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Sensitivity characterization of cladding modes in long-period gratings photonic crystal fiber for structural health monitoring

Shijie Zheng [a,b,*], Baohua Shan [a,b], Masoud Ghandehari [c,d], Jinping Ou [a,b]

[a] Key Lab of Structures Dynamic Behavior and Control (Harbin Institute of Technology), Ministry of Education, Harbin, 150090, China
[b] School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China
[c] New York University Polytechnic School of Engineering, Brooklyn, NY 11201, United States
[d] Center for Urban Science and Progress, Brooklyn, NY 11201, United States

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ABSTRACT

Sensitivity of fiber cladding modes coupled with long-period gratings (LPGs) in photonic crystal fiber (PCF) are investigated with respect to external conditions such as temperature, strain, the surrounding refractive index, curvature, and torsion. What we have found is that the application of MODE Solutions to a given PCF structure can produce a large amount of modes, where the dispersion and group velocities are generally a function of wavelength, hence the cladding modes with ultra-sensitive spectrum behavior for LPG coupling and sensing purpose. By means of analyzing equation of phase-matching condition, we can better understand sensitivity characteristics of cladding modes. The results of numerical computation indicate that the maximum or minimum sensitivity of a cladding mode coupled with PCF-LPG is predetermined by its dispersion, which is also influenced by the PCF structure geometry. The design of the structural geometry gives a large degree of freedom with respect to tailoring its optical properties. Multi-parameter sensing is discussed in light of utilizing the resonances at discrete wavelength locations distinguishing and simultaneously measuring two parameters in a PCF-LPG.

1. Introduction

Photonic crystal fibers (PCFs) with unique optical properties [1,2] have attracted a great deal of attention in the field of fiber optic sensing. The micro-structured air channels along the fiber cladding, the enhanced evanescent field and light-analyte interactions have spurred many possibilities in chemical sensing [3–6]. However, the past studies have mainly focused on the manipulations of the PCF's guided core mode, with less reports on its cladding modes [7–10], while the cladding modes in conventional optical fibers have been implemented in many sensing devices already [11,12]. A better understanding of the characteristics of cladding modes in PCFs would be of great value in both academic research and engineering applications.

In the case of and endless single mode PCF, the cladding modes must be excited by the guided core mode. Most often, long-period gratings (LPGs) are used for this purpose [13–17]. With a periodic perturbation of refractive index in the fiber, and when the inter-modes beat length equals the grating period, the guided core mode couples a sequence of co-propagating cladding modes. This leaves a set of attenuation bands at the transmission spectrum. The coupled resonances may vary by different orders of cladding modes. They are sensitive to external perturbation in terms of the resonant wavelength and transmission intensity. These features enable PCF-LPGs to be exploited as multi-parameter sensing demodulators.

* Corresponding author at: School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China. Tel.: +86 451 86282095.
E-mail address: zhengshijie@hit.edu.cn (S. Zheng).

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PCF-LPGs have been realized by introducing several non-photosensitive methods that involve either physical deformation or residual stress relaxation of the fiber [18–21]. While a number of experiments on the fundamental transmission characteristics of PCF-LPGs have been reported [22–24], the theoretical study on their potential and/or limitations in sensing applications have fewer references.

Here, we numerically identified the optimal cladding modes with various air-channel structures from the point of view of dispersion, intended for general sensing purposes (sensitivity factor γ). Particular sensitivities to temperature, strain, surrounding refractive index, and curvature were theoretically analyzed by phase-matching conditions with respect to possible coupled cladding modes. By investigating fiber geometry parameters (air-channel diameter d and distance between two adjacent air channels Λ_d), we simulated the PCF-LPG sensitivity as function of different external parameters. It was observed that for a given geometrical features, sensitivity to external parameters was dominated by the choice of the cladding mode. Potential application in multi-sensing with cross-sensitivity is also investigated in this study.

2. Cladding modes in PCFs

A solid-core PCF consists of spaced air channels in fiber cladding with a missing hole at the center of the fiber. Since the effective refractive index of cladding is lower than that of the core, the light is guided by the total internal refection at the boundary between silica core and the inner most ring of air channels. In solid-core PCFs, a mode can be guided when its effective refractive index falls into the range between that of silica and that of the lowest order cladding mode. However, the cladding can also support a large number of cladding modes. In contrast to the guided core mode, solid core cladding modes are leaky, and easily radiate or scatter. In this study, we applied the finite difference frequency domain technique to directly discriminate the wave equation in terms of transverse electric field and/or magnetic field with respect to parameters including propagation constant, waveguide dielectric constant, and wave number in free space. Here, a particular cladding mode profile can be determined by numerical computations of Yee's two-dimensional mesh. Calculations were done by a commercially available mode solver.

A typical cladding cross section is shown in Fig. 1(a) as a cross-section structure which has four rings of air channels surrounding the silica core with a hexagonal symmetry (C_{6v}). Shown in Fig. 1(b) is the scanning electric microscopy (SEM) of an endless single mode PCF (ESM-PCF) used in the LPG inscription. The simulation area is defined by a boundary condition. A portion of fiber cross-section shown in Fig. 1(c) was used for the calculation of intensity distributions of guided core mode and cladding modes, where the symmetric boundaries are mirrored for the electric fields. The effective indices of guided core mode and cladding modes are simulated by geometric parameters, where the normalized air-channel diameter (d/Λ_d) ranges from 0.15 to 0.85 in steps of 0.1, and Λ_d is 9 μm. As the degeneracy of modes can be identified by electric field distribution determined by the cross section refractive index profile; the discrepancy of effective indices of two degenerate modes is as small as 10^{-5}, which is larger than the relative error in the simulations. The Sellmeier equation was applied for the calculation of a modes constant. As the cladding modes in PCF are highly dispersive, the sensitivity of PCF-LPG can be resolved.

Fig. 2 shows the modal field patterns of guided core modes and the first five lowest cladding modes with linearly polarized (LP) degeneracy (for the case of conventional step-index fiber). These calculations considered various normalized air-channel diameters (d/Λ_d). It was noted that the structures of higher order cladding modes are more complicated than those of lower orders. On the other hand, the field profiles of lower order cladding modes, such as $LP_{0\ 2-1}$ cladding modes within 0.35 to 0.65 of d/Λ_d, are circular and non-degenerate. They are extended to the whole web structure of silica air channels in the cladding, which are significantly influenced by the fiber geometry. Few core modes have been observed in the fiber structure whose d/Λ_d is larger than 0.65, whereas the cladding modes with less than 0.35 in d/Λ_d are less confined and lossy. Those modes are difficult to couple by guided core modes because of the small coupling coefficient.

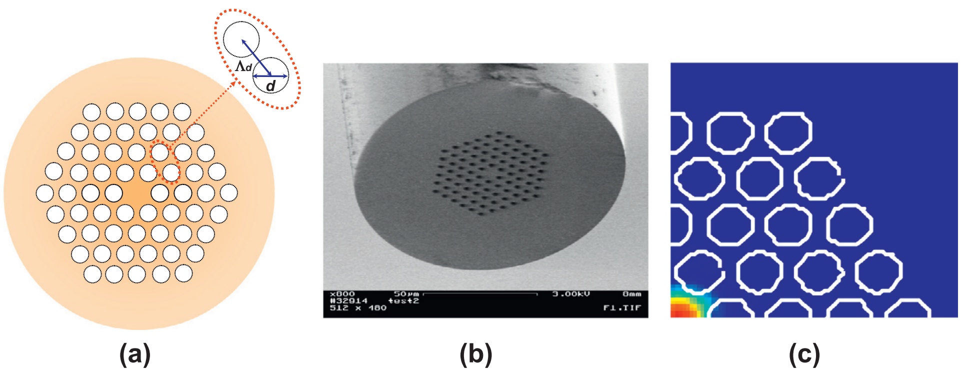

Fig. 1. Structure with hexagonal lattice of air channels in solid-core PCF for numerically analysis, (a) cross-sectional diagram; d: diameter of air channel, Λ_d: distance between adjunct air channels, (b) microscope of scanning electric microscopy (SEM) for PCF used in LPG inscription, and (c) a portion of fiber cross-section used for simulation of electric field under symmetric boundary conditions.