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Simulation on the Optical Field Characteristics of Grating Inscription in a Hybrid Microstructured Optical Fiber

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Abstract

A method that utilizes a fluid-filled elliptical hole configuration to improve the efficiency and quality of grating inscription in a microstructured optical fiber was proposed and analyzed. The quantitative influence of inscription beam, elliptical size, fiber parameter, and fluid index on the grating inscription was analyzed. In addition, the feasibility of utilizing a symmetrical elliptical hole configuration and a rotating inscription technique to modify the inscription energy distribution near the core region during inscription was also discussed. Simulation results show that the optimized hybrid microstructured optical fiber configuration could achieve three times of the inscription efficiency than that of a single-mode fiber.

Keywords: Hybrid Microstructured Optical fiber; grating inscription; elliptical hole; fluid filling

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1. Introduction

Fiber optic devices, especially fiber gratings, play an important role in optical communication and optical sensing applications [6,8,15]. Compared with single mode fiber gratings, microstructured optical fiber grating (MOFG) is one of the latest generation of gratings [1,8,14], which has many advantages, such as wide spectrum reflection peak, large dynamic tuning range, and easy design and fabrication [1].

However, the structure of periodic micro-holes on MOF cladding makes strong scattering and uneven energy distribution during the inscription process, thereby affecting the inscription efficiency and quality to a certain degree [5,11]. Several methods have been proposed for improving this phenomenon, such as filling the micro-holes with index-matched liquid [13], rotating the MOFG angle during the inscription process [9] and decreasing the diameter of micro-holes [10]. Liquid-filled MOF could reduce the scattering from air–glass interfaces concerning the grating as well as enhance the inscription efficiency. The specific influence was analyzed in the reference [12,13]. The index modulation of the grating inscription in MOF was more than doubled for a fixed influence. The role of rotational alignment during grating inscription was examined by the measurement of core luminescence. It seems that the control of the rotational alignment of the fiber was critical for reproducible grating writing [9]. The intensity of the inscribing laser beam was non-uniformly distributed over the core region during the grating inscription on the MOF structure. Tigran Baghdasaryan simulated the non-uniformity of the index modification and its influence on the grating reflection spectrum. For almost all angular orientations of the PCFs relative to the inscription beam, due to the limited overlap of guided mode and lateral refractive index modulation distribution, the non-uniform nature of the index change could seriously affect the reflectivity of the grating. Simultaneously, the influence of MOF tapering was also evaluated, and the transverse propagation of femtosecond pulse laser light through the microholes of MOF was also studied. At the same time, the influence of the PCF orientation angle, the air hole pitch and air hole radius on the energy reaching the core were also analyzed. It was found that the transverse coupling efficiency can benefit from a dedicated design of fiber cladding structure and the grating inscription orientation [2,4,7]. It should be noted that many incidental

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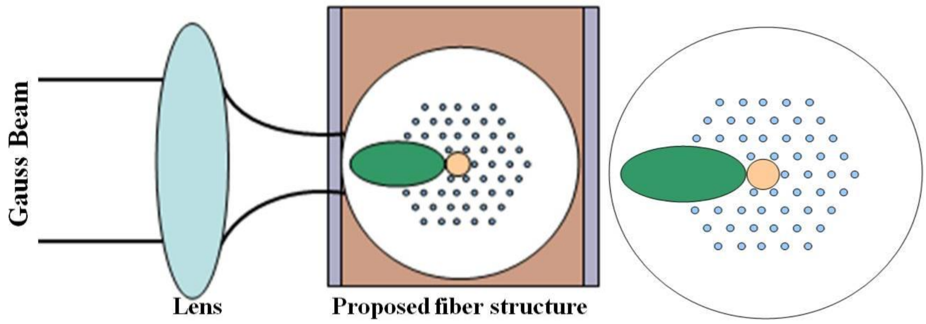
drawbacks, such as the time-consuming filling speed, limited improvement effect, special writing angle and dependence of the fiber parameters limit their potential value in practical applications.

To solve the problem of uneven energy distribution and high beam scattering during the grating inscription process, a new hybrid microstructured optical fiber configuration was described in this study. The obvious characteristic of this configuration was replacing the partial periodic micro-holes with a large elliptical hole. Then, the laser beam will transmit into the core region through the elliptical hole during the grating inscription. Thus, the large proportion of energy scattering in conventional MOFG inscription will be avoided. Through filling this elliptical hole with fluid of special high refractive index, the laser beam could be focused into the core as the converging lens effects could occur here [3]. By utilizing the described optical fiber structure and the new recording method, the inscription efficiency and mode distribution will be improved. Compared with the inscription characteristic of a single mode fiber and the MOF in the same condition, an enhancement of 2.4 times and 3.4 times of grating inscription was confirmed in our simulation. It is also possible to achieve higher inscription efficiency by reducing the core diameter. Moreover, to solve the problem of uneven energy distribution in single-angle inscription, the rotating inscription method in two directions, three directions and bilateral directions were also described. Thus, the symmetry of energy distribution was also ensured in this method, which could be beneficial for decreasing the degree of uneven refractive index distribution and corresponding birefringence. Moreover, the possibility of decreasing the difference of inscription energy distribution between different cores was also analyzed for multi-core MOF configurations.

2. Simulation method

The FDTD and FEM software were utilized here for simulation. The microstructured fiber with model ESM-12-01 and index-mated fluid of Cargille Laboratories were referenced. In order to simplify the simulation, we do not consider the effects of external scattering, refractive index matching of the fluid-absorbed beam and the doping core region. On this basis, the specific influences of the elliptical hole structure and filled-fluid on MOFG inscription energy distribution and efficiency were studied.



(a) (b)

Figure 1. Proposed MOF configuration and the inscription method. (a) Cross section of the described MOF (b)Possible grating inscription method by Gaussian laser beam

Figure 1(a) shows the cross section of the designed single-elliptical-hole MOF structure with an obvious characteristic of replacing the partial periodic micro-holes wit**h** a large elliptical hole. This minimizes the scattering degree of the laser beam and proves that it is possible to increase the inscription efficiency. While filling the elliptical hole with a fluid of high indices, the beam could be focused into the core region through this micro-lens structure, thus this elliptical hole would play the role of a micro-lens. Depending on the type and specific refractive index of the fill fluid, the focus of the micro-lens could be shifted from one location to another to adjust the focus of the core area. Filling an elliptical core with a special index of refraction can adjust the focus to the core area and accordingly improve the recording energy distribution and recording efficiency. At the same time, we have retained a large percentage of micro-holes and the design flexibility of this MOF.

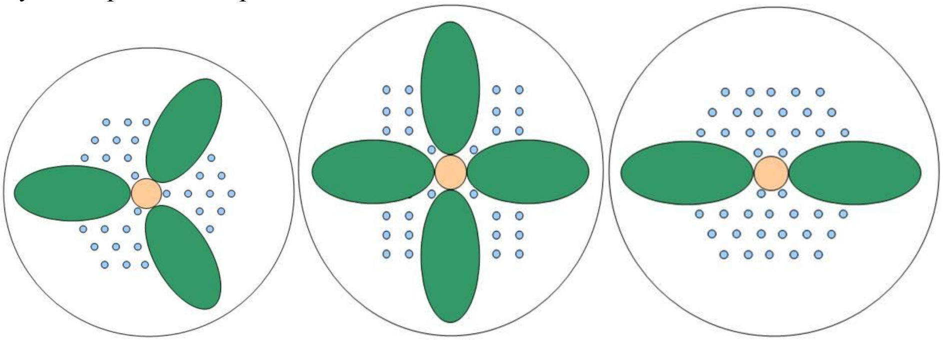
In this paper, the core parameter *R* of the described silica MOF parameter was set as 6μm, 4μm and 2μm respectively. The major and minor radius of the elliptical hole were set as 25μm and 12μm. The refractive index of the silica at a wavelength of 1550nm was set as 1.444024. The parameters of the Gaussian laser beam can be referred from reference [16], whose energy distribution *I(r, z)* could be described as

$$I(r,z)=\frac{|E(r,z)|^2}{2\eta}=I_0(\frac{\omega_0}{\omega(z)})^2\exp(\frac{-2r^2}{\omega^2(z)}) \quad (1)$$

Here, the *E* represents the electric distribution of the Gaussian beam, ω(z) represents the width of the beam waist along the *Z* direction, and $\omega_0=\omega(0)$ represents the width of the beam waist when z equals to zero. The full width at half maximum (FWHM) and the distance to fiber core were set as 40μm and 60μm respectively.

In addition, although the recording efficiency can be improved, the single-elliptical hole MOF structure also has a problem of uneven energy distribution because the energy distribution is greatly affected by the filling fluid index.

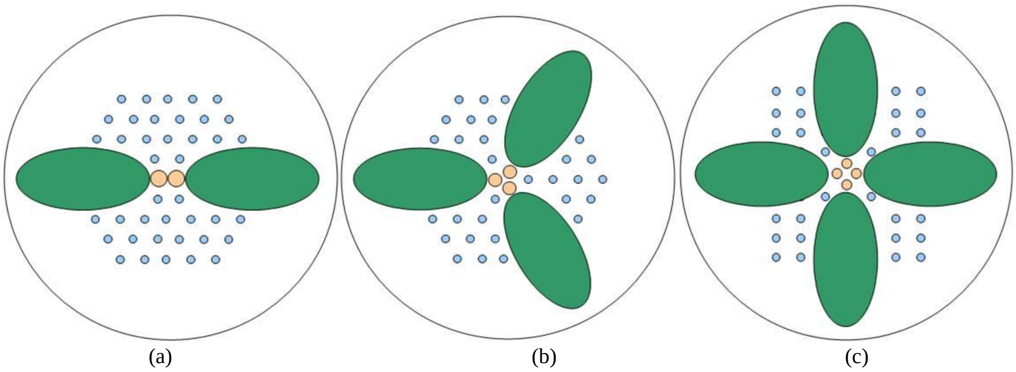
To improve the energy distribution of the core region, the configurations of two/three/four elliptical-holes were also described afterwards. As depicted in Fig.2a and Fig.2b, more holes were introduced to replace the periodic micro-holes. Thus, assisted with the rotating inscription method, the beam energy could be transmitted into the core region cyclically from different elliptical holes. Correspondingly, the phenomenon of uneven energy distribution in a single-hole configuration could be improved to a greater degree, and the degree of birefringence was improved too. Simultaneously, the merit of high inscription efficiency of the previous elliptical-hole fiber structure was also retained.



(a) (b) (c)

Figure 2. Proposed multi-elliptical-holes MOF configuration. (a) MOF of three elliptical-holes (b) MOF of four elliptical-holes (c) MOF of dual-elliptical-holes

For the situation of inscription cyclically, the final energy distribution of the core region was equivalent to a linear plus of energy distribution from each inscription angle. Besides, the effect of birefringence has some special value sometimes. Increasing the uneven energy distributions between different axis could be beneficial to the enhancement of the birefringence effect. To increase the uneven energy distribution between the X axis and Y axis, a dual-elliptical-hole configuration was also described in Fig.2(c) and simulated subsequently. The MOF parameters of Fig.2 were similar to that of Fig.1. Although for conventional multi-core MOF, the inscription energy distribution and mode characteristics between different cores were different at some degree due to the asymmetry property of different cores during the inscription process. Three multi-core MOF configurations, including the dual-core, three-core and four-core structures were introduced, which are depicted in Fig.3. Here, the different cores and elliptical holes were assumed to be distributed symmetrically around the cladding. As the property of fiber mode energy distribution was not involved in this study, the parameters of micro-hole diameter and distribution were not optimized.



(a) (b) (c)

Figure 3. Proposed multi-core MOF configuration. (a) MOF of dual cores (b) MOF of three cores (c) MOF of four cores

3. Simulation results of single-elliptical hole structure MOF and analysis

Firstly, the effects of refractive index n of fluid on inscription energy distribution for a single-elliptical-hole MOF structure were simulated. As can be seen from Fig.4(a), when the index n was set as 1.444024RIU (the index of silica material), the inscription effect of this fluid-filled hole structure was the same as that of elliptical-hole-free MOF. The central part of the Gaussian beam was not influenced significantly after the laser beam was transmitted through the elliptical hole region. On the contrary, the beams of the left and right sides were scattered greatly at this step due to the scattering effect of the micro-holes.

By filling the elliptical hole with a higher refractive index than silica, such as 1.55RIU, the converging lens effects would play an important role, as shown in Fig.4(b). The focal point was at the right of the core region in this situation. It seems that the focus length was large due to the relatively low index contrast of fluid and silica. Accordingly, increasing the fluid index could shorten the focal length to the core region. In Fig.4(c), it seems the focal point was moved to the core region when the index of filled fluid was set as 1.58RIU. In this situation, the energy of the Gaussian beam was highly constrained at the core region, which will contribute to the enhancement of the grating inscription efficiency. According to the forward calculation, the maximum peak energy intensity of the core region was increased from 0.06 to 0.076 when the n was increased from 1.55 to 1.58. Here, the units of energy density are arbitrary. If the fluid index was set as 1.70 RIU, the corresponding focal length will be further reduced and beyond the core area. As depicted in Fig.4(d), the maximum peak energy intensity will be decreased a little. But, the merit of this structure was that the energy distribution was relatively uniform and beneficial to the improvement of energy uniformity.

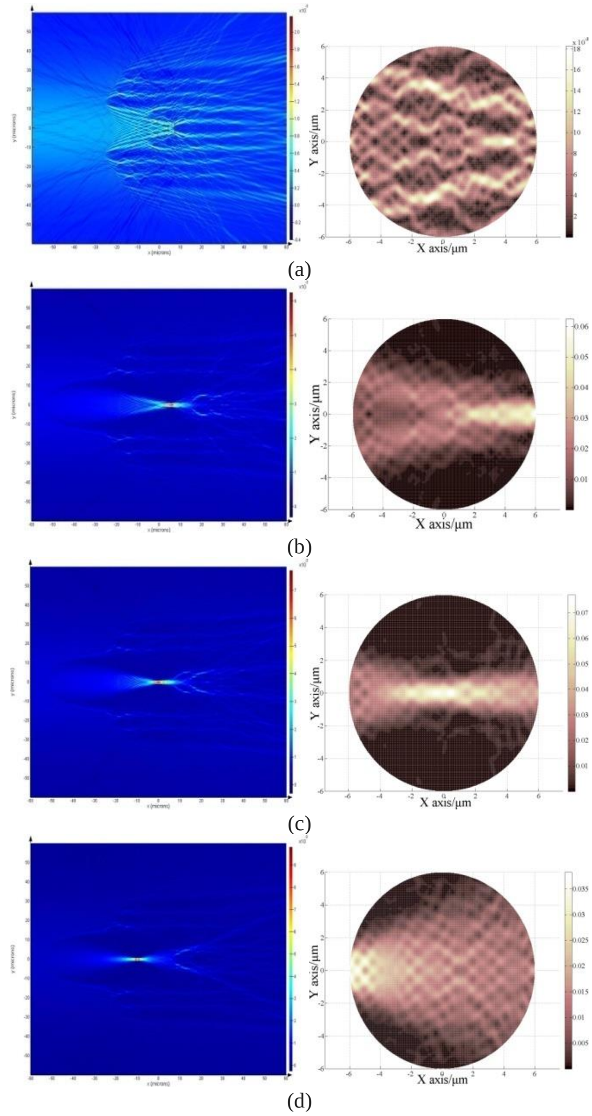


Figure 4. Energy distribution in fluid-filled MOF structures. (a)*n* equal to1.444024 (b)*n* equal to1.55 (c)*n* equal to1.58 (d)*n* equal to1.70

On the basis of the above analysis, the total energy of the core region was calculated by integrating the overall distributed energy. The utilized formula was as follows

$$P_{total} = \iint_{core} P_{xy} ds = \sum_{x}\sum_{y} P_{xy} dxdy \qquad (2)$$

Fig.5 depicts the improvement effect of liquid on the total inscription energy at the core region. It seems that the specific effect was strictly related to the refractive index of filled fluid. The corresponding total inscription energy of the core region was 5.73e-13AU (arbitrary unit) when n equals to 1.444024 and the core radius equals to 6μm. Such value reaches 9.7e-12AU when n equals 1.55RIU. The maximum energy intensity was 1.03e-12AU at this situation. It shows that the grating inscription was enhanced due to the focusing effects of the fluid-filled elliptical hole. When the refractive index of the fluid was further increased, the total inscription energy began to decrease. When the refractive index was higher than 1.8RIU, the corresponding total inscription energy was lower than 6.76e-13 AU. It seems that the grating inscription effects were not good in this situation. When the core radius was less than 6μm, the corresponding total energy of core region decreased. But the relationship of refractive index of filled-fluid and the grating inscription efficiency was similar.

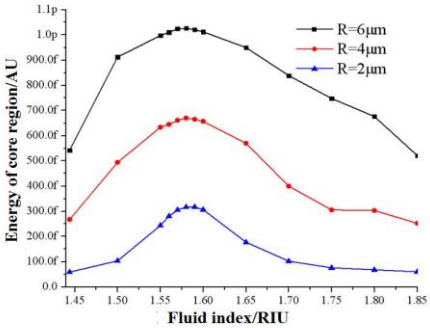


Figure 5. Relationship of refractive index of filled-fluid and the total energy of core region

Furthermore, the inscription effects of the conventional periodic hole MOF and single mode fiber were also analyzed and compared with the upper calculation. The simulated data shows that the total energy of the core region in the periodic hole MOF was 4.2208e-13, 1.8859e-13, 4.7230e-14 when the core radius was 6μm, 4μm and 2μm respectively. The corresponding data was 4.2208e-13, 1.8859e-13, 4.7230e-14 respectively in single mode fiber. Accordingly, compared with the inscription characteristic of a single mode fiber and MOF, an enhancement of 2.4 times and 3.4 times of grating inscription was confirmed by utilizing the proposed single-elliptical hole MOF configuration and inscription method. By reducing the core radius, the enhancement time of inscription could have a further increase. Thus, the effect of the proposed single-elliptical hole MOF configuration and inscription method on increasing the total energy of core region and grating inscription efficiency was proven in our simulation.

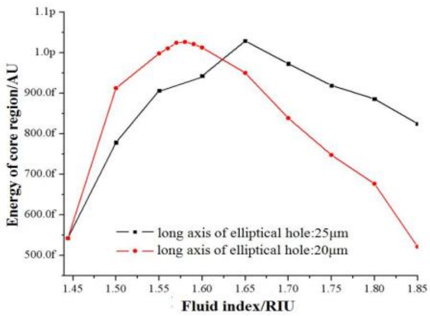
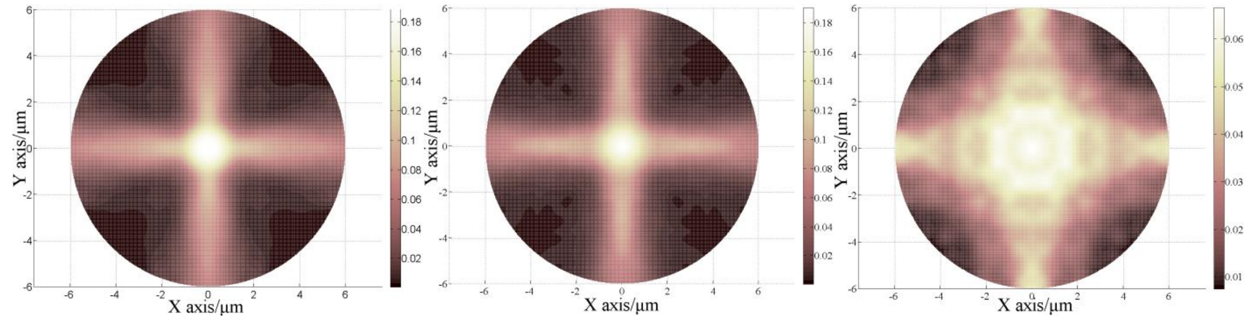


Figure 6. Relationship of elliptical hole parameter and the total energy of core region

In addition, the effect of elliptical hole parameter on the grating inscription was also analyzed. When the parameter of the long axis radius was decreased from 25μm to 20μm, the corresponding total energy of the core region was described in Fig.6. It seems the optimized refractive index was moved to 1.70RIU when the parameter of the long axis radius equals 20μm. Therefore, the parameters of the fluid-filled elliptical aperture are tailored so that they correspond to the focal length changes due to the converging lens effect. It was better to fill the hole with proper fluid according to the specific situation.

4. Simulation result of multi-elliptical hole MOF and analysis

In order to improve the situation of uneven energy distribution and induced birefringence in the single-elliptical hole MOF configuration, two kinds of multi-elliptical hole MOFs were described, including the symmetrical four elliptical hole structure and three elliptical hole structure. The birefringence was expected to be improved by utilizing the merit of the symmetrical hole structure and the rotating inscription method. For four elliptical hole structure, Fig.7 describes the corresponding energy distribution of the core region in this rotating inscription method. It seems that a strictly symmetrical energy distribution appeared in the core region as the unilateral inscription method was symmetrical. This energy distribution status could allow for the best symmetry in the core area's inscription intensity and thus eliminate the degree of birefringence caused by unilateral inscription. Moreover, it shows that the energy distribution was different when the filled fluid was of different refractive indices even though they were still symmetrical. Such a difference could be utilized for designing special grating structures. For example, when the refractive index n was near 1.58RIU and 1.60RIU, the energy distribution of the central core region was relatively high and uniform, while that of the peripheral region was smaller and non-uniform. Here, the core radius was 6μm. Such an energy distribution characteristic could be useful for the thin-core MOF grating design. When the n equals 1.65RIU, the energy distribution of the whole core region was relatively uniform, which could benefit large core fiber grating. Moreover, according to the upper analysis of the single elliptical hole structure, both kinds of MOF had a higher inscription efficiency.



(a) (b) (c)

Figure 7. Inscription energy distribution of four elliptical hole structure. (a)*n* equals to 1.58 (b)*n* equal to 1.60 (c)*n* equals to1.65

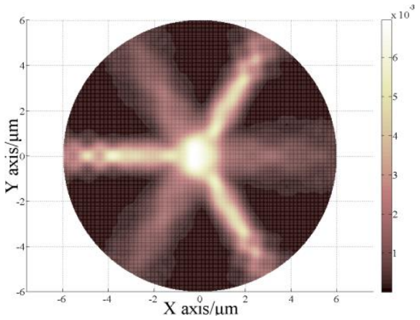
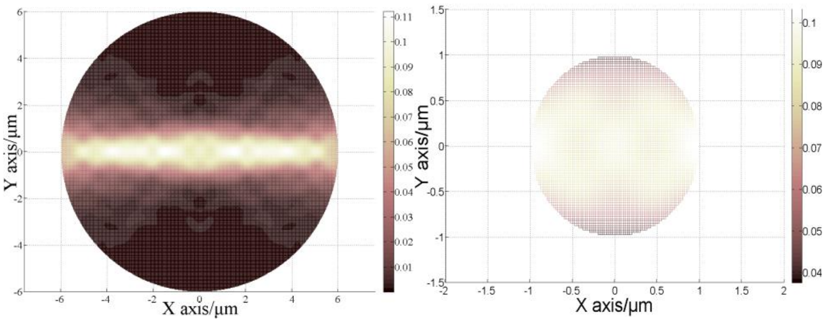


Figure 8. Inscription energy distribution of three elliptical hole MOF structure (*n* equals to 1.58)

For three elliptical hole structure, the corresponding inscription methods and effects could be analyzed according to the upper simulation of the four-elliptical hole structure. Fig.7 depicts the inscription energy distribution of the three-elliptical hole structure. Compared with Fig.7 and Fig.8, we could see that the higher the inscription angle, the better uniformity of energy distribution of the core region. Furthermore, as the three-elliptical hole structure was also strictly symmetrical, the improvement effect on birefringence of both types should be equivalent.



(a) (b)

Figure 9. Inscription energy distribution of dual elliptical hole MOF structure. (a)*n* equals to 1.60, *R* equals to 6μm (b)*n* equal to 1.60, *R* equals to 1μm

For the enhancement of the birefringence effect on the inscription process, a dual-elliptical hole MOF was also proposed, which was demonstrated in Fig.2(c). Fig.9(a) depicts the inscription energy distribution of the dual elliptical hole structure. Here, n equals 1.60 and R equals 6μm. As the inscription was only symmetric in the Y axis but not the X axis, the energy distribution was not symmetrical at the vertical and horizontal directions, and the corresponding inscription intensity and the difference of TE and TM modes were influenced. The effect of such fiber grating inscription should be similar to that of Panda fiber, which has a good birefringence polarization maintaining property. In addition, the symmetry of energy intensity in the core region was also related with the core radius. Fig.9(b) also describes the inscription energy distribution effect of the thin-core dual-elliptical hole MOF. Here, the R equals 1μm. It can be seen that an increase of core radius could contribute to the enhancement of birefringence. Introducing the elliptical core structure, the degree of birefringence could be further enhanced. While selecting the proper core parameters and refractive index of filled fluid, such asymmetry characteristic between the X-axis and Y-axis could be compensated to a large extent or completely, and the low birefringence or zero birefringence characteristic could be feasible in such a configuration. Therefore, the dual-elliptical hole MOF structure also had good control ability on inscription energy distribution and optical mode.

Besides, for the conventional multi-core fiber, there exists a large difference between the different cores as the symmetry of inscription energy distributed could not be assured. To solve this problem, several multi-core MOF configurations were also demonstrated here. The energy distribution characteristic was described in Fig.10. It seems that the energy distribution symmetry of different cores was retained for the proposed multi-core structure, which will be good for narrowing the property difference between multiple cores. Taking the four-core MOF of Fig.10(c) for example, when selecting the proper refractive index of the filled fluid, the birefringence polarization maintaining property could be feasible in each core. The birefringence characteristic of left/right cores and upper/lower cores were different. This unique structure may have special value in fiber sensing and communication applications.

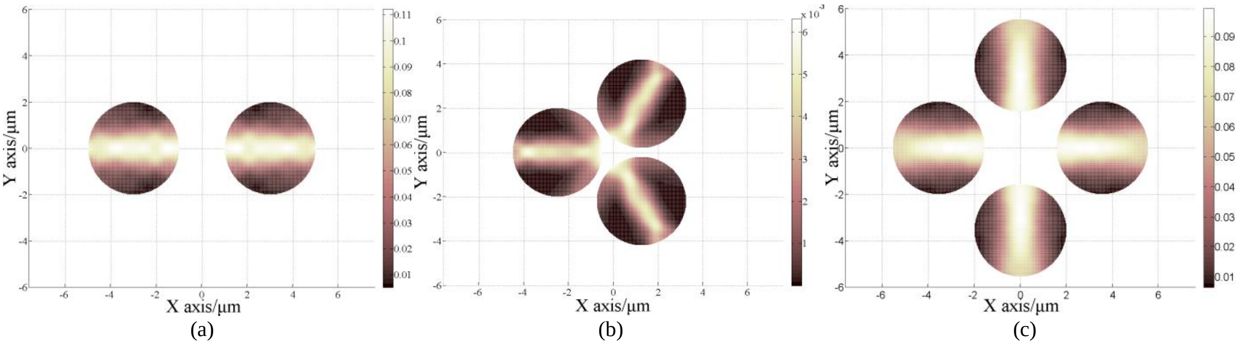


Figure 10. Inscription energy distribution of dual-core MOF structure (*n* equal to 1.6RIU, *R* equals to 2μm)
(a) Dual-core configuration (b) Three-core configuration (c) Four-core configuration

By decreasing the radius of each core simultaneously, such a difference could be reduced gradually and the corresponding birefringence of each core could be reduced too. It was also optimistic to attain a low birefringence of zero-birefringence characteristic in the upper configurations. For the situation of dual-core MOF and three-core MOF, the analysis method was similar.

In short, we think such a proposed fiber configuration and inscription method have very flexible control abilities on inscription energy distribution and birefringence. For example, the inscription efficiency could be enhanced by utilizing the converging lens effect of the fluid-filled micro-holes, and the requirement of laser beam power and intensity could be decreased correspondingly. T the uniformity and the birefringence could also be tailored by adjusting the symmetry of the MOF structure.

5. **Conclusions**

To solve the problems of uneven energy distribution and high scattering during the grating inscription process, a new MOF structure and rotating inscription method were demonstrated in this study. This new structure could be helpful for reducing the scattering loss. While filling the elliptical hole with fluid of specific index, a converging lens effect can further enhance grating inscription efficiency. Compared with the inscription effect of a single mode fiber and conventional MOF structure, a respectively 2.4 times and 3.4 times of inscription efficiency was demonstrated in our simulation. By decreasing the fiber core radius, the inscription efficiency could be further enhanced. Moreover, a rotating inscription method from dual-directions, three-directions and four-directions were also proposed for tailoring the energy distribution of the core region and the corresponding birefringence. The effects of such a rotating inscription on multi-core MOF structure were also analyzed. This paper can be a good reference for single-core/multi-core MOF grating inscription.

Acknowledgements

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