diameter and hole-to-hole spacing [1, 2]. In conventional single-mode fibers (SMF), the single-mode optical bandwidth is typically limited by a higher-order mode cutoff at short wavelengths and macro-bend loss at long wavelengths. The characteristics of the PCF are fundamentally different from this picture ,figure (1) shows Schematic comparison between a step-index fiber and an index guiding PCF [3].

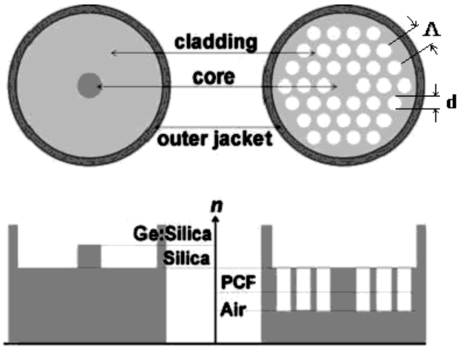


Fig.1 Schematic comparison between a step-index fiber and an index guiding PCF [4].

one of the attractive properties of the PCFs is their possibility to be single-moded over wide wavelength range, surpassing the ordinary single mode fibers which become multi-moded for wavelength below their single mode cut-off wavelength. PCFs, which are specially designed with this property are called the Endlessly Single Mode (ESM-PCF) Most important is the fact that the PCF can be designed to be ESM, a term first coined by Birks et al. al in 1997 they designed two-dimensional photonic crystal of an array of hexagonal air holes centered around a central core of silica possess single mode propagation for a range of wavelengths (458 – 1550 nm). Nielsen et. al in 2003 demonstrated a PCF with an effective area of 600 μm^2 at 1550 nm by optimizing d/p to a value of 0.50 and also they study the possibilities for improved large-mode-area endlessly single-mode photonic crystal fibers for use in high-power delivery applications. In 2005 Saitoh and Mortensen determine the single-mode and multi-mode phases and also find the air hole diameters limiting the endlessly single-mode regime, many researches have done in this field to serve many applications like polarization minting which done by Mishra et. al in 2010 they used Full-Vectorial Finite Element Method to study endlessly single-mode highly polarization maintaining birefringent photonic crystal fiber at wavelength 1.55μm. A simple model used to study the PCF is the effective index model, where the high index core surrounded by the lower effective index of the cladding due to the presence of the periodic holes, guides light by a so called Modified Total Internal Reflection (MTIR) mechanism [5].

Referring to the fact that no higher-order modes are supported regardless of the wavelength. The ESM property has the specious consequence that the waveguide can be scaled to an arbitrary dimension while remaining single mode. However, as the scale of the structure is increased, the susceptibility towards attenuation induced by variations in structural parameters as well as external perturbations such as bending increases limiting the practical dimensions that can be realized [6,7]. The tradition of parametrizing the optical properties in terms of the V- parameter (normalized frequency) stems from analysis of the step index fiber (SIF). The SIF is characterized by the core radius (r), the core index (n_c), and the cladding index (n_{cl}), which all enter into the parameter V_{SIF}, given by [8]:

$$V_{SIF}(\lambda) = \frac{2\pi r}{\lambda}(n_{co}^2 - n_{cl}^2)^2 \qquad 1$$

The usual value V_{SIF}= 2.405 follows naturally from the solution of the first zero of the Bessel function, i.e., J0(V_{SIF})=0. When attempting to establish a simple formalism for the PCF it is natural to strive for a result similar to the V–parameter known from standard fibers. However, a simple translation is not straight forward since no wavelength-independent core- or cladding index can be defined.
Mortensen et al. proposed a formulation of the V–parameter for a PCF given by [8]:

$$V_{EFF}(\lambda) = \frac{2\pi p}{\lambda}(n_{FM}^2(\lambda) - n_{FSM}^2(\lambda))^2 \qquad 2$$

Although this expression has the same overall mathematical form as known from standard fibers, the unique nature of the PCF is taken into account. In equation (2), (p) is the fiber pitch (distance between centers of air holes), $n_{FM}(\lambda)$ is the wavelength dependent effective index of the Fundamental Mode (FM) and $n_{FSM}(\lambda)$ is the corresponding effective index of the first cladding mode in the infinite periodic cladding structure often denoted the Fundamental Space Filling Mode (FSM), the higher-order mode cut-off can be associated with a value of $V_{PCF} = \pi$ [9]. The cut off wavelength of the second order mode is defined to be the wavelength at which the effective index of the second order mode (n_{eff} second mode) become equal to the effective cladding index of fundamental space-filling mode, n_{FSM} ,the definition of the cutoff wavelength this related to the value $\Delta n = n_{eff}(2nd\ mode) - n_{FSM}$ equal to zero [10]. Effective Area (A_{eff}) can be calculated by applying results from standard fiber technology relating the numerical aperture and spot size values in the case of a PCF from the following expression [11]:

$$A_{eff} = \frac{(\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|E|^2\,dxdy)^2}{(\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|E|^4\,dxdy)} \qquad 3$$

E is the electric field derived by solving Maxwell’s equations. From this equation, it is seen that A_{eff} depends on the fiber parameters such as the mode field diameter and core-cladding index difference, where the integrals extend over the entire transverse range[11].

The PCF has attracted growing attention owing to its many unique properties, such as low nonlinearity, ESM operation, Large Mode Area (LMA), and high birefringence The development of LMA- PCF is important for a wide range of practical applications most notably those requiring either the delivery or generation of high power optical beams. Thus, an interesting research of PCF is the realization high power laser applications by means of ESM-PCFs with very LMA. These properties provide scaling potential for fiber laser and amplifier systems [12].

II. EXPERIMENTAL WORK

COMSOL MULTIPHYSICS allows solving wide variety of problems defined by the partial differential equations in a number of fields of Physics by means of FEM. Particularly, in the area of PCF devices it allows to solve the Helmholtz equation with certain kinds of boundary conditions, thus, giving as a result the electromagnetic field distribution inside the device. The structure definition as well as setting the properties of the structure, boundary conditions and node conditions are highly visualized and it makes no difficulties in creating computation model. It is necessary to define an equivalent geometry as infinite to determine characteristics of propagation. For compensating this difficulty, PML boundary condition had been used; PML is an absorbing layer specially studied to absorb without reflection the electromagnetic waves [13]. 2D-Hexaginal lattice PCFs have been designed with refractive index ,n=1.45,cladding diameter of 100±2 µm , two PCF had been designed the first one core formed by omitting single air hole from the center of the fiber and the other by omitting five air holes, two models had been designed with six air holes rings and 0.2,0.4 and 0.6 air filling fraction (d/p); each iteration has been done within range of pitch (p) from 1 µm to 10 µm, and fixed wavelength of 1.55 µm. Effective modal index n_{eff} of a guided mode for a given wavelength is obtained by solving an Eigen value problem drawn from Maxwell's equations n_{eff} is a complex value has both real and imaginary parts. n_{eff}, can be obtained as [14]:

$$n_{eff} = \frac{\beta}{k_0} \qquad 4$$

Here, β is the propagation constant and k_0 is the free space wave number.

III. SIMULATION RESULTS

Table (1) shows core diameters for the designed fibers, by using COMSOL MULTIPHYSICS with different core diameters and air hole diameters.

Table 1 Core diameters for the designed fibers, for d/p equal to ,(a) 0.2, (b) 0.4, (c) 0.6.

(a)

d/p	**p µm**	**ρ µm for fiber core with omitting single air hole**	**ρ µm for fiber core with omitting five air holes**
0.2	1	1.8	3.3
	2	3.6	6.6
	3	5.4	9.9
	4	7.2	13.2
	5	9	16.5
	6	10.8	19.8
	7	12.6	23.1
	8	14.4	26.4
	9	16.2	29.7
	10	18	33

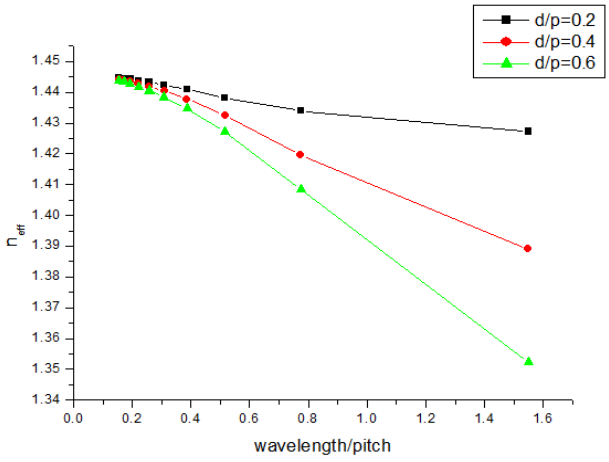
(b)

d/p	**p µm**	**ρ µm for fiber core with omitting single air hole**	**ρ µm for fiber core with omitting five air holes**
0.4	1	1.6	3.1
	2	3.2	6.2
	3	4.8	9.3
	4	6.4	12.4
	5	8	15.5
	6	9.6	18.6
	7	11.2	21.7
	8	12.8	24.8
	9	14.4	27.9
	10	16	31

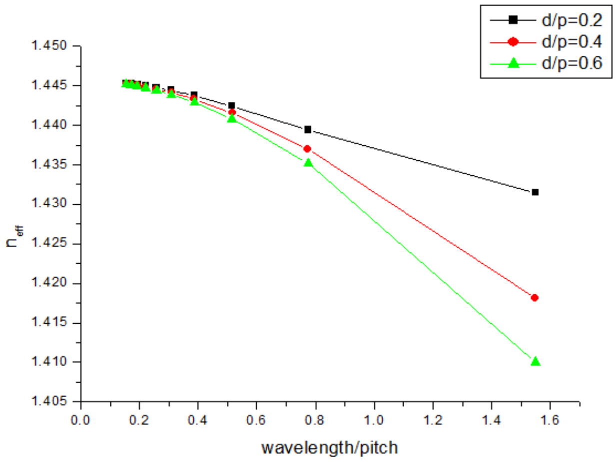
(c)

d/p	**p µm**	**ρ µm for fiber core with omitting single air hole**	**ρ µm for fiber core with omitting five air holes**
0.6	1	1.4	2.9
	2	2.8	5.8
	3	4.2	8.7
	4	5.6	11.6
	5	7	14.5
	6	8.4	17.4
	7	9.8	20.3
	8	11.2	23.2
	9	12.4	25.9
	10	14	29

figure (2) shows the effective indices for the six air holes rings PCFs, and different air filling fraction (d/p) equal to 0.2,0.4 and 0.6 and different core radii. From the figure it's clear that n_{eff} is wavelength depended that decreasing with increasing wavelength.



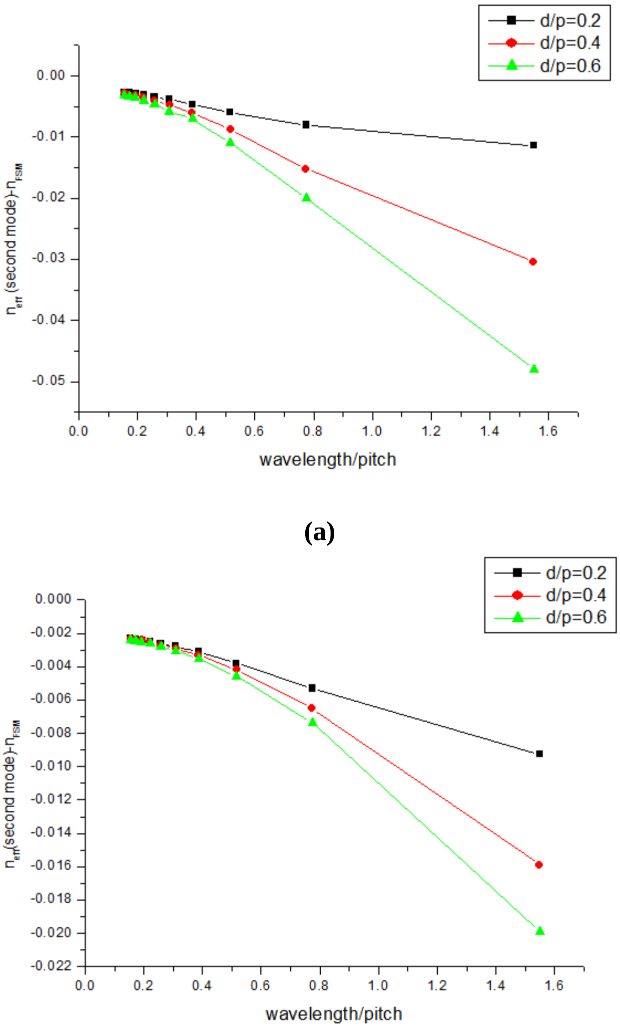
(a)



(b)

Fig. 2 n_{eff} versus wavelength for six air holes rings PCF , different air filling fraction and (a) omitting single air hole to form fiber core, (b) omitting five air holes to form fiber core.

Figure (3) shows the impact of the air filling fraction (d/p) on the value of (Δn) at fixed number of air holes rings, which is equal to six for the designed fibers, when Δn approach to zero it is considered as a definition of the cutoff wavelength.



(a)

(b)

Fig.3 The Impact of the number of air filling fraction with constant air holes rings on the value of Δn, (a) omitting single air hole to form fiber core, (b) omitting five air holes to form fiber core.

Figure (4) shows V-parameter versus (A_{eff}/λ^2) for different air hole diameters corresponding to the ESM limit. its clear from the figure that large core radius have ESM for different air filling fraction more than fiber with small core radius.

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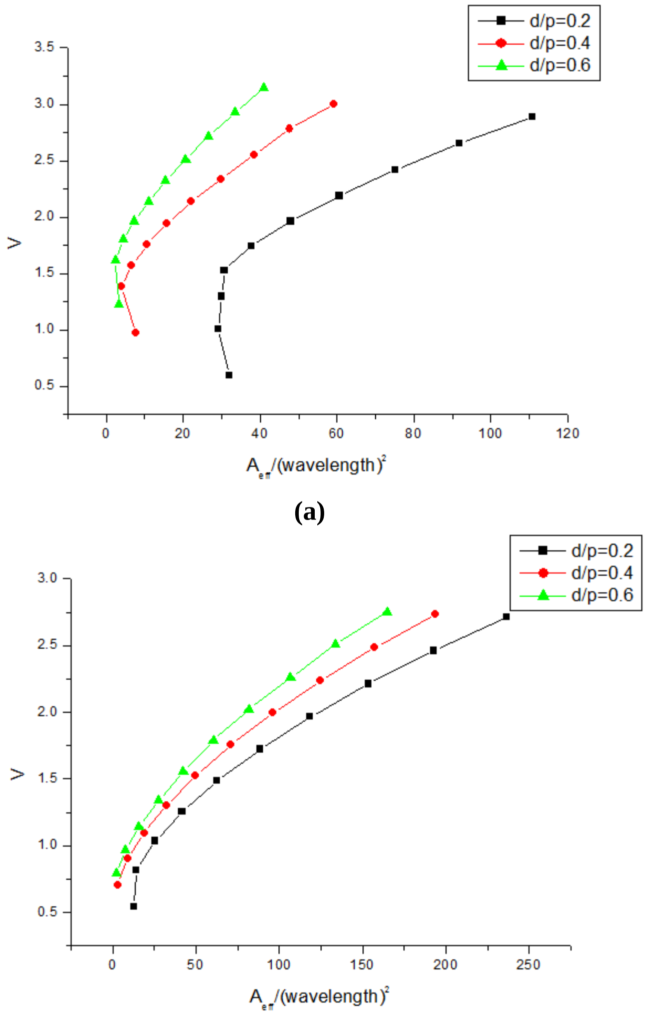

(a)

(b)

Fig.4 V-parameter versus (A_{eff}/λ^2) for different air hole diameters corresponding to the ESM limit (a) omitting single air hole to form the fiber core and (b) omitting five air holes to form the fiber core.

IV. CONCLUSIONS

The Cutoff properties of IG- PCF of six air holes rings for different fiber core radii and different air filling fraction had been studied. All the analyses of the PCF properties have been performed by using the FEM. by comparing V-parameter for different fiber core radii ,it's showed that fiber core diameter limiting the ESM regime ,in spite of each designed fiber had ESM properties but PCF with core formed by omitting single air hole from the center of the fiber had higher V-parameter which is drawn as a function of ($Aeff/\lambda^2$)which is very close to $V_{PCF}=\pi$ for different air filling fraction while Fiber with core radii formed by omitting five air holes from the center of the fiber had less value of V-parameter which is mean that PCF with small core had less susceptible to longitudinal non uniformities , and in general increases for cores formed by increasing number of removed air holes to form the fiber core, the value of ($\Delta n=0$) which is considered as a definition of the cutoff wavelength is also prove that fiber with large core radius have ESM for different air filling fraction more than fiber with small core radius. Large effective area and ESM properties had wide applications, such as polarization-maintaining fiber, amplifier, and fiber laser etc..

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