Design of Photonic Crystal Fiber with Large Mode Area for Flat-top Mode Generation

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Research Article

Keywords: Photonic crystal fiber, Flat-top mode, Large mode field area

Posted Date: June 4th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-524521/v1>

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Design of photonic crystal fiber with large mode area for flat-top mode generation

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Abstract

We report a large mode area photonic crystal fiber with a top-hat mode field. The optical fiber has a multi-layer square structure with air holes and doped layer. A flat and top-hat-like mode intensity profile is provided through the reasonable design of the doped layer. The modal characteristics including effective mode area, dispersion and confinement loss are investigated. The proposed fiber with a top-hat mode generation may have potential applications in laser drilling, laser cleaning, imaging, spectroscopy, and so on.

Keywords: Photonic crystal fiber, Flat-top mode, Large mode field area

1. Introduction.

Flat-top beam has attracted more and more attention these years because of its wide application in the field of material processing, such as laser drilling on printed circuit boards [1]. Moreover, it shows great promise for imaging and spectroscopy applications compared with Gaussian beam [2,3]. The traditional flat-top beam generation method is beam shaping technology. It mainly uses the principle of geometric optics (for example: aspheric lens method and birefringent lens group method) or physical optics (for example: micro lens array method, diffractive optical element method and liquid crystal spatial light modulator shaping method) to achieve [4]. However, this method not only introduces significant losses, but also needs to continuously improve the calculation of the phase distribution to reduce the unevenness of the flat-top mode field [5].

One desirable way to avoid the above defects is to design the special fiber in which transmitted light beam evolves into the flat-top beam profile. In recent years, there are a lot of researches on this new type of optical fiber, which can be divided into two categories. The main feature of the first type is the square core. In 2006, a jacketed square core and air-clad fiber, which can directly generate a flat-top field, has been fabricated [1]. Fibers with square cores have both great bending tolerance [6] and high optical power delivery capability [7]. However, the obtained flat-top mode field is not rather even, as the edges of the mode field are jagged like stamps. The main feature of another flat-top optical fiber is doping in the central region of the core. Researchers have designed an optical fiber with multi-core doped regions in 2013. But the obtained effective mode area (A_{eff}) of the flat-top light field is too small. The side length of the resulted square spot is only 2~3 μm [8]. In high-power laser systems, in order to reduce the adverse effects of nonlinear effects [9], it is necessary to increase the effective mode area and reduce the light power density, as larger A_{eff} can effectively reduce the light power density [10]. Therefore, the flat-top beam with a large A_{eff} has high application value.

The invention of photonic crystal fiber (PCF) provides a simple and effective method to generate flat-top beam. The PCF structure design is flexible and adjustable [11]. In 2006, Lu et al. introduced the flat-top mode to PCF for the first time [12]. The research proved that introducing a low refractive index (n) area into the core can effectively control the distribution characteristics of the fundamental mode field. In this paper, we propose a multilayer PCF with a square structure. It can output a flat-top mode field with large A_{eff} , which has less loss than traditional complex beam shaping systems. The main research method is the finite element method.

2. Design of optical fiber

In order to design a new type of special fiber for the required flat-top beam field generation, three steps are divided: the design of the core, the design of the cladding, and the design and realization of the appropriate refractive index distribution.

2.1 Design of the cladding

The cladding is composed of air holes for photonic crystal fiber. The shape of the air hole is generally circular. The overall arrangement of air holes (mostly hexagonal or toroidal) has a huge impact on the optical field [13]. However, the circular air holes are not beneficial to the generation of flat-top beams. The unique hole shape is chosen, as shown in Fig. 1, which is conducive to the homogenization of light field [1]. The basic structure of the unique hole is a circle with a radius of $8.32\ \mu\text{m}$. Taking two parallel chords $4.8\ \mu\text{m}$ from the center of the circle and removing off the two sides, the rest of the middle is the shape of the air hole required. And the corresponding angle of the two arcs is 60° .

Fig.1 The unique shape of the air hole.

For the arrangement of air holes, the general optical fiber adopts a dense arrangement of air holes to form a cladding [14]. Compared with the traditional dense air hole arrangement, the layered arrangement can reduce the loss with a simple structure and simple fabrication process [15,16]. A layered arrangement is used to form the cladding. Moreover, when the difference between the effective refractive index of the mode and refractive index of the doped layer of the fiber core is less than 5×10^{-4} , it can be considered that a flat-top mode field is generated in the fiber [8,17]. This characteristic is used to select the number of air hole layers in the cladding. When the number of layers is 2, the flat-top beam cannot be produced, since two layers of air holes cannot reduce the refractive index of the cladding to the required value. But for more than 3 layers, the structure becomes complicated and difficult to fabricate. Therefore, 3 layers of air holes are chosen as the fiber cladding, as shown in the blue area in Fig. 2.

Fig. 2(a) Design of the novel flat-top optical fiber (the blue area is the air hole, and the dark gray part is the doped area, (b) enlarged view of the central area of Fig. 2(a).

Fig. 3 The relationship between cladding radius and A_{eff} and loss.

In addition, the relationships between the effective mode area, the loss and the radius of the cladding are investigated, as results shown in Fig. 3. As the radius increases, the effective mode area increases. The loss presents a rough periodic fluctuation. Taking into account the evenness of the light field, the cladding radius of 124 μm is finally chosen.

2.2 Design of the core

The shape of fiber core affects the mode profile. Instead of the conventional round core supporting Gaussian beam [12,18], square core is naturally considered to obtain top-hat-like intensity profile [19]. The doped lattices in this design use this shape. A layer of densely arranged oval pores surrounding the quartz crystal can be used as the core [20]. It is used to achieve the required mode field and larger modal area. Similarly, doped lattices are used to form the core. As the dark gray part shown in Fig. 2(b), the single layer doped lattice is arranged in a square, like a fence. The enclosed quartz crystal serves as the interior of the core. The doped lattice serves as the outer layer of the core.

Regarding the area of the square core, the side length of the square cores were tested as 140 μm , 100 μm , 60 μm and 50 μm , respectively. A square core that is too large will not be able to gather the beam, as shown in Figs. 4(a and b). When the value is 60 μm , the light intensity distribution appears as a flat-top light field. It is indicated

that the reduced side length makes the light field more uniform. Therefore, 50 μm is chosen as a rough value for the following discussion. The relationship between the effective mode area, loss and the side length of the square core has also been studied. As Fig. 5 shows, the effective mode area increases with the increase of the side length. When the loss is minimal, the flat-top beam is not ideal. Taking into account the unevenness of the light field, 49 μm is finally selected as the side length of the square core.

Fig. 4 The output mode when the side length of the doped layer is (a) 140 μm , (b) 100 μm , (c) 60 μm , (d) 50 μm .

Fig. 5 The relationship between the A_{eff} , loss and the length of the doped area.

2.3 Refractive index distribution

In order to produce flat-top light, there is a low-high-low requirement for the refractive index distribution of the optical fiber [19]. As shown in Fig. 6, this means introducing a low refractive index region inside the core [12]. But the n of this area is greater than the n of the cladding. Therefore, the quartz crystal inside the core is used as the low refractive index region. Obviously, the n of this area will be greater than that of the cladding with many air holes [21]. The outer layer of the core is doped so that its n is greater than that of the core. As cladding air holes have been designed above, the third step is mainly focused on the way of doping.

Fig.6 Schematic and refractive index profile of the fiber with square core for flat-top mode generation. R_{cor} is the radius of the core's inner part, R_h is the radius of the core's outer layer.

The doping medium is germanium dioxide (GeO_2). GeO_2 dopants can affect the field distribution of PCF, resulting in new characteristics of mode [22]. Doping in the lattice region has a great influence on the mode field characteristics of the optical fiber [23]. In addition, the limiting loss and bending loss in this type of doped fiber

will be relatively low [24]. Therefore, we adopted doped GeO_2 in the lattice layer outside the core to form a fence with a high refractive index.

Then, the refractive index of the outer ring of the core is determined, and then the doping concentration is determined. The n difference between the outer ring of the core and the inner core of the core should not be too large. Therefore, 1.4506, 1.4504, and 1.4502 are selected for preliminary experiments. Figure 7(b) represents the power flow distribution shape of the central axis section when the n_{eff} of the doped layer is 1.4504. Obviously, the power of the mode field in the entire core part is approximately a constant, and the distribution is flat. However, when the mole percentage of doped germanium dioxide is changed to increase the n_{eff} of the doped layer to 1.4506, the power flow distribution becomes a concave shape in the center. This is mainly because the n_{eff} of the doped layer is too high, and the mode field is more distributed to the outer core, resulting in lower power of the inner core. On the other hand, when the mole percentage of doping is reduced to make the n_{eff} of the doped layer 1.4502, the power flow distribution becomes a convex shape in the middle. This is mainly due to the low n_{eff} of the outer core and the lack of good outward diffusion of the mode field, which results in higher power in the inner core [8].

Fig.7 The power flow of the central axis section of the output mode field: (a) at the $n_{eff}=1.4506$; (b) at the $n_{eff}=1.4504$; (c) at the $n_{eff}=1.4502$.

A finer calculation for the effect of the n_{eff} of the outer layer of the core is performed. Here defines a relative error, which can reflect the degree of unevenness of the mode field, as follows:

$$\Delta = \left[\frac{(P_{\max} - P_{\min})}{P_{\max}} \right] \times 100\%$$

where P_{max} represents the maximum power, P_{min} is its minimum value. The relationship between Δ and n of the doped layer is shown in Fig. 8. The Δ has the minimum value at 1.45046. To meet the requirement that n of the doped lattice is 1.45046, the initial value of the mole percentage of doped GeO_2 should be set to 4.25% [10,24]. Also, as the refractive index of the doped region increases, the effective area increases.

Fig. 8 The relationship between the Δ , A_{eff} of flat-top field and the n_{eff} of doping area.

However, the refractive index profile still needs to be further optimized. As shown in Fig. 9(a), after the refractive index of the doped layer is set to 1.45046, the light field still has some characteristics of Gaussian light. Especially at the four top corners, the light field intensity is significantly weaker than in the central area. We proposed a method to amend this distribution by changing the doping molar concentration, resulting with flatter intensity distribution of the flat-top mode [25]. Considering the symmetry, only one of the four sides of the doped layer needs to be discussed.

Fig. 9 Mode field distribution of: (a) non-gradient doped layer; (b) linear gradient doped layer; (c) fine-tuned linear gradient doped layer.

Fig. 10 Conceptual model of doped layer with height representing refractive index.

The diagonal direction of the light field presents a convex shape, as shown in Fig. 9(a). The increase of the refractive index of the doped area at the corners may suppress this trend. Considering that the closer to the top corner, the more obvious the convex shape, a refractive index gradient was set, gradually increasing from the middle to the ends. The conceptual model of doped layer is shown in Fig. 10, where the height in the figure represents the level of the refractive index. Thus, the value of the refractive index is an increasing arithmetic sequence. The average value is 1.45046. The improved mode field distribution is shown in Fig. 9(b). It can be found that the Gaussian light characteristics of the light field have been greatly improved. The light field is more uniform and closer to a square shape. The degree of unevenness of the mode field can be reduced to about 10%. It needs to be pointed out

that this is already at a level equivalent to that of the flat-top beam obtained through optical device modulation. However, the light intensity distribution at the four corners is still low. Therefore, the refractive index of four corners was further fine-tuned. By gradually increasing it, the most uniform light field was obtained, when the refractive index of the four corners was increased by 5.5×10^{-5} to 7.2×10^{-5} . The optimized result shown in Fig. 9(c) has been obtained.

3. Results

All the parameters of the optical fiber are designed. At a wavelength of 1550 nm, its output light field is shown in Figs. 11 and 12. The mode field presents a square columnar shape with a flat top. The degree of unevenness in the central axis section can reach 0.7% with A_{eff} of $22334.55 \mu m^2$ and the lowest loss of 6.27×10^{-11} dB/m, which has high practical application value. The side length of the flat-top beam spot produced by the traditional optical fiber is only about 4~5 μm . The side length of the light spot in this article can reach 50 μm . Moreover, it can directly generate a flat-top beam, and does not require a complicated process compared with the spatial light modulation method. In addition, as shown in Fig. 13, its dispersion characteristic has also been studied, which are not much different from ordinary optical fibers and will not limit its application.

Fig. 11 (a) The mode field diagram, (b) the power flow of the central axis section of the output mode field.

Fig. 12 The 3D diagram of the output flat-top beam.

Fig. 13 Dispersion characteristic of the optical fiber.

4. Conclusions

Photonic crystal fiber with large mode area has been proposed and designed for top-hat mode field generation. The optical fiber has a multi-layer square structure with air holes and doped layer. The unevenness degree of mode field in the central axis section can reach 0.7% with effective mode field area of $22334.55 \mu\text{m}^2$, based on the optimized design of multi-layer square structure and refractive index profile of doped core layer. The proposed fiber with a top-hat mode generation may have important industry applications, such as laser drilling, laser cleaning, imaging, spectroscopy.

Acknowledge

This work is supported by National Natural Science Foundation of China under Grant 91950105, Science and Technology Innovation Training Programs (SZDG2020013, XZD2020051); 1311 talent plan of Nanjing University of Posts and Telecommunications.

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Figures

Figure 1

The unique shape of the air hole.

Figure 2

(a) Design of the novel flat-top optical fiber (the blue area is the air hole, and the dark gray part is the doped area), (b) enlarged view of the central area of Fig. 2(a).

Figure 3

The relationship between cladding radius and A_{eff} and loss.

Figure 4

The output mode when the side length of the doped layer is (a) 140 μm , (b) 100 μm , (c) 60 μm , (d) 50 μm

Figure 5

The relationship between the A_{eff} , loss and the length of the doped area.

Figure 6

Schematic and refractive index profile of the fiber with square core for flat-top mode generation. R_{cor} is the radius of the core's inner part, R_h is the radius of the core's outer layer.

Figure 7

The power flow of the central axis section of the output mode field: (a) at the $n_{\text{doped}}=1.4506$; (b) at the $n_{\text{doped}}=1.4504$; (c) at the $n_{\text{doped}}=1.4502$.

Figure 8

The relationship between the Δ , n_{doped} of flat-top field and the A_{eff} of doping area.

Figure 9

Mode field distribution of: (a) non-gradient doped layer; (b) linear gradient doped layer; (c) fine-tuned linear gradient doped layer.

Figure 10

Conceptual model of doped layer with height representing refractive index.

Figure 11

(a) The mode field diagram, (b) the power flow of the central axis section of the output mode field.

Figure 12

The 3D diagram of the output flat-top beam.

Figure 13

Dispersion characteristic of the optical fiber.