# Optical and mechanical properties of hollow-core fibers with cobweb cladding structure

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This paper explores the possibility of realizing a hollow-core optical fiber, whose cladding is composed of cylindrical alternating layers of air and high-index material with supporting structure. The optical properties and the design criteria of the proposed fiber are evaluated by the compact two-dimensional (2D) finite-difference time-domain (FDTD) method. In particular, the influence of the number and width of supporting strips on the leakage loss of the fiber is investigated. Furthermore, the mechanical performances of the fiber are estimated by finite-element method, confirming that hollow-core fibers with a reasonable size and number of supporting strips are reliable.

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The air-core optical fibers can be generally classified into two types: photonic crystal fibers and Bragg fibers[1]. Recently, there is a novel class of Bragg fiber, "OmniGuide" fiber with a hollow core, which uses a multilayer cladding that exhibits omnidirectional reflection in the planar limit[2−7]. By creating an omnidirectional dielectric mirror from materials with sufficiently different indices of refraction, they open up a full photonic bandgap. This gives dielectric mirrors omnidirectional reflectivity (efficient reflection for all angles of incidence) for a wide band of wavelengths with very low absorption. However, the main difficulty of realizing the structures is the lack of two materials with a larger index contrast, a lower absorption loss, similar thermal and mechanical properties, along with compatible processing technology. In this letter we present a cobweb cladding structure, which uses a single dielectric material and may solve the problem of structural support.

The structure we put forward is illustrated in Fig. 1. The structure parameters are: $n_1(=1)$, $n_2$, $d_1$, $d_2$, $\Lambda$, $r_{co}$, $N$, $m$ and $W_s$. $N$ is the number of alternating layers, $r_{co}$ is the radius of the hollow-core, $m$ and $W_s$ are the number and width of the supporting strips, respectively. The supporting strips are always symmetric in the cross-section and use the same dielectric material as alternating layers. The dielectric material here is selected as a polymer (PMMA), although other materials also can be applied.

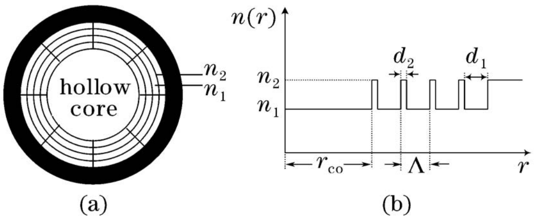


Fig. 1. Hollow-core fiber with cobweb cladding structure.

Firstly, a hollow-core omnidirectional reflection Bragg fiber with and without supporting structure is analyzed with the following parameters: $n_1 = 1$, $n_2 = 1.49$ (refractive index of PMMA), $d_1 = 0.80$ $\mu$m, $d_2 = 0.25$ $\mu$m, $\Lambda = d_1 + d_2 = 1.05$ $\mu$m, $r_{co} = 10$ $\mu$ m, $N = 4$, and operating wavelength $\lambda = 0.77$ $\mu$m (one of lower loss windows for PMMA). The field profile of transverse electric field for the Bragg fiber without supporting structure, which is obtained by applying the two-dimensional (2D) finite-difference time-domain (FDTD) method[8], is illustrated in Fig. 2(a). As the figure illustrates, the field is well confined. If supporting structures are introduced ($W_s = 0.25$ $\mu$m, $m = 8$ and 12, respectively), the field profiles are slightly deformed, as shown in Figs. 2(b) and (c). However, most of field is still confined in the core of the fiber.

Secondly, cobweb-cladding structure is also suitable for the fiber based on antiresonant reflecting guidance mechanism[9]. The configuration would be more favorable, because the high-index layers can be thicker and the spectral properties are not particularly sensitive to the period of the cladding layers. Thus the fabrication is easier to be realized. Antiresonant reflecting for a given

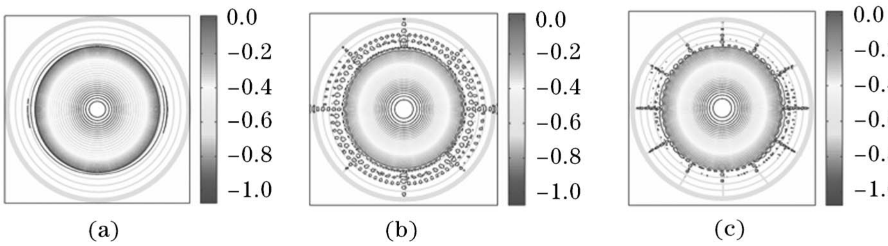


Fig. 2. Transverse field profiles of hollow-core omnidirectional reflection Bragg fibers without supporting structure (a), with supporting structures of $W_s = 0.25$ $\mu$m, $m = 8$ (b) and $W_s = 0.25$ $\mu$m, $m = 12$ (c).

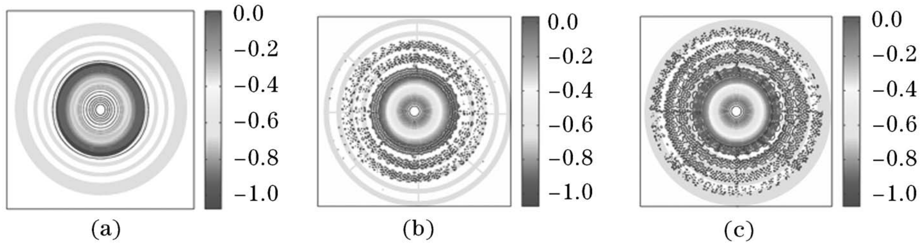


Fig. 3. Transverse field profiles of antiresonant reflecting guidance fibers without supporting structure (a), with supporting structures of $m = 8$, $W_{\rm s} = 0.25$ $\mu$m (b) and $m = 8$, $W_{\rm s} = 0.567$ $\mu$m (c).

optical wavelength ($\lambda = 0.77$ $\mu$m) reaches the maximum value for the possible thicknesses ($d_2$) of the high-index layer ($n_2$) that satisfy the following condition[9]

$$d_2 = \frac{\lambda(2l+1)}{4n_1\left[\left(\frac{n_2}{n_1}\right)^2 - 1\right]^{\frac{1}{2}}}, \quad l = 0, 1, 2, \cdots.$$

For $\lambda = 0.77$ $\mu$m, $n_1 = 1$, and $n_2 = 1.49$,

$$d_2 = 0.174, 0.523, 0.871, \cdots, 2.266\,\mu\text{m}\,(l = 0, 1, 2, \cdots, 6).$$

Thus, the configuration parameters are selected to be $n_1 = 1$, $n_2 = 1.49$, $d_1 = 1.50$ $\mu$m, $d_2 = 2.266$ $\mu$m, $\Lambda = d_1 + d_2 = 3.766$ $\mu$m, $r_{\rm co} = 10$ $\mu$m, and $N = 4$. To check whether the parameters above meet the requirement for the validity of the antiresonant reflecting optical waveguide model, we evaluate $\lambda = 2d_2(n_2^2 - n_1^2)^{\frac{1}{2}} = 5$ $\mu$m using our parameters. This result shows that at shorter wavelength (0.77 $\mu$m) than 5 $\mu$m, the fundamental mode is very well confined by the antiresonant reflecting optical waveguide mechanism. The field profile of transverse electric field for antiresonant reflecting guidance fiber without supporting structure is illustrated in Fig. 3(a). If supporting structures are introduced ($m = 8$, $W_{\rm s} = 0.25$ and 0.567 $\mu$m, respectively), the field profiles are illustrated in Figs. 3(b) and (c). As can be seen by comparison between Fig. 3(b) and Fig. 2(b), the field leakage due to the introduction of supporting structure is stronger than that of omniguide Bragg fiber. However, the leakage can be reduced by increasing the number of alternating layers ($N$) for the antiresonant reflecting configuration, because as a rule, the leakage rate decreases with increasing the number of cladding layers. The leakage of Fig. 3(c), due to width (0.567 $\mu$m) of the supporting strips to be larger in comparison with $\lambda = 0.77$ $\mu$m, is obviously larger.

The number and width of supporting strips should be as small as possible, as long as the structures meet the requirements of mechanical stability. Generally, $m = 6$—12, and $W_{\rm s} = \lambda/3 - \lambda/30$, where $\lambda$ is operating wavelength of the fibers.

The mechanical properties of hollow-core fibers with cobweb cladding structure are analyzed by the finite-element method. Structural parameters of the hollow-core fibers with cobweb cladding structure are $n_1 = 1$, $n_2 = 1.49$, $d_1 = 2$ $\mu$m, $d_2 = 0.23$ $\mu$m, $r_{\rm co} = 10$ $\mu$m, $N = 5$, $m = 12$, $W_{\rm s} = 0.23$ or 0.046 $\mu$m, and outer cladding diameter $D_0 = 100$ $\mu$m. The material is PMMA, whose elastic modulus, Poisson ratio, and yield limit are 3.1 GPa, 0.33, and 61 MPa, respectively. The length of the fiber, $l = 2500$ $\mu$m, is taken. The displacement load on the fiber is imposed at different radii of curvature. The relationship of maximum principal stress on the cross-section with the radius of curvature after load is illustrated in Fig. 4(a), for which the simulation is realized using ANSYS 5.7 software. As shown in Fig. 4(a), when the radius of curvature is $\rho = 3$ mm, the stress reaches the yield limit of the material (PMMA). If the radius of curvature is fixed, $\rho = 20$ mm, under otherwise equal conditions, when outer cladding diameter changes, the relationship of maximum principal stress on the cross-section with the outer diameter is illustrated in Fig. 4(b). When the outer diameter $D_0 = 600$ $\mu$m, the maximum principal stress on the cross-section will reach the yield limit. Flexural rigidity on the cross-section increases as the width of the supporting strips ($W_{\rm s}$) decreases. Thus maximum principal stress on the cross-section with the width of the supporting strips decreases. When the number of the supporting strips $m = 6$, the calculated results are almost identical with the results shown in Fig. 4 at $m = 12$.

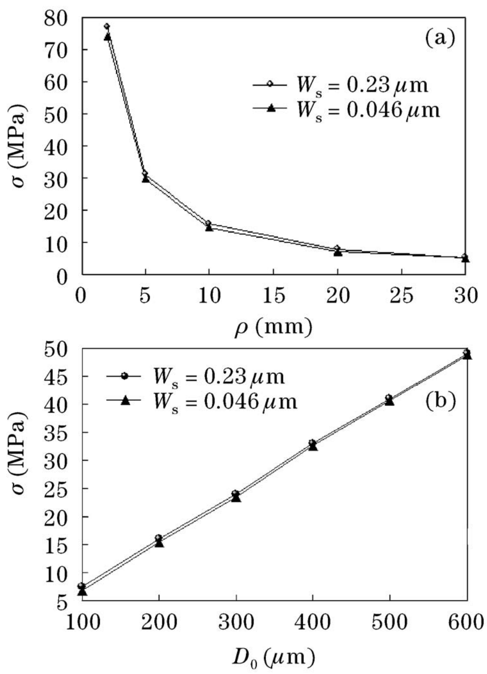


Fig. 4. (a) Relation of maximum principal stress $\sigma$ with radius of curvature $\rho$; (b) relation of $\sigma$ with outer diameter $D_0$, $\rho = 20$ mm.

The fabrication and characterization of the hollow-core fibers with cobweb cladding structure using PMMA material and extrusion etc. techniques are under way.

In conclusion, we propose a new cladding structure (cobweb structure) of hollow-core Bragg fiber using only a single dielectric material. In principle, fibers with this cobweb structure are suitable for replacing all pervious Bragg fibers and the fibers consisting of alternating layers with two materials. The feasibility of Bragg fibers is greatly improved. And a variety of the fibers in the wavelength range of ultraviolet (UV) to terahertz (THz) radiation for specific applications can be made utilizing this structure. Although a small fraction of power is leaked out due to the introduction of supporting structure, properly selected parameters of supporting structure will keep the loss at a low level and make the mechanical intensity suitable for practical applications.

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