Beam-shaping microstructure optical fiber

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Microstructure optical fiber with uniform intensity distribution of the fundamental mode is proposed. The design guide line and characteristics of this kind fiber are demonstrated. The relationship between refractive index profile and structure parameters is investigated. The mechanism of forming uniform fundamental mode in these fibers is analyzed.

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Since the advent of laser, shaping laser beam has been an important topic because Gaussian laser beam is not the desirable one in many applications. In order to obtain shaped laser beam, especially flat-top beam, various techniques have been developed, such as absorptive lens[1] or filters[2,3], refractive[4,5] or reflective[6] optical systems, and diffractive elements[7,8]. These methods are not easily applied in fiber systems.

Microstructure optical fibers attract intensive interest in recent years because of their novel properties and extra freedoms in fiber design. As we know, the basic structure of microstructure optical fibers consists of layers of air-holes around a solid defect core. By controlling the air-hole spacing and air-filling fraction, microstructure optical fibers can be single mode in a broad frequency range and the mode area can be greatly enhanced in contrast to conventional fibers. With these features, microstructure optical fibers provide an excellent medium for high power laser delivery and high power laser generation. We can expect that microstructure optical fibers would be prevalent in the near future. Although modal properties of microstructure optical fibers are greatly determined on the placement and size of air-holes in the cladding, there are few papers concerned microstructure optical fibers with flat-top intensity distribution of the fundamental mode. In this paper, we provide a simple method of designing beam-shaping microstructure optical fibers based on the nature of fiber itself.

In Fig. 1 we show the transverse cross section of a beam-shaping microstructure optical fiber. It consists of three regions, hexagon inner core surrounded by dashed line, the area between the dashed line and the first layer 12 air-holes assigned to outer core, the rest area is cladding. Parameters of air-hole diameter d, air-hole spacing Λ, and edge size L_{core} characterize the structure.

To obtain the intensity distribution of the electric mode field of the fiber, we employ a standard semi-vectorial method. Considering the fiber to be uniform along axis, x-polarized electric field can be written as[9]

$$\left(\frac{\mathrm{d}^2}{\mathrm{d}y^2}+\frac{\mathrm{d}}{\mathrm{d}x}\frac{1}{n^2}\frac{\mathrm{d}}{\mathrm{d}x}n^2+n^2k^2-\beta^2\right)E_x=0, \qquad (1)$$

where n is refractive index profile of the fiber, κ is wave number in free space, and β is propagation constant.

Before solving Eq. (1), it is needed to construct a refraction index function. We take a finite difference method with successive over-relaxation (SOR) algorithms to solve Eq. (1). The detail process can refer to Ref. [10].

Once Eq. (1) is solved, the intensity distribution of E_x can be easily obtained

$$g\left(x,y\right)\propto\left|E_x\left(x,y\right)\right|^2. \qquad (2)$$

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

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

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, the desired index profile $n(x,y)$ is obtained.

To guarantee the fiber to be single mode, the intensity distribution of the electric field is output and plotted at each sampling point.

Until now, the structure and the design method of beam-shaping microstructure optical fiber have been

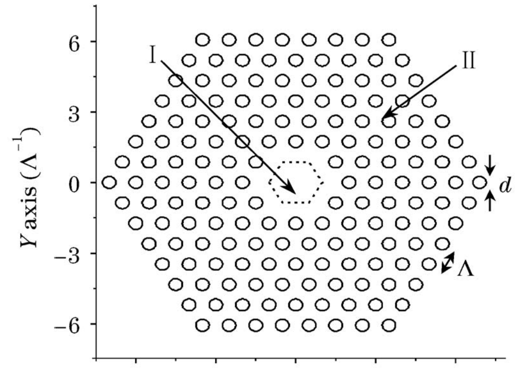

Fig. 1. Cross section of a beam-shaping microstructure optical fiber with a hexagon inner core (I) embedded in the core surrounded by air-silica cladding (II).

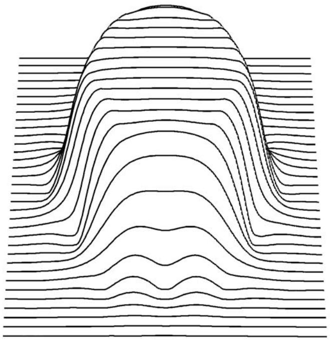

Fig. 2. 3D map of the uniform intensity distribution of the fundamental mode. $L_{\text{core}} = \Lambda$, $\Lambda = 2.0$ μm, $d = 0.6$ μm, $\lambda = 0.8$ μm, the index of silica $n = 1.4533$ and the index of inner core $n_{\text{inner-core}} = 1.4493$.

given. In the following, we take silica glass fiber as an example to demonstrate the feasibility of the method. In order to obtain flattop mode field, the index of inner core should be lower than that of outer core. Here, we consider the inner core composed of doped silica glass with low refractive index, the other region composed of pure silica glass. The index of pure silica glass is taken from sellmeier equation[11]. The index of inner core can be solved from above equations.

Figure 2 shows a typical three-dimensional (3D) map of the uniform intensity distribution of the fundamental mode of the fiber. This figure demonstrates that it is possible to form a uniform fundamental mode intensity distribution in a microstructure optical fiber.

In the following, we also take the light wavelength $\lambda = 0.8$ μm as an example to demonstrate the features of the fiber. Figure 3 shows the index of inner core and the effective index of cladding change with air hole diameter. The effective index of cladding $n_{\text{eff-cladding}}$ can be calculated with plane wave method[12]. It is easily found that the both index of inner core and the effective index of cladding decrease monotonously as air hole diameter increases. In this case, the average index of the core (inner core and out core) also decreases, but is always higher than the effective index of cladding. This figure also shows that the index of inner core is lower than that of out core (1.4533) when forming a uniform intensity distribution of the fundamental mode.

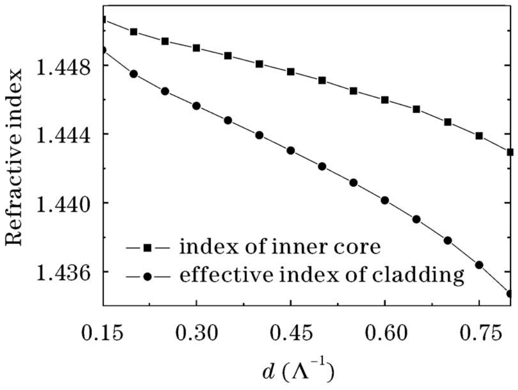

Fig. 3. Refractive index of inner core and effective index of cladding as a function of air hole diameter with $\Lambda = 2.0$ μm, $L_{\text{core}} = \Lambda$, $\lambda = 0.8$ μm.

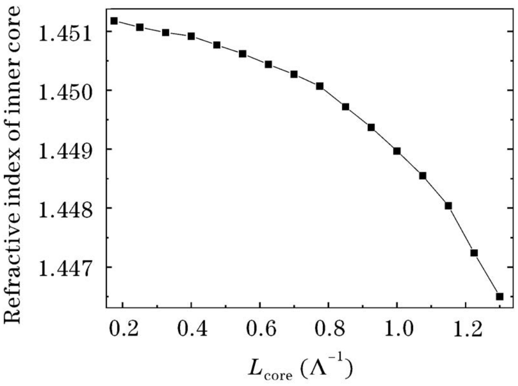

Fig. 4. Refractive index of inner core as a function of edge size of inner core with $\Lambda = 2.0$ μm, $d = 0.6$ μm, $\lambda = 0.8$ μm.

Figure 4 shows the index of inner core as a function of edge size of inner core. As the area of inner core increases, the index of inner core decreases. So the average index of the core (including out core and inner core) also decreases. From these results, we can deduce that light is guided in the fiber by total internal reflection, similar to conventional fibers. But light trace in the core is quite different from that in a standard step-index fiber. At the interface of inner core and out core, reflection and refraction occur because the index of inner core is lower than that of out core. Part of the light energy cannot enter the inner core because of total internal reflection. Energy redistribution takes place as light propagates along the fiber. Finally, a stable homogeneous intensity distribution of the fundamental mode would form. In this process, light reflection and refraction at the interface of inner core and out core are the main reasons of energy homogenization.

The size of inner core not only influences the index of itself, but also influences the spatial profile of the intensity distribution of the fundamental mode. Figure 5 shows the transverse intensity distribution of the fundamental mode changes with edge size of the inner core. As the edge size of inner core increases, the relative size of the central flattop area in the whole intensity distribution of the fundamental mode increases and the edges change more steeply. With this feature, beam-shaping

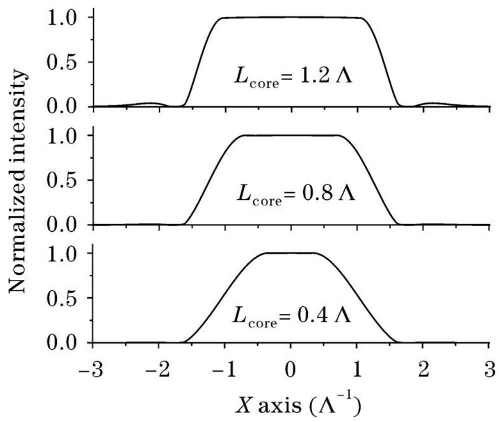

Fig. 5. Transverse intensity distribution of the fundamental mode of the fiber changes with edge size of inner core. $\Lambda = 2.0$ μm, $d = 0.6$ μm, $\lambda = 0.8$ μm.

microstructure optical fibers with different spatial profiles of the fundamental mode intensity distribution could be designed.

In standard single-mode fibers, the distance between the light source and a stable bound state forming is typically less than a centimeter[13]. The spatial transient distance for a beam-shaping microstructure fiber should be in a similar figure. This needs further verification.

Because the flattop mode profile stems from the nature of the fiber, this kind fibers can be used as a beam shaper to convert a Gaussian laser beam into a flattop one. When the inner core is doped with active laser ions, these fibers might have potential in beam-shaping microstructure fiber lasers or amplifiers.

In summary, a new kind microstructure optical fiber with flattop fundamental mode field is proposed. The design method and characteristics of the fiber are demonstrated. To achieve a uniform intensity distribution of the fundamental mode, the interrelationship between structure parameters is analyzed. The results show that the spatial profile of the intensity distribution of the electric fundamental mode field is determined on the nature of the fiber. Light is guided by total internal reflection in beam-shaping microstructure optical fiber. Light reflection and refraction at the interface of inner core and out core are the main reasons of forming uniform fundamental mode intensity distribution.

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