Observation of cladding modes spatio-spectral distribution in large mode area photonic crystal fiber

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Abstract. We report the observation of spatio-spectral distribution in cladding modes of a single-mode large mode area photonic crystal fiber. The cladding modes excitation was achieved without any external fiber exposure. The optical field patterns of the cladding modes within different pump wavelength are investigated. To the best of knowledge the spatio-spectral distribution in cladding modes of large mode photonic crystal fiber is demonstrated for the first time. The results are of immediate interest in applications demanding devices based on core and cladding mode coupling in photonic crystal fibers.

1. Introduction

Photonic crystal fibers (PCF) [1, 2] are of particular interest for a number of applications like gas analysis [3], optical coherence tomography [4], supercontinuum sources [5-8], optical frequency metrology [9-11] etc. To date, much effort has been done on understanding and research of PCFs core modes [12-16] and very little activity is observed in the study of cladding modes. Since working principle of many devices based on standard fibers and PCFs involves cladding modes, it is expected that these modes can also play an important role in the development of novel fiber devices based on PCF. Thus, cladding modes play a crucial role in fiber-optic sensing [17-19], in devices based on core and cladding mode coupling [20]. The number of methods was applied to research cladding modes in PCFs. In most cases a cladding mode excitation was made by external fiber exposure. In this respect, in [21] a coupling by a Bragg grating was used to investigate higher-order leaky modes. In [22] excitation of cladding modes by flexural acoustic waves was reported. Coupling between fundamental mode and cladding modes was realized by long period gratings written in pure silica PCFs [23].

In this paper, we observe excitation of cladding modes in a single-mode large mode area (LMA) PCF without any external fiber exposure (acoustic wave or long-period grating) and demonstrate spatial spectral shaping of cladding modes. These results could play an important part in theoretical problems of light guidance and nonlinear effects in photonic crystal fibers.

2. Experiments

To understand the cladding modes excitation phenomena in a large mode area PCF we used the fiber with the core diameter 20 μm manufactured by a stack-and-draw method [24]. A microscope image of the end face of the fiber used in experiment is shown in figure 1. The fiber supports a single transverse mode for any wavelength, with an 13.2 μm pitch (*Λ*- center-to-center distance between holes) and an 6 μm hole diameter (*d*). The outer diameter of the fiber (*R*) was 160 μm. The structure of the fiber has four layers of air holes arranged in a hexagonal lattice surrounding the silica core.

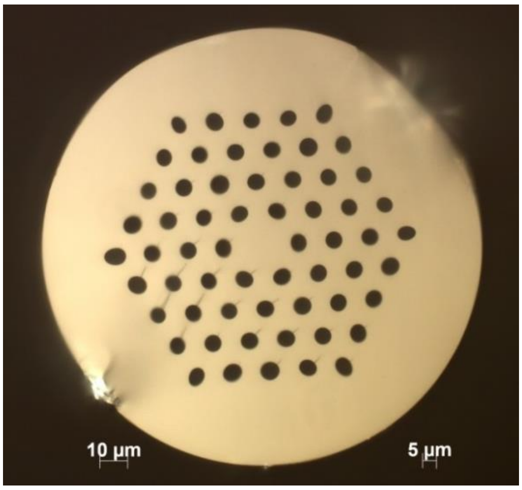

Figure 1. Optical microscope image of the cleaved endface of the PCF. The hole diameter is 6 μm, the pitch is 13.2 μm, the outer diameter is 160 μm.

The refractive indices used for silica and air are 1.45 and 1, respectively. The normalized air hole diameter (d/Λ), and the normalized outer diameters ($2R/\Lambda$) are d/Λ = 0.45, and $2R/\Lambda$ = 12.1, respectively. The PCF with these values was calculated to be a single-mode. The characteristics of the LMA PCF used in the experiments are summarized in Table 1.

Table 1. Characteristics of the LMA PCF.

Core Diameter (μm)	Λ (μm)	d/Λ	Fiber Length (m)	ZDW (nm)
20	13.2	0.45	1	1250

An experimental setup is illustrated in figure 2. A laser source is employed by supercontinuum source (SC-400, Fianium Ltd.) offers a wavelength range of 390 nm extending to 2600 nm with 250 nJ pulse energy and total power of 4 W. The laser operates at repletion rate of 40 kHz and produces pulses with temporal width of ~6 ps. Laser radiation of SC-400 passed through acousto-optic filter (AOTF-FS, Fianium Ltd.).

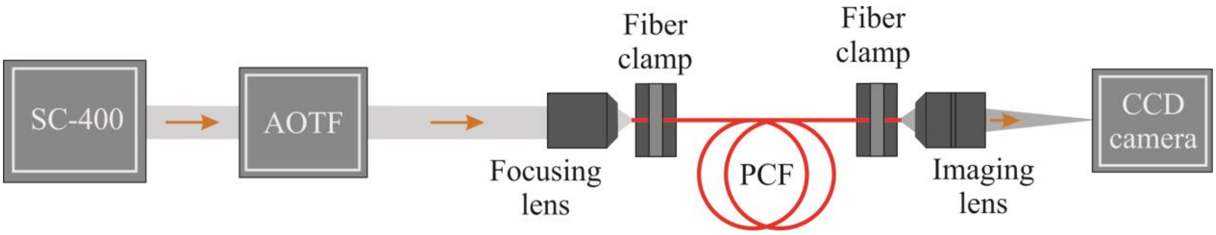

Figure 2. Experimental setup.

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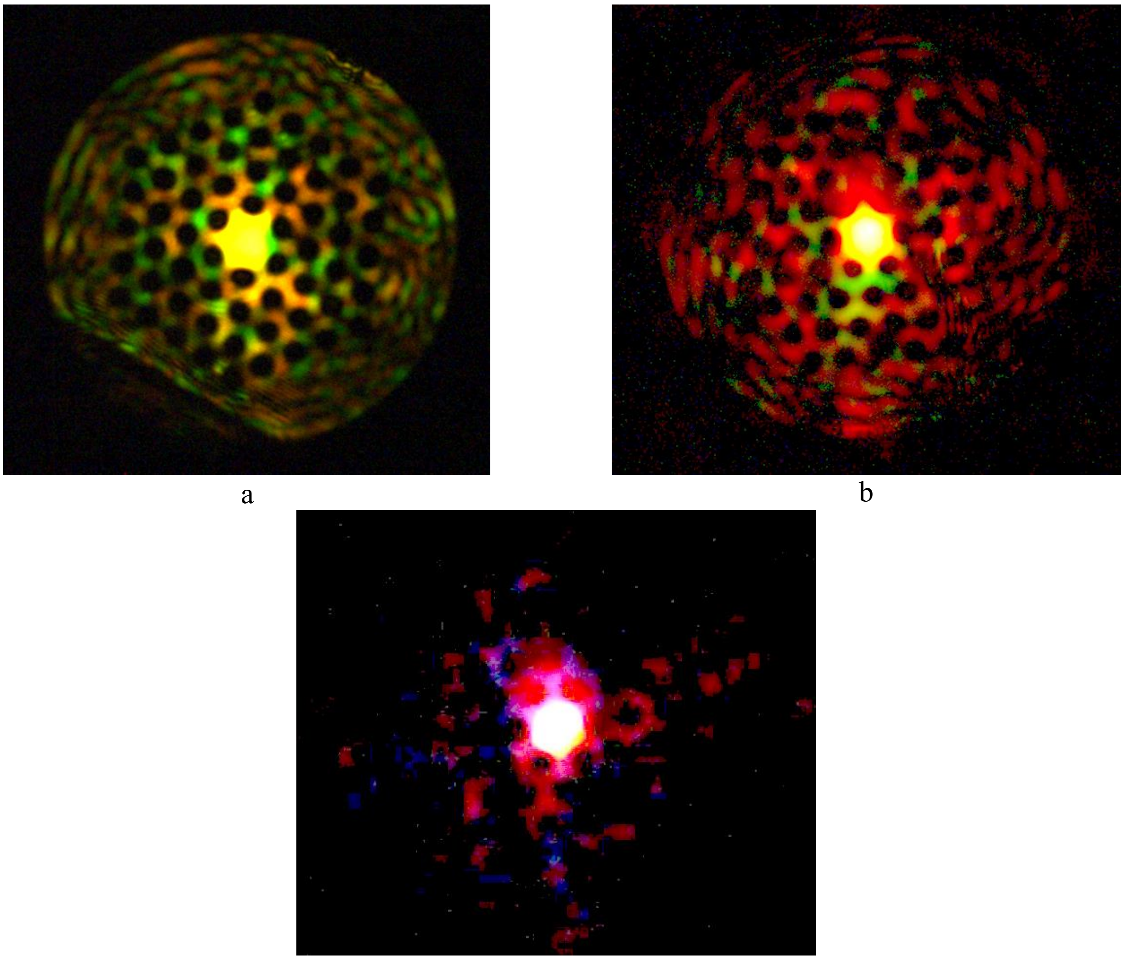
AOTF-FS is fitted with a visible AOTF crystal (400-650 nm) and enables up to 8 simultaneous tunable spectral channels with bandwidth of 2-4 nm to be selected from any SC-400 supercontinuum spectrum. The output radiation from AOTF was focused by a 40X microscope focusing lens into the PCF under test, which was mounted in a special three-dimensional positioning table (MAX361D/M, Thorlabs). To observe the near-field pattern distribution of the fiber output radiation, the transmitted light from the output edge of PCF was detected by a CCD camera (DCU224C, Thorlabs) through 40X microscope objective which acts as an imaging lens.

In our experiment cladding modes excitation was observed by passing radiation from two different AOTF spectral channels through the PCF simultaneously. Obtained near-field images of light transmitted through the fiber is shown in figure 3. Near-field image in figure 3 (a) was obtained when AOTF-FS was tuned to two spectral channels at 532 nm and 600 nm simultaneously, in figure 3 (b) at 532 nm and 650 nm and in figure 3 (c) at 485 nm and 690 nm respectively.



a b c

Figure 3. The near-field images of light transmitted through the PCF when acousto-optic filter (AOTF-FS) was tuned to 532 nm and 600 nm simultaneously (a), at 532 nm and 650 nm (b) and at 485 nm and 690 nm (c).

In figure 3 (a) and (b) the light has spread out into the cladding area, confirming the excitation of the cladding modes. In figure 3 (c) light at wavelengths of 485 nm and 690 nm has also spread out into the cladding area but didn't confirm the excitation of the cladding modes. As opposed to excitation mechanisms based on long period gratings [23] or acoustic waves [22] in our case we obtain cladding modes excitation without any external fiber exposure. We assume the excitation of cladding modes is caused by macrobend and confinement losses of PCF that result in effective coupling between core and cladding modes. During the experiment the dependence of coupling efficiency on wavelength range was found. Thus, coupling is effective at wavelengths of 532 nm, 600 nm and 650 nm in comparison with wavelengths of 485 nm and 690 nm. In Fig. 3 cladding mode spatial spectral shaping is also observed. We assume this spatial spectral shaping can be a result of cladding modes interactions and is of interest to further investigations.

3. Conclusions

In summary, we observe, for what is believed to be the first time, the excitation of cladding modes in a single-mode large mode area photonic crystal fiber by supercontinuum source equipped with tunable acousto-optic filter without any external fiber exposure. The optical field patterns of the cladding modes are presented. This experimental result provides essential information for design and development cladding-mode-based application of PCFs, also the results are of interest in devices based on core and cladding mode coupling and spatial spectral distribution.

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