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Resonant Coupling in Photonic Crystal Fibers

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Abstract

We discuss the resonant coupling phenomenon in hollow-core photonic band-gap fibers for suppression of higher-order-modes, large-mode-area index-guiding photonic crystal fibers with low bending losses for high-power laser applications, and hole-assisted fibers for broadband dispersion compensation.

1 Introduction

After the first proposal and demonstration of photonic crystal fibers (PCFs) in 1996 [1], they have received a considerable attention in optical community due to their superior characteristics and large degrees of freedoms in designing the core and cladding geometries according to the application. PCFs, where tiny air-holes running down its length build the cladding, can be categorized in two main classes; (i) solid-core PCFs where a single or multiple missing air-hole forms the guiding core and the light is guided via total internal reflection, and (ii) hollow-core PCFs (HC-PCFs) where several missing air-holes construct the air-guiding core and the light is guided through photonic band-gap (PBG) effect [2].

In this talk, we focus on hollow-core as well as solid-core PCFs and discuss the main aspects of them for optical communication and industrial applications. Firstly, we will consider the case of an HC-PCF where we point out the suppression of higher-order-modes (HOMs) by creating outer-cores in the cladding through resonant coupling mechanism. And in the second half of this presentation, we will focus on the dispersion compensation, Raman amplification, and lasing performances of solid-core PCFs which use resonant coupling phenomenon effectively. We have adopted a full-vectorial finite element method (VFEM) to model the proposed PCF configurations.

2 Suppression of higher-order modes in HC-PCFs

The potential use of PCFs becomes clearer when the unique properties can be directly related to qualitatively novel functionalities. For example, the ability to guide light in a hollow-core via the PBG effect suggests a new technological regime of transmission with low attenuation, high power delivery with low nonlinearities, or nonlinear optics applications. The main technological issue that exists when guiding the light through HC-PCFs is the inevitable presence of HOMs. Although suppression of HOMs can be observed in small-core PCFs, there exists a fundamental limit of scattering losses due to the surface roughness scattering, which prohibits the further reduction of the fiber's attenuation to the level of the conventional fiber. One possible solution to overpass this limit is to consider large HC-PCFs, leading the multi-mode operation. In order to enhance the suppression of HOMs in HC-PCFs, a resonant coupling mechanism between the HOMs in the central core and the much leaky outer-core modes around a certain wavelength range can be adapted for effectively single-mode operation. In Fig. 1(a) we model an idealized but realistic standard 7-unit-cell HC-PCF [3]. The 7-unit-cell hollow-core size is not so large, and therefore it is difficult to suppress the scattering losses due to the surface roughness. In order to form larger HC-PCFs, three rows of air-holes can be removed and the resulting structure is depicted in Fig. 1(b) (19-unit-cell HC-PCF). We found that the effective index of the fundamental mode in the small-core PCF is quite close to that of the HOMs in the large-core PCF. This fact can enable the index-matching mechanism to take place by bringing two cores (19-unit-cell central core and 7-unit-cell outer core) close to each other, thus enabling resonant coupling over a certain wavelength regime.

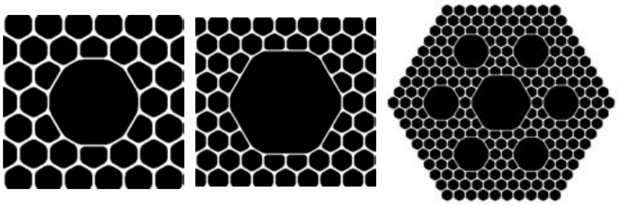
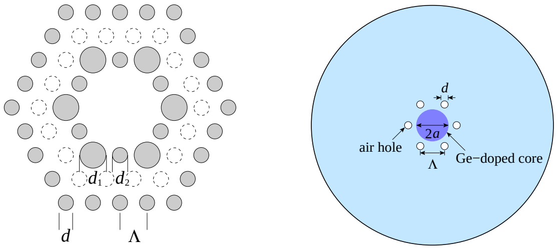


Fig. 1. Schematic cross-sections of (a) an HC-PCF with a 7-unit-cell air-core, (b) an HC-PCF with a 19-unit-cell air-core, and (c) our proposed large-hollow-core PCF profile with a 6-fold symmetric distribution of outer-cores in the cladding for an effectively single mode operation.

In order to enable the index matching mechanism between the HOM in 19-unit-cell core and the fundamental mode in 7-unit-cell core, we proceed by incorporating six 7-unit-cell cores (shown in Fig. 1(c)) into the cladding surrounding the central 19-unit-cell core to expect polarization independent operation. Introducing the several outer cores close to the central core would lead in the enhancement of the confinement loss (CL) of the HOMs in comparison to that of the fundamental mode. Through numerical simulations, it was observed that the CL of HOMs in 19-unit-cell HC-PCF with outer cores stays above 100 dB/km which is 3 times higher in order than that of HOMs in 19-unit-cell HC-PCF without defected outer cores, whereas the CL of fundamental mode remains below 0.1 dB/km. This ensures the effectively single mode operation of the device.



(a) (b)

Fig. 2. Schematic representation of (a) the LMA index-guiding PCF and (b) the proposed dispersion compensating hole-assisted fiber.

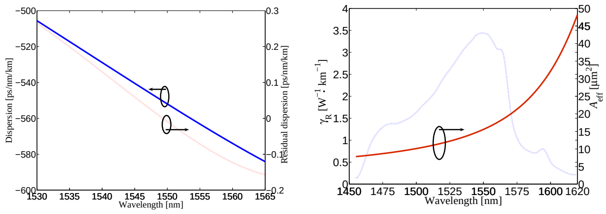
3 Design of a single-mode and large-mode-area PCF and its lasing characteristics

One of the major trends in optical fiber science is to obtain fibers with large-mode-area (LMA), optimized for various applications such as high power delivery, fiber amplifiers, and fiber lasers. In order to ensure the high beam quality and the ultimate controllability of the damage threshold in the fiber's material, it is required to have a LMA property with maintained single-mode operation. We propose an interesting design method for realizing LMA single-mode PCFs, small allowable bending radius, and good beam quality factor. Figure 2 (a) shows the proposed structure [4], where the central core is formed by seven missing air-holes surrounded by 12 air-holes with diameters of d_1 and d_2 arranged alternatively with hole-pitch Λ.

The enhancement of the CL of the higher-order central-core mode can be achieved through the resonant coupling mechanism between the central-core and the leaky ring-core modes. The air-hole diameter-d in the outermost air-hole ring is determined in such a way as to match the effective index of the LP_{11}-like HOM in the central core with that in the ring core, at the desired wavelength λ=1064 nm. The optimized fiber shows large effective mode area of 1400 μm^2 at 1064-nm wavelength, good beam quality factor of 1.15, and CL exceeding the 1 dB/m for the HOM at 1064-nm wavelength. We then investigated the lasing performances of the proposed fiber by doping the fiber core with ytterbium ions in 25 μm doping region radius and noted the influence of the bending on the overlap factor. It was found that the confinement of the pump or signal decreases as the fiber is bent into 5 cm bending radius, whereas the laser output power does not deteriorate so much on bending. This demonstrates the bend-insensitive operation of designed Yb^{3+}-doped, LMA-PCF laser.

4 Dispersion compensating hole-assisted fibers

Another variant of solid-core PCFs is the hole-assisted fibers (HAFs) which have a germanium-doped core surrounded by either one or two rings of air-holes. HAFs are the simplest design of PCFs and easy to fabricate. This fact motivated us to design a HAF which can provide a very large negative dispersion with relatively large mode area. Figure 2(b) shows the intriguing design of dispersion-compensating HAF (DC-HAF), where only one air-hole ring surrounds the doped core. The optimized DC-HAF exhibits the largest negative dispersion around −550 ps/nm/km at 1550 nm with matched relative dispersion slope of transmission fiber as shown in Fig. 3(a). This large negative dispersion is also based on the index-matching mechanism between the effective index of the fundamental mode in the highly-doped core and the cladding index at longer wavelength. The described DC-HAF can act as a broadband dispersion compensator as it satisfies the condition for broadband dispersion compensation. The length of DC-HAF was computed as 2.52 km to compensate for the positive dispersion accumulated over 80-km long conventional single mode fiber link. It is evident from Fig. 3(a) that the DC-HAF leaves a residual dispersion of ± 20 ps/nm, which is below than ±60 ps/nm; a limit for 40 Gbps transmission systems.



(a) (b)

Fig. 3. (a) Dispersion characteristics and (b) the spectral variation of RGE and effective mode area of DC-HAF.

As a next step, we have evaluated its Raman performances in order to overcome the background losses and to amplify the incoming signals. Figure 3(b) depicts the Raman gain efficiency (RGE) and the effective mode area as a function of wavelength. The DC-HAF possesses a peak RGE of 3.4 $W^{-1}.km^{-1}$ at a frequency shift of 12.6 THz and the effective mode area of 15.6 μm^2 at 1550-nm wavelength. The proposed DC-HAF can be employed as a discrete Raman amplifier either in between the optical fiber link or at the end. It has been numerically confirmed that the 2.52-km long DC-HAF Raman amplifier module can provide a gain of 4.2 dB with ±0.8 dB gain ripples by mono-pumping with 560 mW of power and 1460-nm wavelength.

5 Concluding remarks

We have modelled and simulated different designs of PCFs using VFEM. The suppression of HOMs in large HC-PCFs was achieved by resonant coupling and introduction of six outer-cores. The resonant coupling phenomenon was also employed to design a single-mode, LMA solid-core PCF and its lasing characteristics were demonstrated numerically. Finally, a simple and intriguing design of dispersion compensating HAF was proposed and it was shown that the DC-HAF module can compensate for the dispersion in C-band and can also acts as inline Raman amplifier.

6 References

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