Refractive Index Sensor Based on Micro-Structured Optical Fibers with Using Finite Element Method

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Abstract

In this paper a refractive index sensor based on micro-structured optical fiber has been proposed using Finite Element Method (FEM). The designed fiber has a hexagonal cladding structure with six air holes rings running around its solid core. The air holes of fiber has been infiltrated with different liquids such as water, ethanol, methanol, and toluene then sensor characteristics like effective refractive index, confinement loss, beam profile of the fundamental mode, and sensor resolution are investigated by employing the FEM. This designed sensor characterized by its low confinement loss and high resolution so a small change in the analyte refractive index could be detect which is could be useful to detect the change of the information of the biological molecule reaction and also in medical applications in fields like toxins, drug residues, vitamins, antibodies, proteins and parasites.

Keywords: MOF, FEM, RI-MOF sensor

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Introduction

Optical fiber sensors have wide applications in science, the environmental monitoring, and communication technology this is due to their compact in size, high sensitivity, electrical passiveness, immune to electromagnetic interference, wide bandwidth as well be made convenient for tip-based sensing. Most of these optical sensors measure the variations of optical properties because of a change in the refractive index (RI) of a gas or a liquid [1]. Measuring the RI of fluids is very important; so as to depict the optical properties of fluids which is lead to evolution of RI sensors for applying in many fields such as the salinity of water measurement [2], and biotechnology processes [3] also provide important acquaintance on drug/DNA interaction and growth of the cell [4]. Anew type of optical fiber had been developed in the beginnings of nineteeths, called Micro-Structured Optical Fibers (MOF) or Photonic Crystal Fibers (PCFs), in which air holes were developed along the fiber structure [5]. Micro-Structured could be classified according to the guiding mechanism to; index-guiding and band-gap MOF’s. The first type, the core is solid and the cladding is represented by two- dimensional lattices of air holes running along the entire length of the fiber. The RI of the index-guiding MOF is higher than the cladding, so the light will be guided inside the fiber core by means of total internal reflection [6], while in band-gap type the light will be guided by a two- dimensional photonic bandgap because the core in these fibers is air or (hollow core) which its refractive index less than the refractive index of cladding. Due to the band-gap phenomena specific frequencies of light that propagate along the fiber are not allowed to escape from the core but will be reflected and constructively interference inside the core and destructively interference in the cladding [7]it, Figure -1 shows some types of MOFs.

![Figure 1-Some typical structures of MOFs (A) Solid Core-MOF, (B) Suspended core MOF; (C) Hollow Core-MOF, and (D) Kagomé HC-MOF [8].](image)

The unique properties of MOFs lead to developed different and new schemes of optical RI-sensors; a microfluidic RI sensor based solid-core PCF presented by Wu et al. , the RI sensitivity was circa 38,000 nm/RIU [9]. Park et al. implemented a MOF-based reflection kind refractometer insensitive to temperature for RI measurement the sensitivity was 850 nm/RIU [10], and Li et al. [11] attained an optimum sensitivity of 1629 nm/RIU by developing instead a tapered-PCF in transmission. In addition, the unique geometrical structure of MOF allows tuning of propagation properties of the fiber via alteration the air hole position, size and shape [8]. The Sensitivity and the confinement loss considered as the main guiding properties of MOF sensors. Several simulation works that used FEM have been published to gain sensitivity at a maximum and confinement loss at a minimum suitable grade in the environmental and biological sensing applications. Olyae et al. designed index-guiding MOF for gas sensing and they achieved lower dispersion, confinement loss and nonlinear effect simultaneously [12]. Cordeiro et. al submitted a new concept for evanescent sensing application in which both the core and the cladding are micro-structured [13]. Octagonal-MOF with smaller loss and the higher prorated sensitivity coefficient for three analytes like Water, Ethanol and Benzene had been submitted by Ademgil [14].
Kawser et al. designed an O-PCF structure with high relative sensitivity and low confinement loss and investigated the effects of different parameter variations on propagation properties over a wide wavelength range [15], also high sensitivity, high nonlinearity, high birefringence and low confinement loss MOF submitted by Arif et al. 2017 which both core and cladding are micro-structured the core of the MOF structure is designed with two rows of supplementary elliptical air hole.

**Materials and Methods**

In this work, an index guided MOF with hexagonal shaped air holes rings in the cladding area had been designed. The number of air hole rings were six, normalized air hole size \( \frac{d}{\Lambda} \) was 0.4, hole to hole spacing \( \Lambda \) circa 7.5\( \mu \)m, air hole diameter \( d \) 4\( \mu \)m, and core diameter \( \rho \) 10\( \mu \)m, Figure-2 shows the designed fiber.

![Schematic illustration of the proposed MOF.](image)

Finite Element Method (FEM) with Perfectly Matched Layer (PML) boundary condition is depended for the analysis of the structure with a FEM based simulation software COMSOL Multiphysics 4.4. FEM provides the effective investigation of MOF dispersion, amplification and nonlinear properties. Moreover, the complex formula of FEM so beneficial, for instance, to evaluate the MOF leakage or confinement losses, because of the finite number of air-hole rings in the cladding lattice, the following equation with a magnetic field formulation can be derived from the Maxwell equations [16]:

\[
\nabla \times \left( \mu_r^{-1} \nabla \times \vec{E} \right) - k_0^2 \varepsilon_r \vec{E} = 0
\]

This is an eigen value equation, the eigen values are \( \frac{\beta}{k_0} \) the effective indices \( n_{eff} \), and the eigenvectors are the electric field components \( E_x, E_y, E_z \). In (1), \( \vec{E} \) represent the electric field, \( k_0 \) represent the wave number in vacuum, and \( \varepsilon_r \) and \( \mu_r \) are the dielectric permittivity and magnetic permeability tensors, respectively [16].

The modal analyzes performed on the x-y plane cross sectional MOF structure as the wave is propagating in the z direction. The MOF cross-sectional in the transverse X – Y plane is divided into triangular elements with different shapes, sizes, and refractive indices. Any type of geometry, inclusive the MOF air-holes, as well as the characteristics of the medium, can be precisely described.

In particular, the FEM is adequate for analyzing fibers with nonperiodic air-hole arrangements. As well as, it provides a full-vector analysis which is requisite to model MOFs with large air-holes and high index changes, and to predict precisely their properties.

The attenuation resulted from the waveguide geometry is called the confinement losses or leakage losses \( L_c \); confinement losses originates from the finite width of the cladding structure. This is an extra type of losses that happened in single material fibers especially in MOFs because they are commonly made of pure silica, \( L_c \) in dB/m is given by [17]

\[
L_c = -20 \log_{10} e^{-k_0 m |n_{eff}|} = 8.686 k_0 \text{Im}[n_{eff}] \tag{2}
\]
where \( k_0 \) is the propagation constant in free space, and \( \text{Im}[n_{\text{eff}}] \) is the imaginary part of the complex effective refractive index \( n_{\text{eff}} \).

In this work, the air holes of the designed MOF was infiltrated with water, ethanol, methanol, and toluene then confinement loss, the effective refractive index, and the sensor resolution have been studied for each case.

**Results and discussion**

To analyze the sensor characteristics, a large analyte RI range from 1 to 1.48 is investigated at 1-1.7 \( \mu \text{m} \) wavelength. The MOF cladding which is a two-dimensional photonic crystal with 6-rings of the hexagonal lattice air holes in the silica matrix have been infiltrated with different liquids (water, ethanol, methanol, and toluene) which have different refractive indices. Then the numerical analyses on some propagation characteristics of the proposed MOF structures in fundamental mode have been studied.

Figure 3, shows the electric field profile for wavelengths ((a) 1, (b) 1.55, (c) 1.3, and (d) 1.7 \( \mu \text{m} \)) in absence of the analyte, while Figure 4 shows the real part of the effective index \( \text{Re}(n_{\text{eff}}) \) variations with the operating wavelength, and Figure 5 shows the confinement loss behavior with wavelength which is remains at around 0 dB/m due to high confinement of mode.

Figures-(6,9,12, 15) show the electric field profile for wavelengths ((a)1, (b)1.55,(c)1.3, and (d) 1.7 \( \mu \text{m} \)) of samples infiltrated with analyte water, ethanol, methanol, and toluene respectively. It can be noted that the electric field is fundamentally confined in the MOF core region.

Figures-(7,10,13, 16) illustrates the variation of the real part of the effective index \( \text{Re}(n_{\text{eff}}) \) with the operating wavelength, for samples infiltrated with water, ethanol, methanol, and toluene respectively. At longer wavelengths, \( \text{Re}(n_{\text{eff}}) \) is low, while it is inversely proportional with wavelength.

Figures- (8, 11, 14, 17) shows the confinement loss against wavelength for the proposed MOF structure infiltrated with water, ethanol, methanol, and toluene respectively.

The refractive index resolution \( R \) of the corresponding sensor can be obtained as: \[ R = \frac{\Delta n_a \Delta \lambda_{\text{min}}}{\Delta \lambda_{\text{peak}}} \] (3)

Where \( \Delta \lambda_{\text{min}} \) peak-wavelength resolution is assumed to be \( \Delta \lambda_{\text{min}} = 0.1 \text{ nm} \), \( \Delta n_a \) the variation of the analyte refractive index, and \( \Delta \lambda_{\text{peak}} \) the variation of the peak wavelength.

According to above equation, the resolution for the submitted sensor is about 2.33x10\(^{-7}\) RIU, 6 x10\(^{-7}\),1.27 x10\(^{-7}\) RIU, 1.48 x10\(^{-7}\) RIU and 6.9 x10\(^{-7}\) RIU for samples infiltrated with air, toluene, methane, ethanol, and water respectively.

**Figure 3-** Electric field profile of the MOF without analyte with different wavelength, (a) 1\( \mu \text{m} \), (b) 1.3 \( \mu \text{m} \), (c) 1.55 \( \mu \text{m} \) and (d) 1.7 \( \mu \text{m} \).
Figure 4- The real part of $n_{\text{eff}}$ of the fundamental mode as a function of operated bandwidth.

Figure 5- The simulated $L_c$ of the fundamental mode as a function of operated band width.

Figure 6- Electric field profile of the MOF infiltrated with water of different wavelength, (a) 1$\mu$m, (b) 1.3 $\mu$m, (c) 1.55 $\mu$m and (d) 1.7 $\mu$m.
Figure 7- The real part of $n_{\text{eff}}$ of the fundamental mode as a function of operated bandwidth.

Figure 8- The simulated $L_c$ of the fundamental mode as a function of operated band width.

Figure 9- Electric field profile of the MOF infiltrated with ethanol of different wavelength, (a) 1 µm, (b) 1.3 µm, (c) 1.55 µm
Figure 10- The real part of \( n_{\text{eff}} \) of the fundamental mode as a function of operated bandwidth.

Figure 11- The simulated \( L_c \) of the fundamental mode as a function of operated bandwidth.

Figure 12- Electric field profile of the MOF infiltrated with methanol of different wavelength, (a) 1\( \mu \)m, (b) 1.3 \( \mu \)m, (c) 1.55 \( \mu \)m and (d) 1.7 \( \mu \)m.
Figure 13-The real part of $n_{\text{eff}}$ of the fundamental mode as a function of operated bandwidth.

Figure 14-The simulated $L_c$ of the fundamental mode as a function of operated bandwidth.

Figure 15-Electric field profile of the MOF infiltrated with toluene of different wavelength, (a) 1µm, (b) 1.3 µm, (c) 1.55 µm and (d) 1.7 µm.
Figure 16- The real part of $n_{\text{eff}}$ of the fundamental mode as a function of operated bandwidth.

Figure 17- The simulated $L_c$ of the fundamental mode as a function of operated bandwidth.

The characteristics of the effective refractive index of the proposed structures have been studied. The numerical investigation for all samples shows the effective index profiles of the proposed microstructured fiber at different wavelengths. An increase in the operating wavelength results in a linear decrease in effective indices. The confinement losses calculated according to eq. 2, from the results for empty samples high confinement had been obtained; no leakage loss obtained. For the infiltrated samples the confinement loss is increase by the increasing of wavelength; this could be explain as effective refractive index of the fundamental mode began to reach to refractive index of pure silica (at shorter wavelength) propagation become parallel to the fiber axis so the interaction with holly structure will be minimized.

Conclusion

A refractive index sensor based on MOF with hexagonal lattice was suggested. Numerical analysis of the designed fiber is carried out by FEM. For all samples the effective refractive index was decreased with increasing of the wavelength range, also the fundamental modes are highly confined in core region for the samples infiltrated with liquids which their RI is less than the RI of silica (it’s about $10^{-9}$ dB/m); the light is propagate according total internal reflection, while for toluene sample with RI is about 1.48 which is higher than the RI of silica the modes will be widely leakage out of the MOF core (confinement loss about $10^{-6}$ dB/m) the light will be guided according photonic band gap effect, also this sensor has a high resolution (about $10^{-7}$ RIU). This MOF RI-sensor could be used in various medical and environmental sensing applications using different fluids analytes due to its high resolution and low confinement loss.
References