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Cladding Modes Analysis of Photonics Crystal Fiber for Refractive Index Sensors Using Finite Element Method

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Abstract: We developed a Finite Element package to analyze cladding mode field extensions into the air-holes of photonics crystal fiber for refractive index sensing. Our analysis could determine the most sensitive cladding mode for liquid sensing.

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1. Introduction

Refractive index fiber optic sensors involving cladding modes of photonics crystal fiber (PCF) can attain very high sensitivity compared with those using conventional optical fiber [1,2]. Investigating modal characteristics of cladding modes of PCF is therefore of interest for such fiber optic devices. Previously, modal characteristics of PCF cladding have been investigated by using plane wave method [3] but sensing characteristic of the cladding modes has not been addressed. In the case of PCF cladding modes, optical field is not only confined in the silica region but also extend into the air-hole region as evanescent wave. For use as refractive index sensor, since the sensitivity is mainly dependent on the interaction of the liquid/gas in the air-hole with the cladding fields, it is logical to consider the cladding modes with higher intensities extended in the air-hole region to be more sensitive. In this work, we implemented Scalar Finite Element Method (SFEM) to compute the field distribution of cladding modes of PCF and investigate the field intensity extension of the cladding modes into the air-hole region for refractive index and biochemical sensing applications.

2. Implementation of SFEM package & Numerical Results

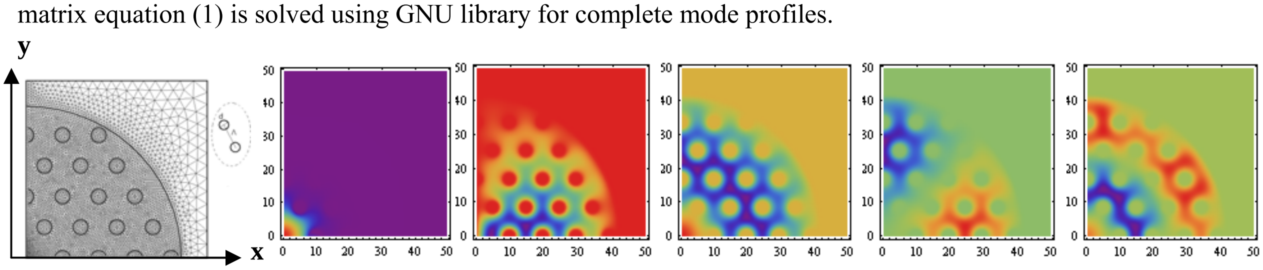
In order to do the modal analysis of PCF, we considered the Helmholtz equation in the scalar approximation for an isotropic and lossless optical waveguide. It should be noted that while vectorial FEM is a more sophisticated approach for analyzing PCF, SFEM is much simpler and sufficient to obtain accurate result given that air filling fraction d/Λ is smaller than 0.45 [4]. Applying the standard finite element technique, we obtained the following generalized eigenvalue problem [5]:

$$[K]\{E_x\}^T - n_{eff}^2 [M]\{E_x\}^T = 0 \qquad (1)$$

where

$$[K] = \sum_e \iint_e \left[\{N\}\{N\}^T - n^2 \frac{\partial\{N\}}{\partial\tilde{x}}\frac{\partial\{N\}^T}{\partial\tilde{x}} - n^2 \frac{\partial\{N\}}{\partial\tilde{y}}\frac{\partial\{N\}^T}{\partial\tilde{y}} \right] d\tilde{x}d\tilde{y} \quad \text{and} \quad [M] = \sum_e \iint_e n^2 \{N\}\{N\}^T \, d\tilde{x}d\tilde{y} \qquad (2)$$

Where n_{eff} is the effective index. E_x is the electric field in x-polarization and n(x, y) is the refractive index. The matrix equation (1) is solved using GNU library for complete mode profiles.



(a). **(b).** LP_{01} LP_{11} LP_{02} LP_{21} LP_{12}

Fig. 1 (a). Meshed PCF geometry**,** due to the symmetry nature of PCF, the quarter cross-section is divided into a patchwork of triangular elements. Silica index =1.45, Pitch Λ = 9.7µm, air-hole diameter d = 0.42 Λ, Outer PCF diameter =83µm **(b).** E_x is the field distribution obtained for the fundamental core mode and the first four cladding modes in PCF by SFEM at λ=1560 nm.

Fig. 1(a) shows the meshed geometry of the PCF structured under investigation, the mesh was refined in the whole silica/air-hole region of the PCF where all the guided modes (both core and cladding modes) are existed. We calculated effective indices and corresponding E_x field distributions of core and several of the first cladding modes of PCF at wavelength λ of 1560 nm.

Fig. 1(b) shows the E_x field distributions of the core mode and the four lowest order cladding modes. Here we obtained only one mode in each LP_{nm} group using SFEM (e.g HE_{11}, HE_{12}, HE_{21}, HE_{31} and HE_{22} modes from left to right). It is interesting to note that the mode profiles in PCF are similar to their counterparts in conventional step-index circular fibers, as similar to results in [3]. To validate our model, the results in Fig. 1(b) were compared with those obtained the vectorial plane wave method (PWM) for the same standard PCF structure shown in Fig. (1a) [3] and found to be in very good agreement.

3. Cladding mode field extensions into the air-holes of the PCF

Using mode field distribution in Fig. 1(b), intensity of the optical field into the air-holes is calculated for determining the most sensitive cladding modes of PCF. Here our argument is that, the more the overlap of optical modes in PCF with the air hole region which implies better interaction of optical field with liquid/gas in the air-holes, the better refractive index or biochemical sensitivity. We considered a circular layer of radial region 1.50μm ≤ r ≤ 2.037 for calculating the extended optical intensity (E_x^2) inside the air-hole of radius 2.037μm because there is no field for r ≤ 1.50μm in our case for all calculated cladding modes (with sufficiently refined mesh to ensure convergence of the SFEM). For a particular mode, the average optical field intensity or relative sensitivity can be expressed as:

$$\text{Relative sensitivity} = \sum_{i=0}^{m} \Big[\int_{\theta}\int_{r} E_{xi}^2\, r\, dr\, d\theta\Big] / m \qquad (3)$$

where m is the total number of air holes in the PCF under investigation and E^2_{xi} is the field intensity extended into the air-hole region.

As can be seen from Fig. 2, the sensitivity of the fundamental core mode (mode number 0) is much lower than those of cladding modes due to the strong confinement of optical intensity in the PCF core. The optical intensity of all of the first 13 cladding modes in is more or less same which means that all of cladding modes of PCF can effectively interact with the surrounding medium which is obviously different to the case of conventional single mode fiber, where cladding mode higher order is widely acknowledged to be more sensitive with surrounding medium. Among 13 cladding modes under investigation in our work, the first (fundamental space filling mode) and 5th modes are found to be most effective to be used for refractive index sensing as their air-hole extended intensities are the highest.

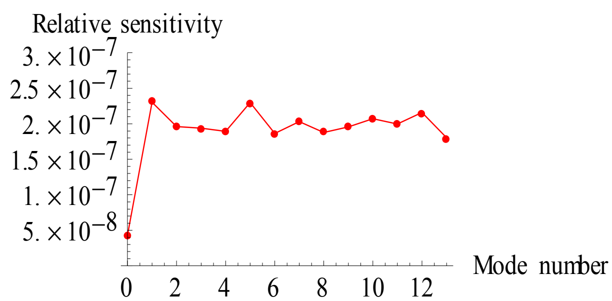


Fig.2 Relative sensitivity of lowest 14 modes in PCF. Mode number 0 is the fundamental core mode.

4. Conclusion

In this work, SFEM was developed to characterize the transverse mode-field distribution of cladding modes of PCF. The cladding optical fields were found to extend into the air-hole region of PCF cladding slightly differently which is different to the higher-order-higher-sensitivity nature of cladding modes of conventional optical fibers. In addition, our analysis allows choosing the most sensitive cladding mode for applications in refractive index or biochemical fiber optic sensors.

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