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Hollow core anti-resonant fiber with split cladding

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ABSTRACT

A split cladding fibers (SCF) is proposed as an additional design to the anti-resonant type fiber. The introduced split cladding helps to reduce the fabrication distortion. We use numerical simulations to compare the Kagome fibers (KFs) and the proposed split cladding fibers (SCFs) over two normalized transmission bands. It reveals that SCFs are able to maintain the desired round shape of silica cladding walls, hence improving the confinement loss (CL) compared to the KF. Fabrication of the SCF is demonstrated by the stack-and-draw technique. The near filed mode patterns are measured to prove the feasibility of this fiber design.

OCIS codes: (060.2280) Fiber design and fabrication; (060.2400) Fiber properties; (060.4005) Microstructured fibers.

1. INTRODUCTION

The unique guiding property of hollow core photonic crystal fibers (HC-PCFs) promises the potentials of achieving lower Rayleigh scattering, lower transmission loss and lower nonlinearity compared to conventional fibers [1]. Hollow-core inhibited coupling fibers (HC-ICFs), or so-called hollow core antiresonant fibers (HAFs), are a branch of the HC-PCFs. The HAFs support light guiding by a coupling inhibition [2]. This type of fiber permits relatively low transmission loss, and multiple broad transmission bands [3]. Furthermore, because its transmission loss is largely determined by the scattering from the cladding layers rather than the material loss, the HAF is able to transmit the mid-IR range [4].

The HAF was first demonstrated in the Kagome structure [5]. Investigation to reduce the confinement loss (CL) has been the main focus of the fiber design. A hypocycloid-core shape was reported to enhance the coupling inhibition between the core and cladding modes [6, 7], suggesting that the core shaping would play a crucial role in the CL reduction. This observation leads us to exploring a design to maintain the cladding inner wall shape that forms the air core. For example, the KF typically suffers from distorted core shaped caused by the fiber drawing process. Such deformation can be avoided by introducing radial gaps in the cladding area.

In this work we present an alternative design for the KFs to reduce the CL. The cladding layers are radially split in our design to alleviate the core shape deformation during the fiber drawing process. The gaps created by the radial separation do not deteriorate the fiber performance, and the CL comparable to the KFs is attainable in the split cladding design. Furthermore, the proposed design helps to diminish vertices formed in the cladding layers during the fiber fabrication, which is additional benefit toward low transmission loss. Although there are several simplification designs of HAF with single cladding ring layer [8,9], their cladding is not scalable with additional layers [4]. Our split cladding structure allows multiple cladding layers to control the CL, which is useful for many applications including a gas-filled Raman scattering. The details of our theoretical investigation and fiber fabrication are represented as below.

2. SPLIT CLADDING FIBER DESIGN

The tube lattice fiber (as shown in the TLF structure in Fig.1) has a circular air core formed by surrounding silica walls in the cladding. This ideal fiber shape is altered by the high temperature fiber drawing process due to the surface tension of molten silica. The high temperature fiber drawing introduces deformation in the core shape from circular to hexagon-like core. The resulted structure is illustrated in Fig. 1 as KF. The core-cladding boundary of the KF consists of two different walls denoted as 1 and 2. This alternating boundaries account for the core shape deformation [10]. In addition to the core deformation, the fabrication process produces vertices in the cladding layers. The induced vertices cause extra loss due to Fano resonances between core modes and cladding modes [11], and limit the performance of KFs. To avoid the fabrication deformation and reduce the number of scattering vertices, we propose a modified design composed of split claddings.

2.1 Design

The proposed split cladding fiber (SCF) is represented in the figure 1. An ideal structure neglecting the fabrication deformation is represented as ISC in Fig. 1. The structure including the fabrication deformation is denoted as SCF in Fig. 1. As shown in the figure, the number of cladding vertices in SCF is much less than that in KF, and the silica walls in SCF are more rounded as compared to the KF. Moreover, the SCF structure possesses only one wall boundary shape, diminishing core shape distortion without compromising the desired negative curvature. It may be of concern that the discontinuous cladding layer would induce additional loss. Thus we investigate the loss in the SCF in a broad transmission band. A two cladding layer SCF is assumed in the theoretical study.

Fig. 1. Fiber fabrication induced distortion in KF and proposed SCF structures. The surface tension of molten silica during the fiber drawing modifies the structures deviated from the ideal cases. IKF represents the ideal structure of the kagome fiber (KF). ISC represents the ideal structure of the split-cladding fiber (SCF) a , d , and t denote inner core radius, pitch size and core wall thickness respectively. The different wall shapes in the KF are indicated by 1 and 2.

We used the open source finite-element software Polymode [12] to perform our numerical simulations. Figure 2 shows the calculated transmission spectra of the different fiber structures. All the fibers have the same inner core radius ($a = 9.76 \mu\text{m}$) and silica wall thickness ($t = 1 \mu\text{m}$). The pitch size, d' , in the TLF and KF is $8 \mu\text{m}$ while the SCF and ISC has $11.8 \mu\text{m}$ of the pitch size, d . Normalized frequency, F , is defined as $F = \frac{2\pi f}{c} \sqrt{n^2 - 1}$, with f being the frequency, n the dielectric refractive index (here, $n = 1.45$), and c the vacuum light speed. The local peak losses observed in the transmission bands in Fig. 2(a) are caused by coupling between the cladding mode and the fundamental mode [13]. The results show that the ISC can mark the same CL as the TLF. More interestingly, the ISC supports a broader transmission band. When considering the effect of the surface tension caused by the drawing process, the KF and SCF will represent more realistic structures. It is clear from Fig. 2 that the SCF promises the same performance as the ISC with no increase in

the CL. The structure deformation occurred in the SCF is moderate, and keeps most of the silica walls rounded, creating only small number of scattering vertices. However, the transition from the TLF to the KF is accompanied with transforming most of the cladding walls to flat surfaces, hence large number of vertices. The vertices enhance Fano resonances between core and cladding modes and increase the transmission loss [11]. As shown in Fig. 2, the CL is one magnitude lower in the SCF than in the KF and is comparable to that in the nested antiresonant nodeless fiber (NANF) with the same core size [14]. We note that the CL becomes lower in NANF than 2SCF when the transmission window moves towards longer wavelength region ($F < 1$). However, modified 2SCF can reach to similar CL as NANF in the longer wavelength region. We discuss about the long wavelength region in Section 2.2.

Fig. 2. (a) Confinement loss and (b) effective refractive index with normalized frequency in different anti-resonant fiber structures: tube lattice fiber (TLF, green curve), kagome fiber (KF, blue curve), split cladding hollow core fiber (SCF, black curve), ideal split-cladding fiber (ISC, red curve) and nested antiresonant nodeless fiber (NANF, purple curve). All the fibers have the same inner core radius.

We also note that the SCF exhibits as broad transmission window as the ISC. The pitch size in SCF, d' , is larger than its counterpart in the KF (or the TLF), d , when the same core size is compared. The larger pitch size accounts for the broader transmission bands when core wall thickness is fixed [15]. Besides, in the fiber fabrication, the KF fiber drawing requires precise pressure control to maintain the negative curvature of the core-cladding boundary. This is not necessary in the SCF fiber fabrication.

The insignificance of the structural deformation is confirmed again in the effective refractive index overlap between the SCF and the ISC as represented in Fig. 2(b).

2.2 Effect of normalized gap width on the transmission loss

In Fig. 3, the CL at normalized frequencies of $F=2.63$ (blue line) and effective area of fundamental mode (green line) are evaluated for different values of the normalized gap width, $g = \frac{w}{a}$, where w is the actual gap width, and a is the inner core radius. As a maintains the same, structure with larger gap width has smaller pitch size. The lowest basement loss is attainable in $g = 0.3 - 0.4$. In the region of $g < 0.3$, the cladding hole size becomes close to the hollow core size, which makes the effective mode index of the cladding air mode close to the fundamental mode effective index.

Besides, when the gap width becomes wider, > 0.5 , the CL becomes higher. The fast increasing of effective mode area at this range accounts for the increased CL. The observation in figure 3 is applicable to other normalized frequencies, F , albeit varied in CL values.

The local loss peaks are caused by the strong coupling between core mode(s) and cladding modes which is explained in ref. [7].

Fig. 3. Confinement loss (blue line) and effective area (green line) of $F=2.63$ vs. the normalized gap width, $= \frac{w}{a}$, where w is the gap width, a is the inner core radius. The a is assumed as $9.78 \mu\text{m}$.

3. FIBER FABRICATION AND EXPERIMENT RESULTS

We used the conventional stack-and-draw technique [22] to fabricate the SCF with three cladding rings. The scanning electron microscopic (SEM) image of the fiber is shown in Fig. 4 (a). The fiber diameter is $282 \mu\text{m}$ with $47.7 \mu\text{m}$ core size, $19.5 \mu\text{m}$ pitch size, and $2.14 \mu\text{m}$ wall thickness. The fiber cross-section is consistent with the expected surface tension influence discussed in Fig. 1. Overall, the curvature of the first two inner rings are well preserved compared to the traditional KF, hence induces smaller number of the scattering vertices in the structure. The near field mode pattern of the 1.65 m long fabricated fiber is measured at different wavelength. Fig. 4 (b) and (c) is the near field mode pattern at 700 nm ($F = 6.42$) and 1690 nm ($F = 2.66$) respectively. Pure fundamental-like modes can be observed at these transmission wavelengths.

Fig. 4. (a) SEM of the fabricated 3-ring SCF. The fiber diameter is 282 μm with 47.7 μm core diameter, 19.5 μm pitch size, and 2.14 μm wall thickness. (b) Near field mode pattern at the output of 1.65 m long fabricated fiber when wavelength is 700 nm. (c) Near field mode pattern at the output of 1.65 m long fabricated fiber when wavelength is 1690 nm.

4. CONCLUSION

In conclusion, we proposed SCFs as an alternative design for KFs. The split cladding structure is robust against fabrication deformation, and offers low CL accounting for reduced scattering points and core shape deformation, and scalable cladding layers to further reduce the transmission loss.

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