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Design guidelines and characteristics of beam-shaping microstructure optical fibers

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Abstract

Microstructure optical fibers with flat-top fundamental mode are first proposed by introducing a low-index inner core into the core of index-guiding microstructure optical fibers. The design guidelines and characteristics of beam-shaping microstructure optical fibers are demonstrated. The interrelationships of inner-core index with laser wavelength, air hole diameter and size of inner core are investigated. The influence of the relative size of inner core on the spatial profile of the fundamental mode is demonstrated. Moreover, sensitivity of the flat-top fundamental mode profile from the slight change of the optimum inner-core index value is studied. Starting from these results we deduce that it is possible to fabricate beam-shaping microstructure fibers with nowadays technique.

Keywords: Beam shaping; Flat-top fundamental mode; Microstructure optical fibers

1. Introduction

Microstructure optical fibers attract much attention in recent years because they provide more freedoms in fiber design. By carefully arranging the array of air holes in the cladding, novel properties, such as endlessly single mode [1], large effective mode area [2] and regular mode field shape [3–5], have been exhibited in microstructure optical fibers. In this paper, we are interested in the modal properties of microstructure optical fibers with regular mode field shape. Previous work [3,4] have reported microstructure optical fibers with triangular or square shape mode field by specially placing the air holes in the cross section of the fibers, but the intensity distribution of the fundamental mode field is center-convex. By introducing a low-index inner core, which having a regular shape, into the core of index-guiding microstructure optical fibers, optical fibers with flat-top intensity distribution and regular shape of the fundamental mode could be obtained. We call these fibers beam-shaping microstructure optical fibers because they can shape Gaussian laser beams into flat-top ones.

In the following, we first introduce the design guidelines, and then report the numerical results about the characteristics of the beam-shaping microstructure optical fibers, and finally discussions and conclusions are given.

2. Theoretical model

The cross-section of beam-shaping microstructure optical fiber with hexagonal mode field is shown in Fig. 1. In this scheme, the shape of inner core is consistent with that of out core, and also identical to the fundamental mode field shape of the fiber.

To model the fiber, we consider the fiber to be uniform in the light propagation direction z, thus the x-polarized electric field E_x can be expressed by semi-vectorial Helmholtz equation as [6]:

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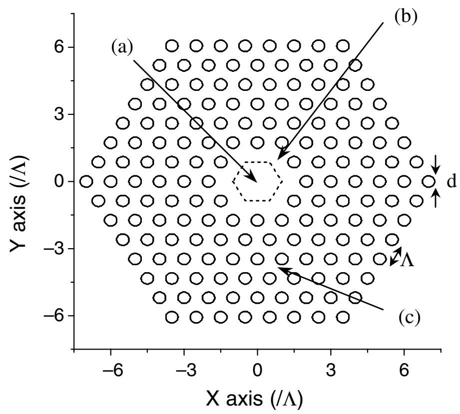

Fig. 1. The cross-section of a beam-shaping microstructure optical fiber with a hexagonal inner core (a), out core (b) and cladding region (c), where d is the diameter of air hole, Λ is the distance of nearby air holes.

$$\left(\frac{d^2}{dy^2}+\frac{d}{dx}\frac{1}{n^2}\frac{d}{dx}n^2+n^2k^2-\beta^2\right)E_x=0, \tag{1}$$

where n is the refractive index profile of the fiber, k is a wave number in vacuum, and β is a propagation constant.

If Eq. (1) is solved with the finite difference method [7], light intensity distribution $g(x,y)$ of E_x can be obtained

$$g(x,y)\propto|E_x(x,y)|^2. \tag{2}$$

To design a flat-top fundamental mode microstructure fiber, the value of $g(x,y)$ at the fiber center and the maximum value of $g(x,y)$ at the region beside inner core should be found. Here, we define the flat-top error Δ as

$$\Delta=\frac{g_{\text{center}}(x,y)-g_{\max}(x,y)}{g_{\max}(x,y)}. \tag{3}$$

According to Eq. (3), numerical calculation programs for beam-shaping fibers can be realized by try and error. When $\Delta=0$, a flat-top fundamental mode of the fiber is formed, and when $\Delta<0$, a center-concave fundamental mode of the fiber is formed, otherwise, a center-convex fundamental mode of the fiber is formed.

In order to guarantee the fiber to be single mode, the intensity distribution of the electric mode field is calculated and plotted for verification.

3. Numerical results and discussions

We take silica fibers as an example to demonstrate the characteristics of the beam-shaping microstructure optical fibers. In this case, the low-index inner core is made from doped silica, the out core and the back ground glass in the cladding is made from pure silica glass. The refractive index of pure silica glass at different laser wavelength can be referred to [8], and the value of inner-core index is calculated from above equations.

In Fig. 2, the map surface and contour plot of a typical flat-top fundamental mode of the fiber with parameters of $L_{\text{inner-core}}=\Lambda=2.0$ μm, $d=0.6$ μm, and $\lambda=0.8$ μm are illustrated. It shows the intensity distribution of the fundamental mode is flat-top in the center.

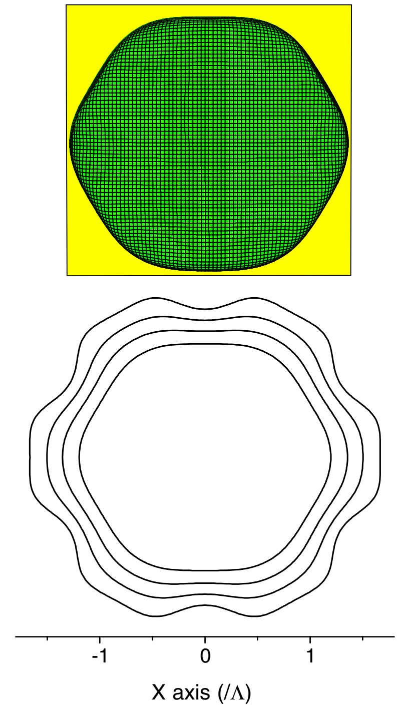

Fig. 2. Typical maps of the flat-top fundamental mode of the beam-shaping fiber. The top panel shows the surface profile of the flat-top region of the fundamental mode, the bottom panel shows the two-dimensional intensity distribution of the fundamental mode.

Fig. 3 provides the index of inner core, the index of out core and the effective index of cladding as a function of laser wavelength. The effective index of cladding is calculated with a plane wave method [9]. As can be seen from this figure, both the index of inner core and that of out core are decreased with increasing laser wavelength, and the index difference between them increases as laser wavelength increases. Because the out-core index is larger than the effective index of cladding for a fixed laser wavelength, we

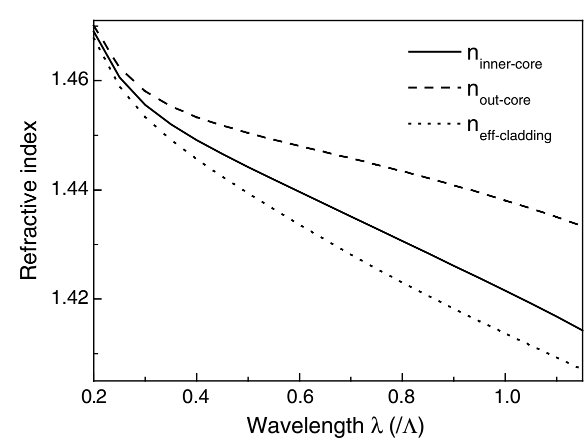

Fig. 3. Inner-core index, out-core index and the effective index of cladding as a function of light wavelength, where $\Lambda=L_{\text{inner-core}}=2.0$ μm, $d=0.6$ μm.

deduce that light is trapped in the core region by total internal reflection.

In fiber design, we also care about the dependence of the index of inner core on the size of air holes and itself. In Figs. 4 and 5, inner-core index and out-core index as a function of diameter of air hole and edge size of inner core are demonstrated. From these figures it is easily found that inner-core index is decreased when the diameter of air hole and the size of inner core increase.

The influence of the relative size of inner core on the shaped flat-top fundamental mode profile is shown in Fig. 6. In this figure, we compare the profiles of the fundamental mode with different relative size of inner core. The results indicate that increasing the relative size of inner core could enlarge the uniform region of the fundamental mode and decrease the edge of it. This feature can be used to design beam-shaping microstructure optical fibers with different mode profile.

In the calculation, we find that the refractive index value of doped silica glass for inner core should be carefully monitored in fiber fabrication. When it is higher or lower than optimum value, the profile of the fundamental mode will be center-convex or center-concave (see Fig. 7(a)). Sensitivity

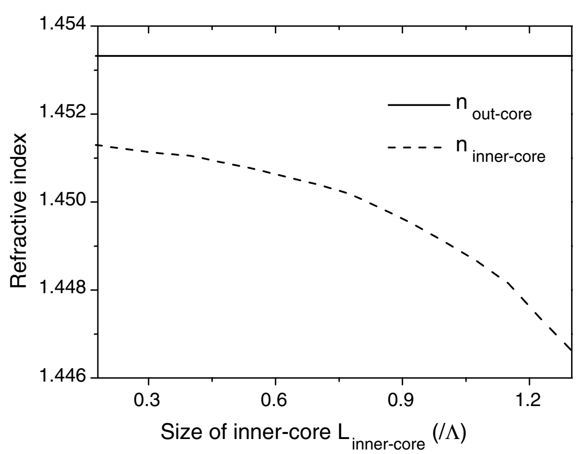

Fig. 4. Inner-core index and out-core index as a function of the relative size of inner core, where $\Lambda = 2.0$ μm, $d = 0.6$ μm, $\lambda = 0.8$ μm.

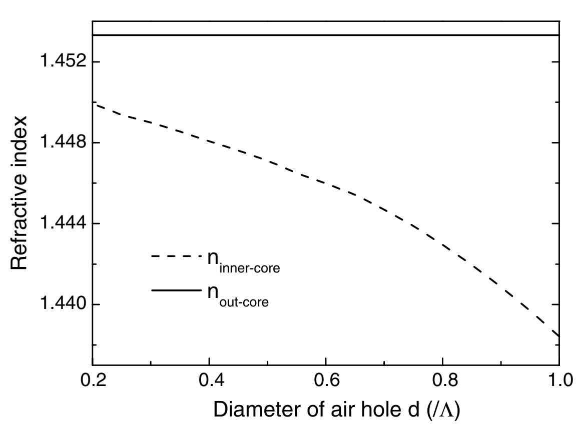

Fig. 5. Inner-core index and out-core index as a function of air hole diameter, where $\Lambda = L_{\text{inner-core}} = 2.0$ μm, $\lambda = 0.8$ μm.

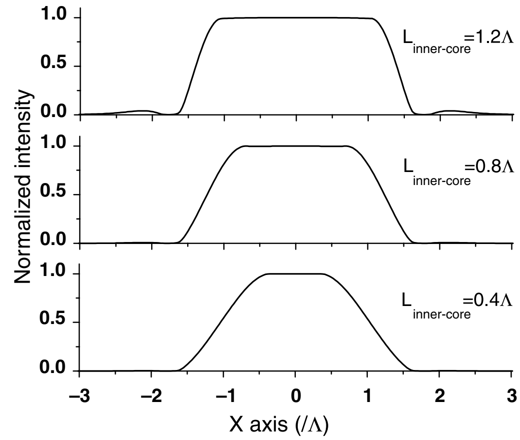

Fig. 6. Comparison of the transverse profile of the flat-top fundamental mode at different relative sizes of inner core, where $\Lambda = 2.0$ μm, $d = 0.6$ μm, $\lambda = 0.8$ μm.

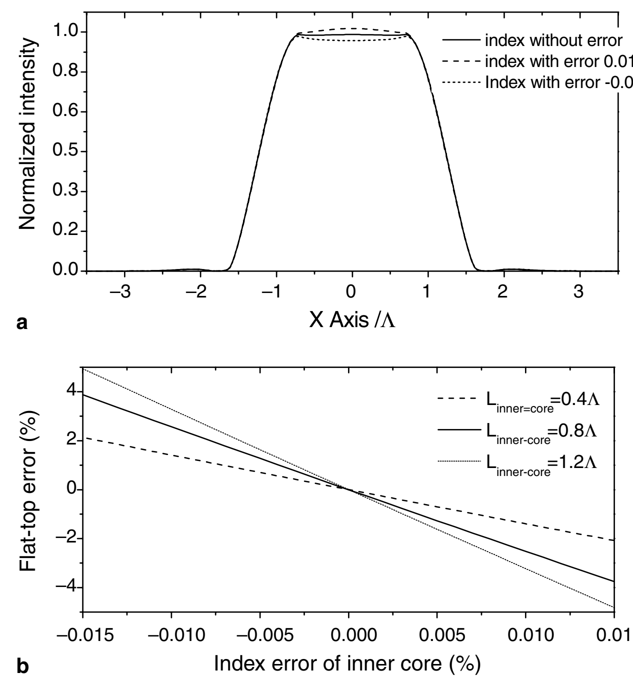

Fig. 7. (a) The profiles of the fundamental mode with different inner-core index. (b) Flat-top error of fundamental mode versus index error of inner core. In the calculations, $\Lambda = 2.0$ μm, $d = 0.6$ μm and $\lambda = 0.8$ μm.

of the flat-top fundamental mode influenced by the index variation of inner core is shown in Fig. 7(b). It demonstrates that the flat-top error of the shaped flat-top mode can be controlled under the scope of ±1% if the index error of inner core is lower than ±0.0035%. With nowadays technique, the index error of doped silica glass can be well controlled within ±0.001%, so it is possible to fabricate this kind beam-shaping fiber with high quality.

In a standard single mode fiber, the distance from a light source to stable bound state is typically less than a centimeter [10], the necessary length for a beam-shaping microstructure optical fiber to shape laser beams should obey a similar manner. Shaping laser beams with beam-shaping microstructure optical fibers might have advantages in these points. First, the mode property of the fibers is determined on their structures, so laser beams with different intensity distribution can all be shaped into the same one. Second, once inner core of the beam-shaping fibers is doped with laser active ions, the fibers can be used as beam-shaping fiber laser amplifiers or beam-shaping fiber laser oscillators.

4. Conclusions

Design guidelines and characteristics of beam-shaping microstructure optical fibers are first demonstrated in this paper. The feasibility of fabricating these fibers is also investigated. The numerical results indicate that a carefully chosen low-index inner core can effectively change the profile of the fundamental mode. The index of inner core changes with light wavelength and structure parameters. With this method, beam-shaping microstructure optical fibers with different mode shape and different mode profile can also be designed. Beam-shaping microstructure optical fibers not only can be used to shape laser beams, but also have potential applications in beam-shaping laser amplifiers and beam-shaping laser oscillators.

Acknowledgments

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