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Optimization of Bending Loss for Higher Order Modes of Anti-Resonant Hollow Core Fibers

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Ultra-low loss fiber design seeks an attention towards all the possible source of losses such as confinement loss (CL), macro-bending loss (BL), Rayleigh scattering loss (RSL), surfaces scattering loss (SSL), and fabrication loss [1,2]. It is found that hollow core anti-resonant fiber (ARF) with nodeless structure does not have SSL due to non-touching tubes and RSL is ignored due to less interaction of light in hollow air core with surrounding silica tubes [3]. Fabrication tolerances should be worked out while choosing the fiber design parameters. CL becomes the dominating loss in these fibers and it can be lowered by optimizing the fiber design. In field applications, bending of these fibers become a major source of loss. One needs to work on the fiber structure/design to reduce its loss under bending conditions – bending axes and bending radii. Under bend conditions, the core modes and cladding modes start leaking and coupling with each ither which results in the loss of core modes and coupling of cladding modes into the core. The fiber design is optimized such that the higher order modes (HOM) are avoided/suppressed and fundamental modes (FM) are confined inside the core having lowest possible CL using mode analysis based on Finite element method in COMSOL [4].

In this work, the optimized design is utilized by fine tuning the gap (g) between cladding tubes to achieve low bending loss for FM without coupling of HOM inside the core. The structure of ARF is shown in Fig. 1a indicating its design parameters. The refractive index profile $(n(r))$ is modified for bent fiber (n_b) using the expressions [5] $n_b = n(r)(1 + (1 - \chi)r/R_b)$ where the elastic coefficient(χ) of silica is -0.22 and zero for air. The fiber profile is shown in Fig. 1b when bending is around X- and Y- axis along with the straight fiber. The bending loss is calculated at wavelength (λ) of 650 nm from imaginary effective mode index (n_{eff}) using [5] $BL = 40\pi\, Im(n_{eff})/[ln(10)\,\lambda] \times \pi R_b$ in dB/turn by tuning the bend radius (R_b) as shown for unoptimized case using g=2 µm around X- axis in Fig. 1(c) and Y-axis in Fig. 1(e). In unoptimized case, the FM suffers highest loss while HOM guidance is more at R_b of 55 cm. The BL is optimized using g=4 µm around X- and Y- axis in Fig. 1(d) and 1(f) respectively where all the HOMs – TE, TM, $HE_{21a,b}$ and FM suffer similar loss peaks. The optimized BL peak is shifted towards smaller R_b (< 40 cm) for FM. BL peak value is reduced for both the FM and HOMs and is found to be of ≥ 0.1 dB/turn for HOM and is < 0.1 dB/turn for FM.

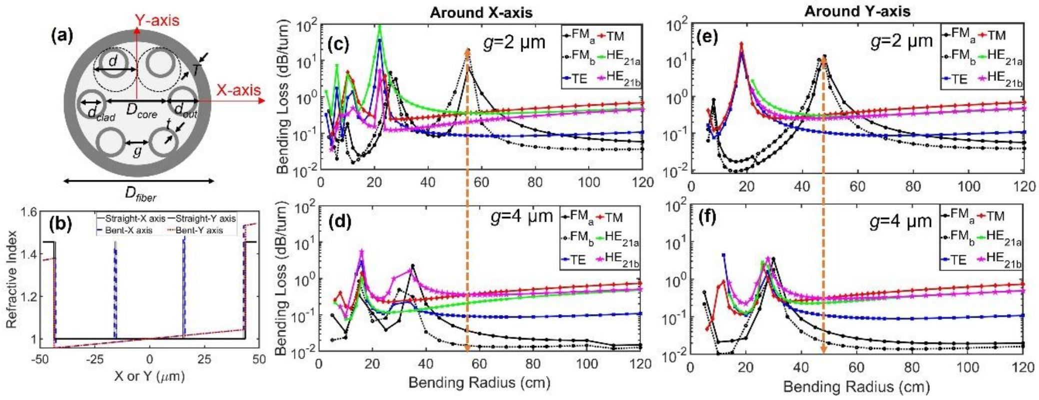

Fig. 1 (a) Schematic of fiber structure, (b) Refractive index profile of straight and bent fiber around X- and Y- axes, bending loss spectra around X-axis for (c) unoptimized, (d) optimised and around Y-axis for (e) unoptimized and (f) optimised designs.

It is concluded that the bending loss is optimized for HOM having the comparable loss peaks as FM and larger BL at R_b>40 cm to maintain the single mode guidance in hollow core ARF under bending condition.

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