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 flat-top 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, bending loss, confinement loss and field profile are investigated. The proposed fiber with a top-hat mode generation has 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 been attracted more and more attention in these years because of its wide application in the field of material processing, such as laser drilling on printed circuit boards (Haynes et al. 2006; Zhu et al. 2020; Xu et al. 2018; Wang et al. 2009; Zhang et al. 2013). Moreover, it shows great promise for imaging and spectroscopy applications compared with Gaussian beam (Velsink et al. 2021; Zhou et al. 2020). The traditional flat-top beam generation method is beam shaping technology. It mainly uses the principle of geometric optics [for example: aspheric lens method (Frieden 1965) and birefringent lens group method (Dickey and Holswade 2001)] or physical optics [for example: micro lens array method (Buettner and Zeitner 2002), diffractive optical element method (Dickey and Holswade 2001) and liquid crystal spatial light modulator shaping method (Yu 2012)] to achieve. However, this method not only introduces significant loss, but also needs to continuously improve the calculation of the phase distribution to reduce the unevenness of the flat-top mode field (Dirk et al. 2019).

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One desirable way to avoid the above defects is to design a special fiber in which transmitted 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 (Haynes et al. 2006). Fibers with square cores have both great bending tolerance (Chow et al. 2015) and high optical power delivery capability (Peng et al. 2011). 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 ($A_{\text{eff}}$) of the flat-top light field is too small. The side length of the resulted square spot is only 2–3 μm (Zhang et al. 2013). In high-power laser systems, in order to reduce the adverse effects of nonlinear effects, it is necessary to reduce the light power density (Saitoh et al. 2010). Therefore, the flat-top beam with a large $A_{\text{eff}}$ has high application value, as larger $A_{\text{eff}}$ can effectively reduce the light power density (Wang et al. 2009).

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 (Wadsworth et al. 2004). Lu et al. (2006) introduced the flat-top mode to PCF for the first time. 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 $A_{\text{eff}}$, which has less loss than traditional complex beam shaping systems. The main research method is the finite element method. COMSOL Multiphysics is the tool we used. All numerical simulations and theoretical calculations were done with a perfectly matched layer.

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 (Kawsar et al. 2016). The study uses the full vector finite element method for numerical simulation. The refractive index of silica is affected by wavelength. Use Sellmeier formula to solve:

$$n_{\text{silica}}^2(\lambda) = 1 + \sum_{j=1}^{m} \frac{B_j \lambda^2}{\lambda^2 - \lambda_j^2}$$

where $\lambda_j$ is the jth resonant wavelength and $B_j$ is the intensity of the jth resonant wavelength. The first three items are usually used, and the parameters are shown in Table 1.

The confinement loss (CL) is an essential parameter that affects the quality of signal transmission in optical fiber transmission, which is caused by the overflow of the optical
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The confinement loss can be calculated from the imaginary part of the effective modal index (Saitoh and Koshiba 2003). It is given by formula (Kaneshima et al. 2006):

\[ CL = \frac{20}{\ln(10)} \cdot \frac{2\pi}{\lambda} \cdot \text{Im}(n_{\text{eff}}) \]  

Table 1: The parameter of Sellmeier

| B_1 | B_2 | B_3 |
|-----|-----|-----|
| 0.6961663 | 0.4079426 | 0.8974794 |
| \lambda_1 = 0.0684043 | \lambda_2 = 0.1162414 | \lambda_3 = 9.896161 |

In addition, a unique shape, like a playground running track, is thought to be better for flat-top beam generation. As shown in Fig. 1, circle, rectangle, and the racetrack shape with arc angle \( \theta \) greater (Fig. 1c) and less (Fig. 1d) than 90° are selected for comparison. Obviously, the mode profile of Fig. 1d is with the less unevenness. Next, the arc angle \( \theta \) is studied to determine the optimal racetrack shape as shown in Fig. 2. The mode profile under the \( \theta \) equal to 60° is with the less unevenness. For the size, the length of the hole \( L_h (L_h = 2L) \) as shown in Fig. 3) can determine the entire hole. According to Fig. 3, the larger the \( L_h \), the larger the \( A_{\text{eff}} \), and the smaller the CL. However, considering that the

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**Table 1** The parameter of Sellmeier

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|---------|---------|---------|
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**Fig. 1** The beam profiles in the x axis for the holes a circle shape, b rectangle shape, c and d racetrack shape with arc angle greater and less than 90°, respectively
The mode field is not uniform enough with too large $L_h$, 9.6 μm is finally selected. The basic structure of the unique hole of racetrack shape is a circle with a radius of 8.32 μm. Taking two parallel chords 4.8 μm 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, as shown in Fig. 4. And the arc angle of the two arcs is 60°.

![Fig. 2](image1)  The mode fields when the $\theta$ of the hole is a 75°, b 60°, c 45°

![Fig. 3](image2)  The relationship between $A_{eff}$, CL and air hole $L_h$

![Fig. 4](image3)  The unique shape of the air hole

mode field is not uniform enough with too large $L_h$, 9.6 μm is finally selected. The basic structure of the unique hole of racetrack shape is a circle with a radius of 8.32 μm. Taking two parallel chords 4.8 μm 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, as shown in Fig. 4. And the arc angle of the two arcs is 60°.
For the arrangement of air holes, the general optical fiber adopts a dense arrangement of air holes to form a cladding (Birks et al. 1997). Compared with the traditional dense air hole arrangement, the layered arrangement can reduce the CL with a simple structure and simple fabrication process (Song et al. 2018; Xian et al. 2008). 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 $5 \times 10^{-4}$, it can be considered that a flat-top mode field is generated in the fiber (Zhang et al. 2013; Chen 2007). 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. 5.

Next, the density of the air hole arrangement, i.e. the duty cycle, is studied. For symmetry, it is reasonable to consider only one edge. The proportion of the sum hole thickness to hole distance between the two neighboring air holes is the duty cycle, which is selected according to the simulation results shown in the Fig. 6. And the 82.7% is chosen. For the outermost air holes, the distance between holes is 10.5 μm, the thickness of the wall between neighboring holes is 0.96 μm, and the distance between hole layers is 26 μm. There are three layers of air holes here. Each layer is 0.7 times smaller than the outer layer. In addition, the relationships between the effective mode area, CL and the radius of the cladding are investigated, as results shown in Fig. 7. As the radius increases, the effective mode area increases. The CL presents a rough periodic fluctuation. Taking into account the evenness of the light field, the cladding radius of 124 μm is chosen.

### 2.2 Design of the core

The shape of fiber core affects the mode profile, in which the conventional round core support Gaussian beam (Lu et al. 2006; Blau and Dan 2019). Using rectangular dielectric waveguides in laser can output flat-top light (Kang et al. 2009), inspired by this, we also

![Fig. 5](image)

**Fig. 5**  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 a
tried to use square core. The doped lattices in this design use this shape. A layer of densely arranged oval holes surrounding the silica can be used as the core to demonstrate high birefringence (Chau 2014). Similarly, doped lattices are used to form the core. As the dark gray part shown in Fig. 6b, the single layer doped lattice is arranged in a square, like a fence. The enclosed silica 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 lengths of the square cores were tested as 100 μm, 70 μm, 50 μm and 40 μm, respectively. A square core that is too large will not be
able to gather the beam, as shown in Fig. 8a, b. When the value is 70 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, CL and the side length of the square core has also been studied. As Fig. 9 shows, the effective mode area increases with the increase of the side length. When the CL 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.

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 (Kang et al. 2009). As shown in Fig. 10, this means introducing a low refractive index region inside the core, of where the $n$ is greater than the $n$ of the cladding (Lu et al. 2006). Therefore, the silica inside the core is used as the low refractive index region. Obviously, the $n$ of this area will be greater than that of the

![Fig. 8](image)

Fig. 8 The output mode fields when the side length of the doped layer is a 100 μm, b 70 μm, c 50 μm, d 40 μm
Fig. 9 The relationship between the $A_{\text{eff}}$, CL and the length of the doped area.

Fig. 10 Schematic and refractive index profile of the fiber with square core for flat-top mode generation. $R_{\text{cor}}$ is the radius of the core’s inner part, $R_h$ is the radius of the core’s outer layer.
cladding with many air holes (Chau 2014). 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.

The doping medium is germanium dioxide (GeO$_2$), which can affect the field distribution of PCF, resulting in new characteristics of mode (Zhang et al. 2012). Doping in the lattice region has a great influence on the mode field characteristics of the optical fiber (Schreiber et al. 2005). In addition, the CL and bending loss in this type of doped fiber will be relatively low (Huseyin and Shyqyri 2011). Therefore, we adopted doped GeO$_2$ in the lattice layer outside the core to form a fence with a high refractive index.

Then, in the core, the refractive index of the outer ring is determined, so that obtains doping concentration. The $n$ difference between the outer ring and the inner ring should not be too large in the core. Therefore, 1.4506, 1.4504, and 1.4502 are selected for preliminary experiments. Figure 11b represents the power flow distribution shape of the central axis section when the $n_{\text{eff}}$ of the doped ($n_{\text{doped}}$) 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 $n_{\text{doped}}$ to 1.4506, the power flow distribution becomes a concave shape in the center. This is mainly because the $n_{\text{doped}}$ 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 $n_{\text{doped}}$ set as 1.4502, the power flow distribution becomes a convex shape in the middle. This is mainly due to the low $n_{\text{eff}}$ of the

![Figure 11](image_url)

**Fig. 11** The power flow of the central axis of the output mode field: a at the $n_{\text{doped}}=1.4506$; b at the $n_{\text{doped}}=1.4504$; c at the $n_{\text{doped}}=1.4502$
outer core and the lack of good outward diffusion of the mode field, which results in higher power in the inner core (Zhang et al. 2013).

A finer calculation for the effect of the $n_{\text{eff}}$ 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:

$$
\Delta = \left[ \frac{(P_{\text{max}} - P_{\text{min}})}{P_{\text{max}}} \right] \times 100\% \tag{3}
$$

where $P_{\text{max}}$ represents the maximum power, $P_{\text{min}}$ is its minimum value. The relationship between $\Delta$ and $n$ of the doped layer is shown in Fig. 12. The $\Delta$ has the minimum value at 1.45046. To meet the requirement that the $n_{\text{doped}}$ lattice is 1.45046, the initial value of the mole percentage of doped GeO$_2$ should be set to 4.25% (Wang et al. 2009; Huseyin and Shyqyri 2011). Also, as the refractive index of the doped region increases, the effective area increases.

However, the refractive index profile still needs to be further optimized. As shown in Fig. 13a, when the $n_{\text{doped}}$ 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...
The diagonal direction of the light field presents a convex shape, as shown in Fig. 13a. 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. 14, 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, which grows linearly from 1.45037 for the middle doped holes to 1.45057 for the edge doped holes. The average value is 1.45046. The improved mode field distribution is shown in Fig. 13b.

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 $5.5 \times 10^{-5}$ to $7.2 \times 10^{-5}$. The optimized result shown in Fig. 13c has been obtained.

3 Results

All the parameters of the optical fiber are designed. Next, the transfer characteristics of this flat-top PCF are calculated and studied.

3.1 Bending loss of fiber

The calculations of bending loss are carried out using FEM with PML boundary conditions (Tsuji and Koshiha 2004). The bending fiber is replaced by a straight fiber with an equivalent refractive index distribution (Olszewski et al. 2007; Martynkien et al. 2007):

$$n(x, y) = n_0(x, y) \exp \left( \frac{p}{R_b} \right)$$

where $p = x$ or $y$, depending on the bending direction, and $R_b$ stands for the bend radius. The bending direction is set to the positive x-axis direction.

The bending loss, $L_B$, is defined as

$$L_B = \frac{20}{\ln 10} \text{Im}[\beta] \approx 8.686 \text{Im}[\beta]$$

in decibels per meter, where Im stands for the imaginary part. And the $\beta$ is the propagation constant of the bent fiber (Tsuchida et al. 2005). Though calculation, the wavelength characteristic of the bending loss of the fiber is shown in Fig. 15. As the wavelength increases, the bending loss decreases overall. Like the bending loss of the other large mode area PCF (Martynkien et al. 2007), a secondary maximum appears during the descent. It is most probably caused by phase matching between the fundamental mode and one of the cladding modes.

3.2 Mode filed of fiber

This PCF is a three-mode fiber as shown in Fig. 16. The $LP_{11}$ and $LP_{21}$ modes have different degrees of homogenization distortion due to the influence of the doping layer. At a wavelength of 1550 nm, its output light field is shown in Figs. 17 and 18. 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 22,334.5 $\mu$m$^2$ and the lowest CL of $6.27 \times 10^{-11}$ 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 $\mu$m. The side length of the light spot in this article can reach 50 $\mu$m. 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. 19, its dispersion characteristic has also been studied, which are not much different from ordinary optical fibers and will not limit its application. Benefiting from the technological advancement of fiber fabrication, it is
Fig. 16  The LP_{11} mode (a and b) and LP_{21} mode (c and d) field

Fig. 17  a The mode field diagram, b the power flow of the central axis section of the output mode field
possible to fabricate the flat-top beam PCF with nowadays technique, such as the Sol–gel method (Kawsar et al. 2016).

4 Conclusions

A new 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 22,334.55 μm², 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 has many important industry applications, such as laser drilling, laser cleaning, imaging, and spectroscopy.

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Data availability Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

Declarations

Conflict of interest The authors declare no conflicts of interests.

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