Experimental excitation and characterization of cladding modes in photonic crystal fiber

Sun Do Lim,1,3,* Hyun Chul Park,3 In-Kag Hwang,2 Sang Bae Lee,3 and Byoung Yoon Kim1

1Department of Physics, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, South Korea
2Department of Physics, Chonnam National University, 300 Yongbong-dong, Buk-gu, Gwangju, 500-757, South Korea
3Photonics Research Laboratory, Korea Institute of Science and Technology, 39-1 Hawolgok-dong, Wolsong-gil 5, Seongbuk-gu, Seoul, 136-791, South Korea

* sdlim@kist.re.kr

Abstract: We extend the previous theoretical study on the effect of outer silica cladding to the analysis on real field profiles in a practical PCF. Clear field profiles for the first higher-order cladding modes are presented and discussed. The observed mode fields are reproduced by numerical calculations, and it turns out that they correspond to LP16 mode groups. Optical properties of the observed modes such as lobe direction and polarization are also investigated. The results of this study will be useful in the design of the PCF-based optical devices utilizing cladding mode coupling.

References and links

1. Introduction

Since the advent of photonic crystal fiber (PCF) [1], PCF has been applied across a number of optical fiber industries. Most of the applications thus far have focused on the core-guided modes, but in recent years considerable attention has been directed toward the use of cladding-guided modes. It is expected that the use of the cladding modes cannot only offer a greater degree of freedom in the design of the PCF-based optical devices as in the conventional optical fiber [2–4], but also lead existing fiber-optic components to novel applications. To appreciate the use, the guidance mechanism and the optical properties of the cladding modes in an actual PCF structure should be understood in detail. To date, there have been several direct and indirect efforts regarding the analysis of PCF cladding modes. The first investigation was carried out based on a PCF with a germanium (Ge)-doped photosensitive core [5–7]. In the work, a photo-induced Bragg grating was written in the core of the PCF and far fields of the light reflecting off the grating at each resonance wavelength were analyzed. Thereafter, a diversity of techniques for realizing a long period grating (LPG) in Ge-free pure-silica PCFs have been demonstrated and in these works have also provided the field images of the transmitted light after writing of the LPGs [8–12].

However, most of the LPG-based works focused mainly on the fabrication methods of the grating in the PCFs, so that the analyses on the mode fields were not detailed. Furthermore, the light fields in some studies were unclear or too complicated to be interpreted as a mode. Also, incorrect definitions and designations for the PCF cladding modes were improperly used in some cases. The confinement and the guiding mechanism of the cladding mode should be reconsidered. We believe that the major reason for the difficulties in the analysis of the PCF cladding mode in the past was due to the outer silica cladding effect on the mode field distribution. H. C. Park et al. (2007) recently made the theoretical analyses for the cladding modes of the PCF with outer silica regions [13]. Realized was that the presence of the outer silica jacket in the PCF tends to push the optical field of the cladding modes toward the rim of the PCF, and they become “ring mode” whose major fields are tightly confined in the outer silica cladding. The theoretical analysis was made for the PCF with a restricted thickness of the outer cladding due to the lack of computing capacity.

In this work, we extend the previous theoretical study on the effect of the outer cladding to the experimental analysis [14]. Specific cladding modes can be precisely excited by proper introduction of the acoustic LPG and a sufficiently long interaction length. Numerical reproduction of the observed mode fields can also be carried out by optimization of the computing method and process. The simulations based on the ideal structural parameters reveal that the observed modes correspond to LP_{16} mode groups. The effects of the outer cladding thickness and the air-hole disorder on the mode field profiles, as well as the optical properties of the observed modes, are described.

2. Observations of the cladding mode fields

Many index-guiding PCFs consist of three parts: a silica core, an inner holey cladding, and an outer silica cladding. The thickness of the outer silica cladding typically ranges from 10 to 40 µm for the 125-µm outer cladding diameter, which depends on the number of air-hole layers and the normalized air-hole diameter (d/λ) of the PCFs. Here, d is the average air-hole diameter and λ is the average center-to-center distance between the air holes. The PCF used in the experiment has inversion and six-fold rotation symmetry in the air-hole structure (Fig. 1).
The diameter (d), the pitch (λ), and the outer cladding diameter (D) were measured to be about 3.7, 8.24, and 125 µm, respectively. Scanning electron microscope (SEM) images were used for dimension estimations. Numerical calculation based on the structural parameters reveals that the wavelength of the second-mode cutoff lies below 1500 nm. In the single-mode region over 1500 nm, an efficient coupling between the core and the cladding modes that have a substantial fraction of their fields in the holey cladding region can take place by periodic perturbations [15]. In our experiment, a flexural acoustic wave was used to couple the core mode to the cladding modes, which is generated by an acoustic transducer consisting of a thin PZT disk and a glass horn. The acoustic wave gives rise to micro-bends along the bare-section of the fiber, which results in the periodic index change to the fiber, thereby acting as an LPG. The period of the LPG can be controlled by the frequency of an RF signal applied to the PZT. A schematic of the experimental setup for the near-field observation is shown in Fig. 2.

The total grating length is about 24 cm. The transmission spectrum of the acoustic LPG was measured and is shown in Fig. 3.

A broadband light source was launched into the input of the acoustic LPG (Fig. 2). The light coupled to the cladding modes at each phase-matching condition is absorbed by the polymer.
jacket of a conventional single mode fiber (SMF) leading the non-resonance light to an optical spectrum analyzer (OSA). The applied acoustic frequency was 4.25 MHz (theoretical grating period: ~458 µm). The four resonance peaks in the transmission spectrum are located at the wavelengths of 1541.1, 1564.3, 1572.1, and 1581.6 nm. These peaks are considered to be due to the coupling of lowest-order cladding modes that are possibly coupled from the core mode. It should be noted that clear spectral peaks for the other higher-order cladding modes could not be found in the transmission spectrum. It can be only stated that there were difficulties in coherent coupling to the other higher-order cladding modes of the PCF. The maximum separation of about 40 nm among the spectral peaks of the same mode group is an unusual phenomenon in uniform-core conventional fiber, but the large peak splitting have been frequently shown in PCF in previous works [15,16]. For the cladding modes, the mode fields are distributed in two different sections (holey cladding and silica ring cladding region) and experience two physical boundaries (core-holey cladding and holey-silica cladding) that are involved in formation of the field profiles. These can provide more degree of freedom in the field formation compared to the previous case. We believe that the splitting in wavelength between the notches was originated from the w-shaped index profile of the PCF.

In order to observe the cladding-mode at each resonance wavelength, a tunable laser source was used instead of the broadband light source. After the modal interaction, the cladding-mode light propagates an additional 5 cm-long PCF before the observation. An adhesive tape with a width as small as 1 mm was used as an acoustic damper to minimize the field distortion of the cladding modes that may occur. It was empirically found that this perturbation had little influence on the cladding-mode field deformation. The transmitted light was directly observed at the cleaved end face of the PCF with an IR CCD camera using a 25 × microscopic lens. Mode field profiles at the four resonance wavelengths appear in Fig. 4.

As they appear in the figures, the observed cladding modes have 6 radial lobes and 2 circumferential nodes at the fiber center, that would be the properties of the LP_{16} mode for a conventional optical fiber. One significant difference here is the higher number of circumferential nodes in the outer region of the field profiles, which we believe are from the combined effect of the air-hole voids at the apex of the hexagonal air-hole structure and the relatively large irregularity in the outermost air holes. As a basic approach to the verification of this conjecture, we performed numerical calculations for the observed field profiles. For the analogous reproduction of the field profiles, accurate dimensions of the structural parameters such as air-hole diameter and pitch were used, including the small deviations from the perfect symmetry. However, there was an intentionally small change in one physical parameter, which is the outer cladding diameter and it was set as 132 µm. This will be discussed in detail in the last section. The deviations in the air-hole diameter and the pitch were found to be up to 3.5% and 3%, respectively. We used a finite element method for the numerical calculation. The refractive indices used in the calculation were set as 1.444 for silica and 1 for air at a wavelength of 1.6 µm. In order to achieve the mode field profiles, the cross section of the PCF has to be properly split into a large set of elementary subspaces, which is called a ‘meshing’ process. Note that the software devoted in this study solves the Maxwell equations for a global matrix system for the entire subspace taking into account continuity conditions at the
boundary of each subspace. We found that a relative index error between two adjacent modes is about $2 \times 10^{-6}$, which means that the computing resolution is sufficient to discretize the adjacent cladding modes in the range of our interest. Figure 5 shows the calculated mode fields corresponding to the observed four modes in Fig. 4, respectively.

Fig. 5. Mode field distributions (E), (F), (G), and (H) are the calculation results that correspond to the experimental observations (A), (B), (C), and (D) in Fig. 4, respectively.

It was found from the calculation of spatial overlap integral between electric fields of the modes that the modes are respectively orthogonal. In this case, the effective refractive indices of the fundamental mode and the fundamental spacing filling mode (FSPM) whose index is regarded as that of the cladding were calculated to be 1.441666, and 1.438728, respectively. The effective indices for the calculated cladding modes in Fig. 5 are (E) 1.438641, (F) 1.438658, (G) 1.438686, and (H) 1.438695, respectively. According to the calculations, they are not ‘leaky modes’. It was also found that each mode has two eigen-polarization states, and the index differences between the polarization states were less than $2 \times 10^{-6}$ except the last (H) with about $3 \times 10^{-6}$. The maximum separation of the spectral peaks in Fig. 3 can be reasonably explained based on the calculated mode indices above and the modal beat-length dispersion of the PCF [17].

3. LP$_{1n}$ modes in an ideally structured PCF

We begin with an assumption that the radial lobes and the circumferential nodes of the fields in the outer silica region arise from the combined effects of the irregularity of the inner and outer air holes and the omissions of air holes at the apex of the hexagonal lattice structure. In order to identify and classify the observed modes, a perfectly structured PCF without the air-hole omission was modeled with the average physical parameters of the real PCF. According to previous research, the optical properties of the PCF with $C_6\nu$ symmetry in the air-hole structure can be treated as those of the fiber with the circular symmetry [18].

Fig. 6. $E_x$-field distributions for spatially anti-symmetric modes in the PCF (a) LP$_{11}$ mode – (c) LP$_{18}$ mode @ $\lambda = 1.6 \, \mu m$. 

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Thus, this kind of PCF is expected to have similar mode classifications to those of the step-
index uniform-core fiber. Note that throughout this work, cladding modes with anti-symmetric
field distributions will be under consideration. The previous study [13] indicates that the PCF
with the thick outer silica cladding pushes the relatively lower-order cladding modes out of
the holey cladding region, making them ring modes. In this work, only the LP_{11}, LP_{12}, and
LP_{13} modes were taken into account. The extended calculations appear in Fig. 6. The figure
shows the E_x field distributions for eight lowest-order cladding modes at 1.6 μm. Labeling the
ring modes by an LP mode classification, the five lowest-order modes can be designated as
the LP_{11}~LP_{15} ring modes. They also have nearly degenerated constituent modes as in the
case of the conventional step-index fiber. The lowest-order cladding mode whose major
intensity begins to be in the holey cladding region is the LP_{16} mode. From the LP_{16} mode, the
effective mode index is lower than that of FSFM, which also indicates that the LP_{16} mode is
the first cladding mode to which the fundamental mode can be possibly coupled. Figure 7 (a)
plots the effective refractive indices for the LP_{1n} modes.

![Plot of the effective refractive indices for the LP_{1n} modes and comparison of indices of LP_{16} mode groups in real structure to those of LP_{1n} and LP_{17} modes in ideal structure](image)

Considering the number of radial lobes and the mode indices, as shown in Fig. 7(b), it is
reasonable to designate the observed cladding modes as an LP_{16} mode group.

4. Discussion

We also calculated the cladding modes for the same ideal PCF structures but with a different
number of air-hole layers. Figure 8 shows the effective refractive indices for the LP_{1n} modes
in each structure.

![Plot of the effective refractive indices for the LP_{1n} modes in the PCF with different number of air-hole layers](image)

The figure substantially shows the same results of our previous study in that the number of the
LP_{1n} ring modes is determined by the thickness of the outer silica cladding for a given
refractive index of the material. As shown in the figure, when the number of the air-hole layers increases, the order of the first higher-order cladding modes decreases.

The PCF with a broad outer silica region can be treated as a fiber with a w-shaped index profile. The mode field profiles in such a fiber are complicated, and easily transformed even by a small variation of the material index. In that sense, the refractive index of silica should be properly considered in the numerical calculations in order to obtain the similar field profiles of the observations. However, it turned out that the complicated field profiles, particularly in the outer cladding region, could not be reproduced solely by varying the material index in a reasonable range of the variation. In order for a good reproduction of the observed field patterns in the outer cladding region, we had to slightly enlarge the outer cladding diameter with the other parameters unchanged. This originates from the fact that the thickness of the outer cladding is closely related to the total number of the radial lobes and the circumferential nodes in the outer cladding region, as if those of the higher-order core modes in a multimode fiber are involved in the core diameter. To this end, the cladding diameter of 132 µm for the given silica index of 1.444 was used, which eventually results in similar field profiles in the outer cladding region. The cladding diameter was also determined by a trial and error method.

Each ring mode labeled as an LP mode also consists of four true modes that have similar electric field vectors to those of the modes in the conventional SMF. The electric field vectors of the four constituent modes for the LP_{11} ring mode are shown in Fig. 9.

![Fig. 9. Four constituent modes of the LP_{11} ring modes. Electric field vectors (a), (b), (c), and (d) correspond to the HE21 × 2, TM01 and TE01, respectively.](image)

We also conducted an experiment to see if the four spatial modes in Fig. 4 preserved the lobe orientation in the holey cladding region. As previously reported, the resonance peak splitting or disappearing phenomena of the optical fiber can take place with an angular misalignment between the optical and the acoustic axes [16]. We found that the four resonance peaks in Fig. 3 suffer from splitting or suppression at specific acoustic oscillation directions (Fig. 10).
This indicates that the lobe orientations of the four observed modes are preserved during propagation, and they can be considered as the eigen modes that are not comprised of constituent true modes.

We investigated the polarization dependence of the four resonance peaks, which were slightly up- and/or downshifted within, or up to, 1.8 nm according to the polarization variation. The notch depths also changed but not significantly. Based on the calculations, each cladding mode has two eigen-polarization modes and the index differences between the polarization states are much smaller than those between the four cladding modes.

We dropped index-matching oil on the side of the fiber cladding just before the output in order to see if the observed mode field patterns were comprised of a combination of core mode and ring modes that might be coupled from somewhere. It was empirically found that the observed mode fields completely disappeared when the properly chosen index matching oil was dropped, which means that no core mode exited. We could not suppress only the ring mode field patterns with an oil drop test accompanying the temperature tuning, which was performed several times. Thus, it was concluded that the observed mode field patterns are for the cladding modes.

5. Summary and conclusion

The cladding modes of the PCF with a thick outer silica cladding were observed and compared with the numerical calculations. The cladding modes were excited by a properly introduced acoustic LPG. The numerical calculations carried out based on the finite element method compared well to the experimental observations. The calculations for the cladding modes in an ideally structured PCF with broad outer silica indicate that the observed cladding modes can be categorized into the LP16 mode group.

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