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Published in:
2016 Conference on Lasers and Electro-Optics (CLEO)

Link to article, DOI:
10.1364/CLEO_AT.2016.JTu5A.99

Publication date:
2016

Document Version
Peer reviewed version

Anisotropic Anti-resonant Elements gives Broadband Single-mode Low-loss Hollow-core Fibers

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Abstract: Hollow-core fibers with node-free anisotropic anti-resonant elements give broadband low-loss fibers that are also single-moded. At 1.06 μm silica-based fiber designs show higher-order-mode extinction-ratio >1000 and losses below 10 dB/km over a broad wavelength range.
OCIS codes: (060.2280) Fiber design and fabrication; (060.5295) Photonic crystal fibers; (060.2310) Fiber optics

1. Introduction

Recently, hollow-core anti-resonant (HC-AR) fibers with a ‘‘negative-curvature’’ of the core-cladding boundary have been extensively studied owing to their low loss and wide transmission bandwidths [1–4]. The guiding mechanism of the HC-AR fiber relies on the combination of a inhibited coupling (IC) between the core and cladding modes and the anti-resonance [3]. The key unique feature of the HC-AR fiber is that the coupling between the core and cladding modes can be made anti-resonant (strongly inhibited) by suitably arranging the anti-resonant tubes in the cladding, which results in low loss and much broader spectral bandwidths. HC-AR fibers have been proposed with circular anti-resonant tubes [1,2]; "ice-cream cone"-shaped anti-resonant tubes [5]; circular single nested and nested-in-nested anti-resonant tubes [2,3]; and adjacent nested anti-resonant tubes [4]. In contrast to the fibers reported in the literature, the present work consists of node-free anisotropic anti-resonant tubes placed on the inner wall of a capillary. By using anisotropic (e.g. elliptical) anti-resonant tubes instead of isotropic, i.e. circular ones, one gets at the same time (a) an increased negative curvature in the core, (b) a node-free (non-touching) design, and (c) a larger distance from the core to the outer capillary. All these properties could not be achieved simultaneously in the previous reported designs [1–5]. We find that HC-AR fibers with node-free elliptical nested elements offers two orders of magnitude lower leakage loss as well as effectively single-mode operation when compared to HC-AR fibers with circular nested elements.

2. Numerical results

First we optimized our proposed HC-AR fibers for six circular and elliptical anti-resonant tubes with a fixed R=15 μm, t=0.42 μm at 1.06 μm. Figure 1(a) shows the leakage loss as a function of air-hole radius for six circular tubes: it increases when the air-hole radius is enlarged. The lowest leakage loss was found ~0.05 dB/m for an air-hole radius (r) of 10.20 μm, which is around one order of magnitude lower compared to when the air-holes are touching each other. This well-known result from using circular tubes is now compared to the case using elliptical anti-resonant tubes. We define ellipticity as $\eta = r_y/r_x$, where r_x and r_y are the radius of major and minor axis of the anti-resonant tubes respectively. Figure 1(b) shows that the lowest leakage loss of ~5 dB/km was obtained for η ~0.65,

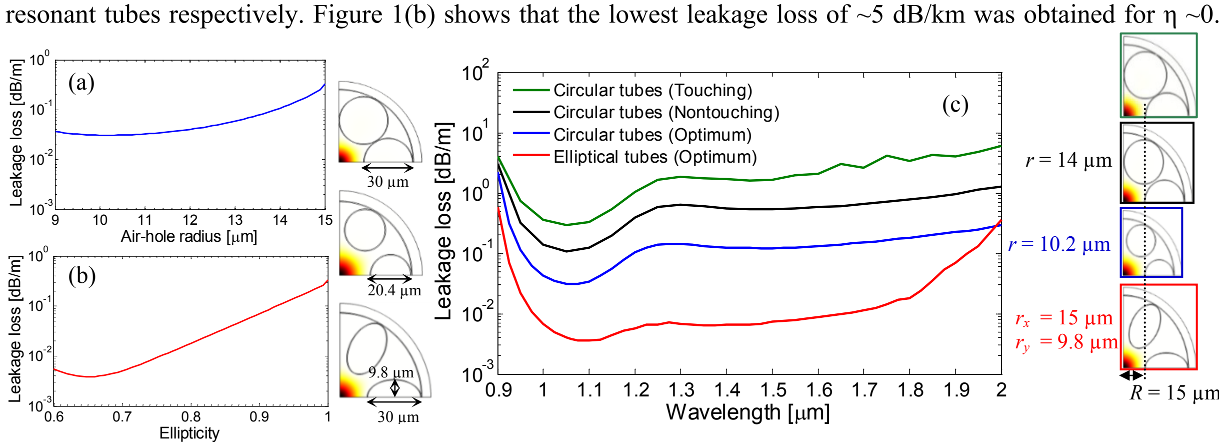

Fig. 1. Calculated leakage loss as a function of (a) air-hole radius, (b) ellipticity at 1.06 μm, and (c) Comparison between the simulated leakage losses as a function of wavelength for different HC-ARFs. All considered structures have the same core radius R = 15 μm and uniform silica strut thickness t = 0.42 μm.

i.e., r_x = 15 μm and r_y = 9.80 μm. It can be seen from Fig. 1(b) that the leakage loss can be reduced two orders of magnitude by suitably squeezing the anti-resonant tubes in the axis perpendicular to the radial direction.

The low-loss performance is also broadband, as figure 1(c) shows. The green curve shows the loss curve of six circular anti-resonant tubes in which tube walls are touching each other. The black curve shows the loss of HC-AR fiber having six circular anti-resonant tubes with the air-hole radius reduced to 14 μm as to ensure the walls of adjacent tubes no longer touch; the leakage loss is slightly higher than 0.1 dB/m at 1.06 μm. This is a well-known result from the circular case: separating the tubes there is a reduction of leakage loss [3]. However, the air-hole radius can be reduced even further as to minimize the loss, which is shown in the blue curve of Fig. 1(c): the leakage loss is lower in the entire wavelength regime ranging from 0.90 to 1.8 μm than that shown in green and black curve. Finally, the red curve shows the loss spectrum of six elliptical tubes with the optimized air-hole radius; the leakage loss is 1-2 orders of magnitude lower than what is possible with circles and stays below 10 dB/km from 1.0-1.65 μm. We have also investigated the coupling between the core-guided modes and cladding modes, which is shown in Fig. 2. The first three cladding modes (red broken lines) have slightly larger Δn_{eff} than the first higher-order core-mode (LP_{11}) which increases the possibility of strong phase-matching between the cladding modes and higher-order-modes (HOMs). This effect is more evident for the strong elliptical anti-resonant tubes (η~0.60-0.70) in which coupling between the cladding modes and HOMs is more likely to occur. Figure 2(a) also shows the so-called HOM extinction-ratio (HOMER, i.e. loss-ratio between the HOMs and the LP_{01} mode). A maximal HOMER was found ~2500 for η ~0.61 whereas a fiber with circular anti-resonant tubes has HOMER<10. The wavelength dependence of leakage loss and HOMER is shown in Fig. 2(b). The HOMER can be made in excess of 1000 and 150 for *η*~0.61 and *η*~0.65 in the spectral range 1.0-1.75 μm and 0.95-1.9μm respectively, which indicates that the proposed HC-AR fiber can operate as an effectively single-moded fiber.

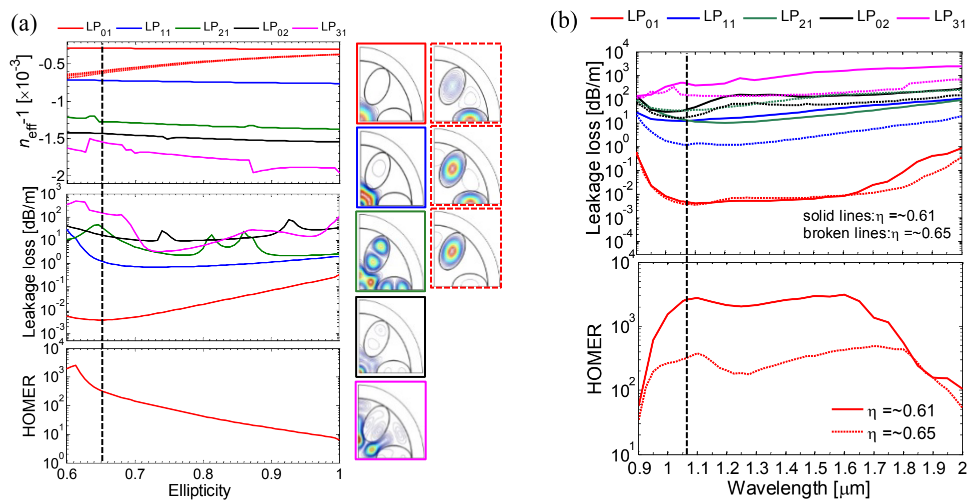

Fig. 2. (a) Effect of changing the ellipticity on relative effective index, leakage loss, and HOMER with a fixed *R*=15 μm, *t*=0.42 μm and λ=1.06 μm. and (b) wavelength dependence of leakage loss and HOMER.

3. Conclusion

We proposed a hollow-core anti-resonant fiber design with node-free anisotropic nested elements, which allows low loss and effective-singe mode guidance simultaneously over a broad wavelength range. This is because the anisotropy allows at the same time to get nested elements with increased negative curvature, a node-free design, and a large distance from the core to the capillary, all elements that improve the loss performance. We showed a silica-based design optimized for 1.06 μm having a higher-order-mode extinction ratio over 1000 in the range λ = 1.0-1.75 μm while keeping the LP_{01}-mode-loss below 10 dB/km in the 1.0-1.65 μm range. This design idea is generic and can be implemented in other HC-AR fiber types as well.

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