Single mode, Low-loss 5-tube Nested Hollow-core Anti-resonant Fiber

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Abstract: A 5-tube nested hollow-core anti-resonant fiber is proposed to simultaneously achieve ultra-low loss (< 1dB/km), broader transmission window, lower bend loss, and larger higher-order mode suppression than fibers with a different number of cladding tubes. © 2019 The Author(s)

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1. Introduction

Recently, Hollow-core anti-resonant (HC-AR) fibers have been extensively studied and developed by several research groups due to their extraordinary ability of light guidance in an air-core, low-loss, and wide transmission bandwidth [1–7]. One of the unique features of hollow-core fiber is that >99.99% can be guided in the central air-core with only a tiny fraction of light overlapping with the surrounding glass structure, hence increasing the optical damage threshold and reducing material absorption significantly [3,7]. The guiding mechanism of this fiber relies on the combination of a inhibited coupling (IC) between the core and cladding modes and the anti-resonance [3,8]. The coupling between the core mode and cladding modes can be made strongly inhibited (phase mismatched) by suitably arranging the anti-resonant tubes in the cladding, which results in low loss and much broader spectral bandwidths [8]. In order to control the modal content and attenuation, several types of HC-AR fibers have been proposed, investigated, and fabricated to date, including HC-AR fibers with circular anti-resonant tubes [1], “ice-cream cone” shape anti-resonant tubes [9], elliptical anti-resonant tubes [7], and nested anti-resonant tubes [3–5]. Recently, a single ring HC-AR has been reported with 8 non-touching circular tubes with a propagation loss of 7.7 dB/km at 750 nm and a bend loss of 0.03 dB/turn at a bend radius of 15 cm [8]. Although these are impressive numbers, such loss levels are still not sufficient to compete with the telecommunication standard [10]. Importantly, this particular 8-capillary design does not provide effectively single-mode operation [8]. Recently, a conjoined HC-AR fiber have been experimentally demonstrated by Gao et al. [10] with loss of 2 dB/km, low bend loss, and effectively single-mode performance.

Here we propose a 5-tube nested HC-AR fiber with propagation loss <1 dB/km and single-mode operation at telecommunication wavelengths. In order to get full information on modal contents of the fibers, we thoroughly investigate the propagation losses of the fundamental mode (FM) and higher-order modes (HOMs) as a function of the cladding parameters. We reveal that a proper selection of the number of the cladding anti-resonant tubes and the cladding geometry is crucial for minimizing propagation loss and for effectively single-mode operation. We have demonstrated for the first time, to the best of our knowledge, that a 5-tube cladding arrangement exhibits ultra-loss, wider transmission band and stronger HOMs suppression than cladding designs with different numbers of anti-resonant tubes.

2. Fiber geometry and numerical modeling

Figure 1(a) shows the geometry of a 5-tube HC-AR fiber used in our investigations. We considered a core diameter of 30.5 μm (Dc) and a silica wall thickness of t = 1120 nm, which is identical to the fiber structure reported in [10]. The inner nested tube has a diameter d = D/2 and wall thickness of t = 1120 nm. The outer tubes are separated by a gap distance, g forming a node-free core boundary [3]. The node-free configuration provides better loss properties and flatter transmission spectra compared to closed core boundary structures [3].

The numerical analyses were performed using a finite-element based COMSOL mode solver. In order to accurately model the leakage loss of the fiber, we used perfectly-matched layers (PML) outside the fiber domain, and both mesh size and PML parameters were optimized according to prior studies [3].

3. Simulation results

We first compare the propagation loss of nested HC-AR fibers with 5, 6, and 7 tubes. The calculated propagation loss spectra and near-field profiles of the fundamental modes for the three fiber designs are presented in Fig. 2. In these calculations, the power overlap with the silica walls was used to estimate the effective material loss. Material
Fig. 1. (a) Geometry of the proposed 5-tube HC-AR fiber. The fiber has a core diameter $D_c = 30.5 \, \mu\text{m}$, a uniform silica wall thickness $t = 1120 \, \text{nm}$, and outer tube separation, $g$. The diameter of the inner nested tubes $d$ is defined by $d = D_c/2$. (b) Mode field profile of the fundamental mode at 1550 nm.

Fig. 2. Calculated loss spectra of nested HC-AR fibers with five, six, and seven tubes. All fibers have the same core diameter $D_c = 30.5 \, \mu\text{m}$, a uniform silica strut thickness $t = 1120 \, \text{nm}$, and same gap distance $g$. The black dashed line represents surface scattering loss. The color of the frame corresponds to the color of line of the plot.

loss was then added to the leakage loss and SSL in order to obtain the total propagation loss. The SSL arises from imperfections of the fiber which result in light scattering from the air-glass interfaces. However, HC-AR fibers exhibit low SSL as compared to HC-PBG because the field intensities at the air-glass interfaces are relatively low [6]. The SSL was calculated accordingly to the method reported in [3]. We calculated SSL of $\sim 0.23 \, \text{dB/km}$ at 1.55 $\mu\text{m}$. The solid red line shows the propagation loss of a 5-tube nested HC-AR fiber with a loss level of $\sim 0.52 \, \text{dB/km}$ at 1.55 $\mu\text{m}$. The solid green line is the propagation loss of the 6-tube nested HC-AR fiber. In this case the propagation loss is $\sim 2 \, \text{dB/km}$ at 1.55 $\mu\text{m}$. The solid green line corresponds to the D-shaped HC-AR fiber with $\sim 0.95 \, \text{dB/km}$ loss at 1.55 $\mu\text{m}$. Finally, the solid blue line depicts the loss spectrum of 7-tube nested HC-AR fiber with a loss value of $\sim 33 \, \text{dB/km}$ at 1.55 $\mu\text{m}$. The results in Fig. 2 clearly indicate that the 5-tube HC-AR fiber shows improved loss performance (lower loss and broader transmission window) compared to 6 and 7-tube fibers.

In order to better understand the modal contents of HC-AR fibers, we show contour plots of the FM and HOMs propagation loss as a function of normalized tube diameter ($D/D_c$) and normalized nested tube diameter ($d/D$) for a 5-tube nested fiber in Fig. 3. From these maps it is possible to identify design regions for low loss and effectively single-mode operation. It is evident from Fig. 3(b) that the FM loss remains $< 1 \, \text{dB/km}$ in the range of $0.7 < D/D_c < 1.15$ and $0.5 < d/D < 0.7$. For a normalized tube diameter, $D/D_c < 0.68$, the FM mode loss progressively increases with decreasing values of $d/D$. Figure 3(c) shows the loss of HOMs (lowest loss among the LP_{11} and LP_{21} modes). The HOM loss can be made as high as 6000 dB/km for $D/D_c \approx 1.13$ and $d/D \approx 0.68$ while maintaining the FM loss below 0.5 dB/km. This large loss value of HOMs is due to the strong coupling between HOMs and cladding modes [3,6,7]. Our results indicate that HOMs can be strongly suppressed by properly engineering the anti-resonant
cladding structure. In addition, Figure 3(d) shows the calculated higher-order mode extinction ratio (HOMER), which is defined as the ratio between the propagation loss of the HOM with the lowest loss and the propagation loss of FM [3,7]. For $D/D_c \approx 1.13$ and $d/D \approx 0.68$, the HOMER is $>12000$. To the best of our knowledge, this is the highest reported HOMER value in any HC-AR fiber. The calculated HOMER for 6-tube HC-AR fiber is $\sim$200 which is far lower than 5-tube nested HC-AR fiber. The 5-tube nested HC-AR fiber exhibits small bend loss of 1 dB/km at 5 cm bend radius, and also insensitive to tight bend condition.

4. Conclusion

We demonstrated a new 5-tube nested HC-AR fiber design with wider transmission bandwidth and lower propagation loss (0.52 dB/km) than equivalent 6 (or more) anti-resonant cladding tubes fibers. Moreover, we found that strong suppression of HOMs is achieved. In particular, the 5-tube nested HC-AR fiber has a HOMER $\sim$12000 whereas 6-tube fibers have a maximum HOMER of $\sim$200. The results presented here indicate that precisely engineering the cladding of HC-AR fiber is crucial for achieving ultra-low loss and effective single-mode operation and could lead to novel designs with improved performance.

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References