

Article

Design and Characteristics of Diamond-Assisted Ring-Core Fiber for Space Division Multiplexing

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Abstract: In this paper, a novel diamond-assisted ring-core fiber (DRF) is proposed. With the introduction of a low-refractive-index diamond-shaped region located in the center of the core, the proposed fiber effectively eliminates spatial degeneracy of the LP_{mn} mode groups and maintains a low level of birefringence. Under the fiber structure parameters proposed in this paper, the effective refractive index difference (Δn_{eff}) between the spatial modes supported by the fiber in the entire C-band is greater than 2.25×10^{-4} , and the Δn_{eff} between adjacent modes falls within the scope of $(2.11 \sim 9.41) \times 10^{-4}$. The degree of degenerate separation between the two polarization modes of all modes is very low, which is 2~3 orders of magnitude lower than that of the spatial mode. By discussing the mode characteristics of DRF and several other center-assisted ring-core fibers, the method that can be used to manipulate the spatial mode degenerate separation with structural symmetry is obtained, which can be applied to provide guidance for similar fiber designs. The proposed fiber structure is a promising candidate in space division multiplexing systems.

Keywords: few-mode fiber; degenerate mode; space division multiplexing; effective refractive index difference



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1. Introduction

The rapid development of various emerging information technologies has put forward higher requirements for the capacity of optical communication systems [1]. The capacity of the transmission system based on traditional single-mode fiber is close to the Shannon limit [2], and new technologies are urgently needed to expand the capacity. As a promising candidate for increasing the capacity of optical communication systems, space division multiplexing (SDM) technology has shown great potential. The introduction of the SDM system is expected to increase the transmission capacity by an order of magnitude [3], which is currently a hot research topic [4]. Few-mode fiber-based SDM systems use different modes as channels in a fiber core to transmit signals independently, and have been proven to overcome the capacity limitations of single-mode fiber transmission systems [5,6]. Conventional step-index few-mode fibers (FMFs) will inevitably cause inter-mode crosstalk while increasing the number of modes [7], which will greatly affect the quality of the transmitted signal. Multiple-input-multiple-output (MIMO) digital signal processing (DSP) is required in the receiver to compensate for inter-mode crosstalk [8]. However, the increase in the number of modes will increase the complexity of the system [9] and bring extra power consumption to the system. It has been shown that by designing a new FMF structure, the Δn_{eff} between adjacent modes can be greater than 10^{-4} [10,11]. This can greatly reduce the crosstalk between modes so as to simplify or even eliminate the MIMO DSP. To achieve this goal, researchers have made many efforts to optimize the structure of FMFs [12–14].

In a few-mode fiber-based SDM system, the number of multiplexing channels that the fiber can provide depends on the number of supported modes. Therefore, the design of special FMFs for SDM is mainly focused on increasing the number of transmission modes and maintaining a large mode interval [15–19]. However, there is a trade-off between the

number of higher-order modes and the Δn_{eff} [20]. For the linearly polarized mode (LP), the LP_{mn} mode has two spatially degenerate modes, denoted as LP_{mna} and LP_{mnb} . Obviously, if these two spatial modes can be fully utilized in multiplexing, the multiplexing potential of optical fibers can be further tapped on the basis of using the original scalar mode. In the conventional step-index circularly symmetric fiber structure, the effective refractive index (n_{eff}) of the two are the same, and the two spatial modes are in a degenerate state. By designing a new fiber structure to make the Δn_{eff} between two spatial modes greater than 10^{-4} , the spatial degeneracy can be eliminated. The crosstalk between modes is greatly reduced, and these modes can be utilized more easily in SDM systems. Based on the above design goals, several different few-mode fiber structures have been proposed, mainly including elliptical-core FMFs [18,21,22], elliptical-ring core FMFs [14,17,23], and panda-type FMFs [20,24,25]. An elliptical core fiber was proposed in [18], which can support three modes including the fundamental mode. The Δn_{eff} between LP_{11a} and LP_{11b} over the entire C-band can reach 9×10^{-4} . The authors of [17] introduce four air holes around the elliptical ring core, which can support 10 modes, including all spatial and polarization modes. The minimum Δn_{eff} between adjacent modes at 1550 nm is greater than 1.65×10^{-4} . A panda-type elliptical core fiber is proposed in [19], which can support 6 spatial modes and polarization modes, and the minimum spacing between modes in the C + L band is greater than 1.95×10^{-4} .

In this paper, a novel diamond-assisted ring-core fiber (DRF) structure is proposed, which can effectively separate the spatial degeneracy of the LP_{mn} mode groups while maintaining a low level of polarization separation with the introduction of a central low-index diamond region. The fiber supports nine modes over the entire C-band, and the Δn_{eff} between adjacent modes is in the range of $(2.11 \sim 9.41) \times 10^{-4}$. At the same time, the level of polarization separation is lower than 3.68×10^{-6} , which is 2~3 orders of magnitude lower than the separation degree of scalar mode and spatial mode.

2. Fiber Structure

The schematic cross-section and refractive index profile of the DRF proposed in this paper are shown in Figure 1 below. The cladding and core radius of the fiber are $R = 62.5 \mu\text{m}$ and $r = 12.5 \mu\text{m}$, respectively. The structural parameters of the center-assisted diamond are described by two mutually perpendicular diagonals in the x -axis and y -axis directions. The intersection of the two diagonals coincides with the center of the fiber core, and their lengths are $2a = 7 \mu\text{m}$ and $2b = 22 \mu\text{m}$, respectively. The refractive index of the core is $n_1 = 1.449$, and the refractive index of the cladding is the same with the center-assisted diamond region, which is $n_2 = 1.444$.

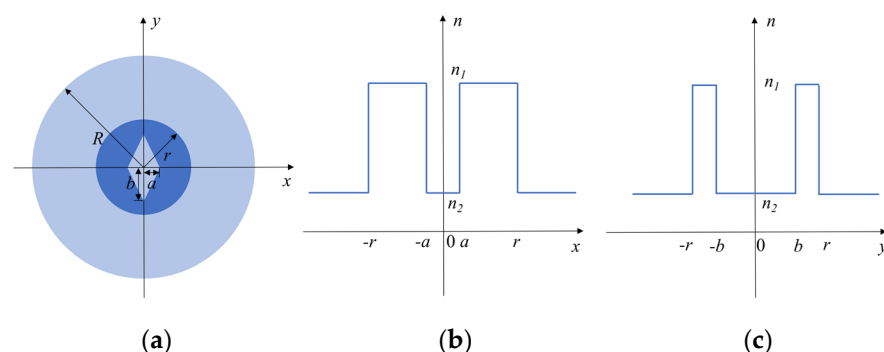


Figure 1. (a) The cross-section of diamond-assisted ring-core fiber (DRF); (b) refractive index distribution in x -axis direction; (c) refractive index distribution in y -axis direction.

3. Characteristic Analysis of DRF

3.1. Modal Properties of DRF

For conventional FMFs, the propagation constants of the two spatial modes of the LP_{mn} mode are the same due to the circular symmetry of the fiber structure. The two spa-

tial modes are considered to be degenerate. The DRF proposed in this paper breaks the circular symmetry of the conventional step-index fiber after introducing the center-assisted diamond-shaped region, which makes the n_{eff} values of the two spatial modes different, so as to separate the degenerate spatial modes. In this paper, the modal characteristics of the optical fiber are obtained by COMSOL simulation software. Figure 2 below shows the change of the n_{eff} and the Δn_{eff} between adjacent modes in the wavelength range of 1530 nm~1565 nm. For the convenience of distinction, the n_{eff} curves of the two spatial modes of the same mode group are represented by solid and dashed lines in the same color. DRF supports nine modes of transmission. For conventional step-index fibers, the n_{eff} curves of the two spatial modes of the LP_{mn} mode should be coincident. With the introduction of the central diamond, the n_{eff} curves of the two spatial modes are clearly differentiated into two groups, and the Δn_{eff} between adjacent modes is greater than 2×10^{-4} . The spacing between adjacent modes at 1550 nm is 2.21×10^{-4} , 5.1×10^{-4} , 5.37×10^{-4} , 3.77×10^{-4} , 9.21×10^{-4} , 2.28×10^{-4} , 2.56×10^{-4} , and 4.69×10^{-4} , respectively.

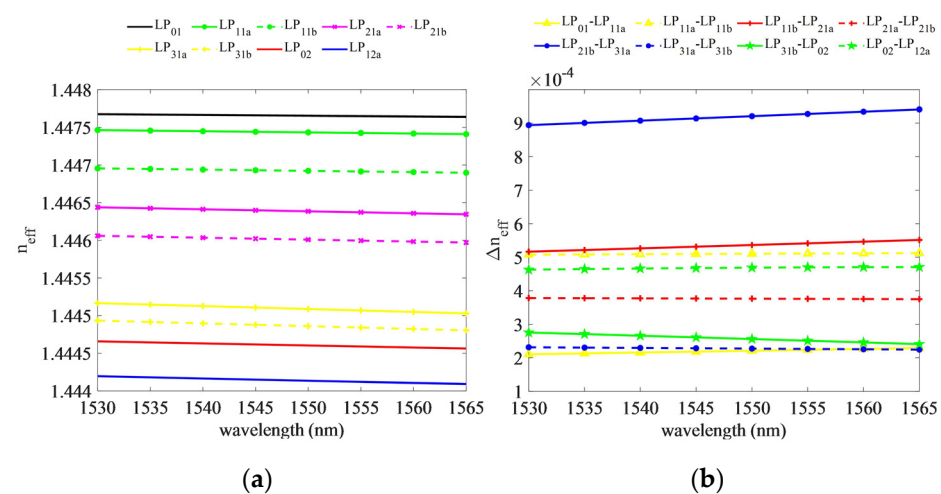


Figure 2. The calculated (a) effective refractive index (n_{eff}) and (b) effective refractive index difference (Δn_{eff}) of diamond-assisted ring-core fiber for different modes.

The normalized mode distribution of the DRF is shown in Figure 3. In the structural design of FMFs, breaking the circular symmetry is usually a common method to generate mode polarization separation [20,26–28]. That is to say, the degenerate separations of the spatial and polarization modes are simultaneous and the separation levels of both are in the same order of magnitude. However, in an SDM system that only uses mode division multiplexing, such mode characteristics can create additional difficulties for good multiplexing of signals. In this paper, several different wavelengths in the C-band are selected, and the polarization separation levels of the nine modes supported by the DRF at different wavelengths are calculated. The results are shown in Table 1. It can be seen that the polarization separation level of each mode at different wavelengths is lower than 3.68×10^{-6} , which is 2~3 orders of magnitude lower than the degree of degenerate separation of spatial modes. The DRF achieves degenerate separation of spatial modes while keeping the degree of polarization separation at a low level. Such mode characteristics can make better use of LP_{mn} mode groups in SDM systems without adding additional difficulty to multiplexing.

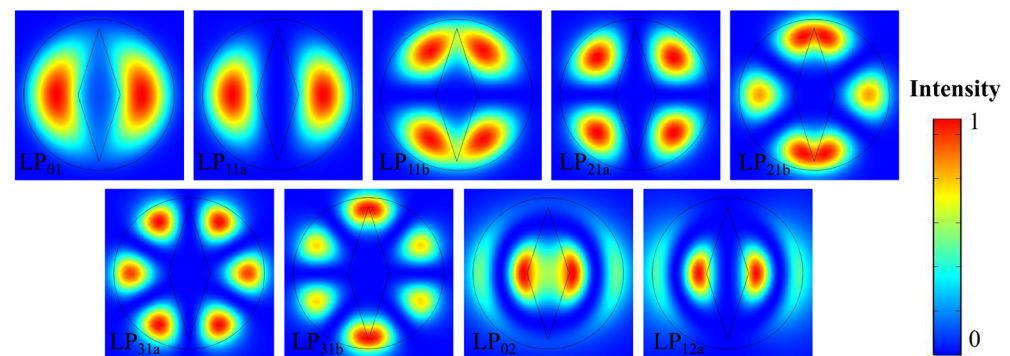


Figure 3. Normalized mode distribution of diamond-assisted ring-core fiber (color in this figure represents the intensity of the normalized mode distribution).

Table 1. The Δn_{eff} (10^{-6}) between polarization modes of individual modes at different wavelengths.

	LP ₀₁	LP _{11a}	LP _{11b}	LP _{21a}	LP _{21b}	LP _{31a}	LP _{31b}	LP ₀₂	LP _{12a}
1530 nm	2.48	2.94	0.39	1.47	0.42	1.19	1.01	3.01	3.68
1535 nm	2.49	2.96	0.37	1.48	0.43	1.19	1.01	2.99	3.61
1540 nm	2.50	2.97	0.37	1.49	0.43	1.20	1.02	2.97	3.53
1545 nm	2.51	2.99	0.37	1.49	0.44	1.20	1.02	2.94	3.45
1550 nm	2.51	3.01	0.36	1.49	0.45	1.21	1.02	2.92	3.36
1555 nm	2.53	3.02	0.35	1.50	0.45	1.21	1.02	2.89	3.27
1560 nm	2.53	3.04	0.35	1.51	0.46	1.21	1.02	2.87	3.17
1565 nm	2.54	3.05	0.34	1.51	0.46	1.21	1.02	2.84	3.06

3.2. Influence of Structural Parameters on Fiber Properties

The obvious mode characteristic of the DRF proposed in this paper is that it can effectively separate the two spatially degenerate modes in the LP_{mn} mode group, so that the Δn_{eff} is greater than 10^{-4} . The mode is characterized by the introduction of a diamond-shaped region of low refractive index in the core. Therefore, the structural parameters of the center-assisted diamond are the key parameters affecting the properties of DRF. This paper discusses the influence of the diagonal length of the diamond in the x -axis and y -axis directions on the fiber mode characteristics, as shown in Figure 4, below. For ease of presentation, here we take half the length of the diagonal, namely a and b .

Figure 4a,b present the effects of a on the n_{eff} and Δn_{eff} , respectively, in the range of (0.5–5) μm . The results show that when the value of a is relatively small, the n_{eff} values of the two spatial modes of the LP_{mn} mode group are similar, and the distance between them is less than 10^{-4} . As a increases, the n_{eff} curves of the two spatial modes are separated from each other, the spacing gradually increases, and the Δn_{eff} starts to be larger than 10^{-4} . However, the spacing between some adjacent modes becomes smaller as a grows, such as LP₀₁ and LP_{11a}. In addition, the order in which the modes appear varies with the change of a . The LP₀₂ mode first appears earlier than LP_{31a} and LP_{31b}. When a is greater than 2 μm , the order of the three modes becomes LP_{31a}, LP₀₂, LP_{31b}. As a continues to increase, the order of the final three modes is fixed as LP_{31a}, LP_{31b}, LP₀₂. Therefore, during the change of a , the Δn_{eff} between LP_{31b} and LP₀₂ gradually becomes smaller at first, and then gradually becomes larger after it is less than 10^{-4} . When a is greater than 4.2 μm , the LP_{12a} mode is cut off. Therefore, the selection of a should comprehensively consider the above changing trends. In this paper, the value of a is 3.5 μm .

Figure 4c,d present the effects of b on the n_{eff} and Δn_{eff} in the range of (6–12) μm , respectively. The influence of b on the fiber mode characteristics is similar to that of a . The increase in b helps the degenerate separation of spatial modes, but reduces the spacing between some adjacent modes. In this paper, the value of b is 11 μm .

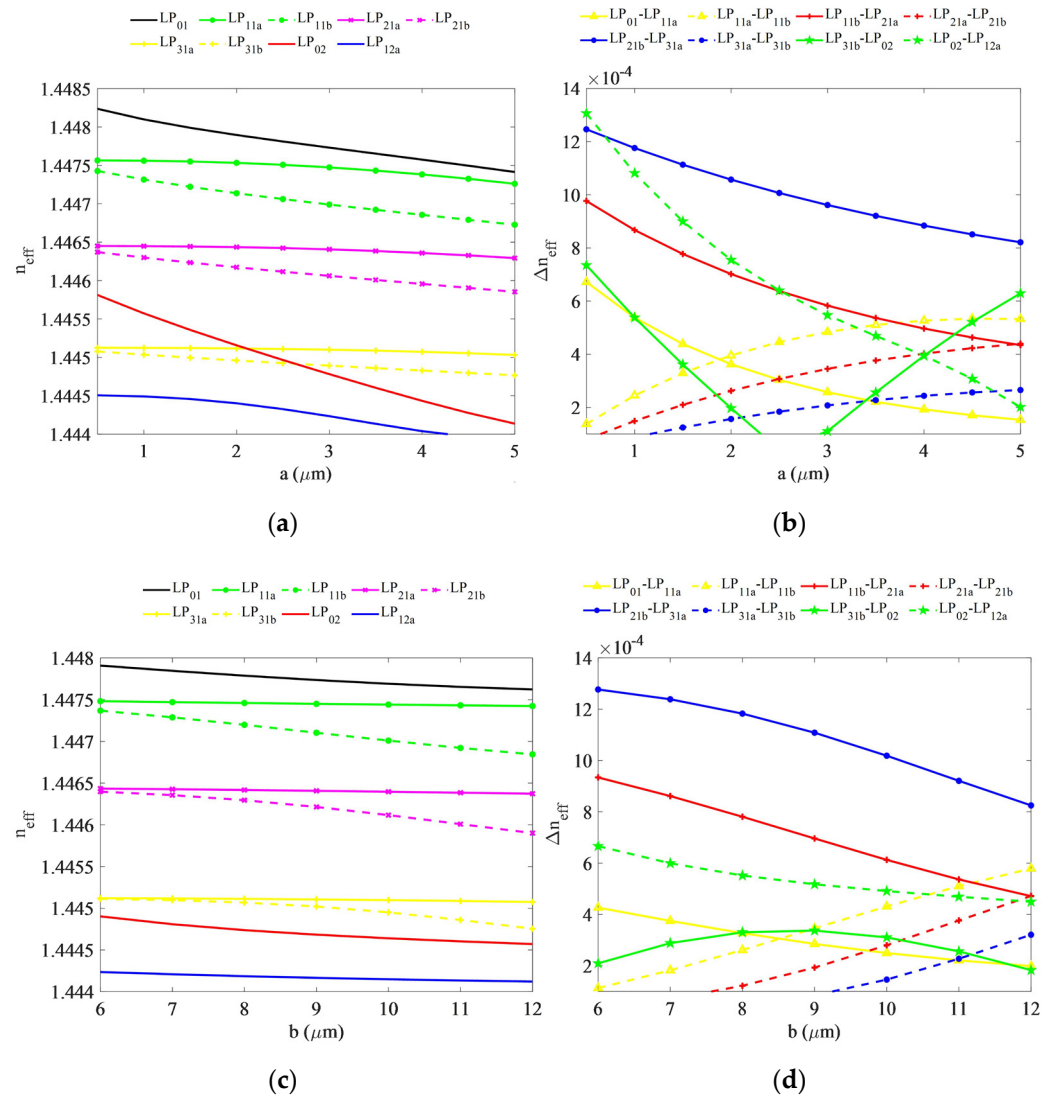


Figure 4. The effect of a on (a) the effective refractive index (n_{eff}) of each mode and (b) the effective refractive index difference (Δn_{eff}) between adjacent modes; the effect of b on (c) the n_{eff} of each mode and (d) the Δn_{eff} between adjacent modes.

3.3. Fabrication Tolerance

Considering the practical application scenarios, in addition to the mode characteristics of the optical fiber, the feasibility of the optical fiber preparation is also an important indicator for evaluating the performance of the optical fiber. The size of the cladding and core radius of the DRF proposed in this paper is comparable to that of the conventional FMF, and the core-clad refractive index difference is 0.005, which is also the commonly used value of the current commercial fiber. The optical fiber preform can be obtained by referring to the preparation method of the current conventional step-index optical fiber. The DRF preparation focuses on the preparation of center-assisted diamond. A diamond-shaped hole can be obtained in the center of the preform by the method of center drilling, and then the hole is filled with pure quartz material to obtain a complete optical fiber preform. Finally, the desired optical fiber can be obtained through the drawing process. All of the above-mentioned processes are mature preparation processes, and the DRF has good preparation feasibility.

The key to the DRF maintaining good mode properties is the introduction of center-assisted diamond. At the same time, this is also a challenge in the preparation process. Therefore, it is very important to discuss the influence of fabrication errors that may occur

in the preparation process of DRF on the mode characteristics. In the preparation of optical fiber preform, the core and cladding are concentric circle structures with the center of the circle coinciding. According to the structural characteristics of DRF, the intersection of the two diagonal lines of diamond is required to coincide with the center of the core and the cladding, when drilling a diamond hole in the center. Due to fabrication errors, the center point of the diamond may deviate from the center of the core and cladding. In this paper, the influence of the diamond on the n_{eff} of each mode when the diamond deviates from the center point in the x -axis and y -axis directions is calculated, and the results are shown in Figure 5. Current fiber manufacturers on the market require core-cladding concentricity to be less than $0.5 \mu\text{m}$ [29], so we are also discussing the effect of offset on fiber mode characteristics in this range. When the offsets dx and dy are in the range of $0.5 \mu\text{m}$, the mode properties of the DRF's separated spatially degenerate modes are not affected. The two spatially degenerate modes of LP_{mn} are still separated, and the Δn_{eff} between adjacent modes is greater than 10^{-4} . The rate of change of n_{eff} caused by the offset of the diamond in the x -axis and y -axis directions is less than 0.04% and 0.004% , respectively. The above results show that DRF has a good process error tolerance for the case where the diamond deviates from the center point, which can reduce the difficulty of the process.

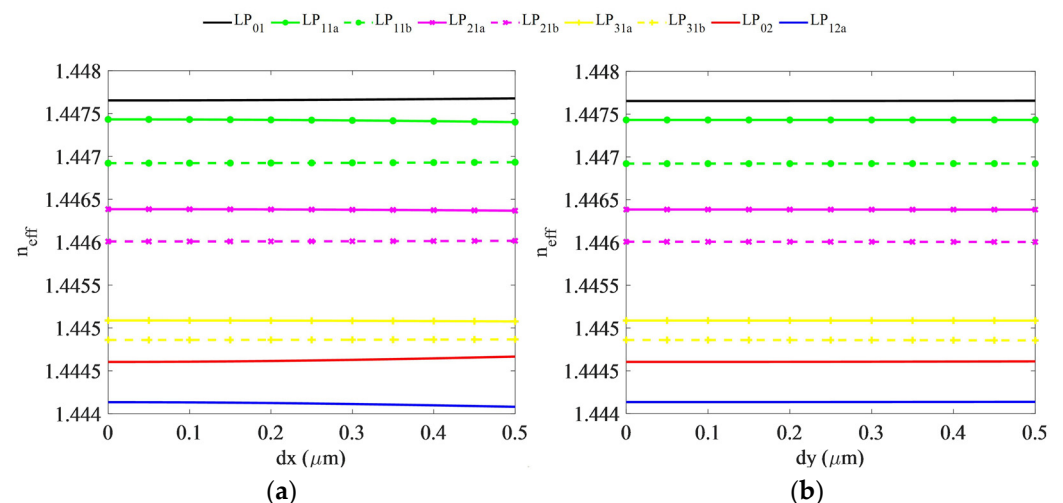


Figure 5. The influence of (a) offset in the x -axis direction (dx) and (b) offset in the y -axis direction (dy) on effective refractive index (n_{eff}) for each mode.

The process error tolerance of DRF is discussed further. Considering the possible structural deformation during the fabrication process, this paper discusses the influence on the mode characteristics when the four inner corners of the center-assisted diamond are gradually turned into rounded corners. Figure 6 shows the n_{eff} variation curves of nine modes within the range of $1 \mu\text{m}$ of the fillet radius (r_1). When the four inner corners of the diamond gradually become rounded due to the structural deformation within a certain range, the n_{eff} value of each mode will change slightly, but the mode characteristics of the DRF will not be changed. The calculation results show that the change rate of n_{eff} caused by the deformation of the four inner corners is less than 0.07% . The above results show that DRF can accept structural deformation within a certain range, and has more flexibility in the preparation process, without strict shape requirements.

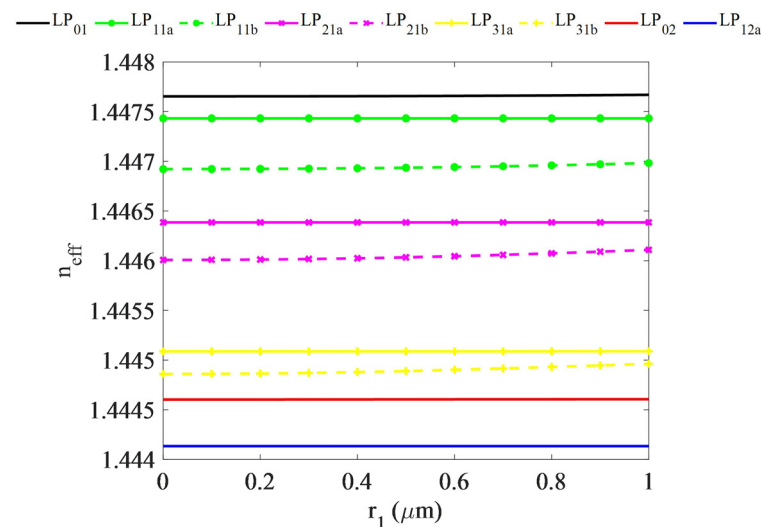


Figure 6. The influence of corner radius on effective refractive index (n_{eff}) for each mode.

4. Discussion of the Relationship between the Structural Symmetry and Spatial Mode Degenerate Separation

The optical fiber structure that can realize spatial degeneracy separation is generally made by changing the circularly symmetric structure of the optical fiber, so that the n_{eff} values of the two spatial modes are different. Some of these fiber designs have structures with large core-clad refractive index differences [14,20,28]. However, the DRF proposed in this paper maintains the conventional core-clad refractive index difference size while maintaining a low level of polarization separation. For special fiber structures with such modal properties, we have reported rectangle-assisted ring-core fiber (RRF) [15], ellipse-assisted ring-core fiber (ERF) [16], and square-assisted ring-core fiber (SRF) [30]. By introducing a low refractive index region into the core, they can effectively separate spatially degenerate modes while ensuring a low level of polarization separation, and the fiber structure has the size of the core-clad refractive index difference of conventional fibers, which has a good application prospect in SDM systems. On the basis of the previous work, the influence of the center shape of the core on the spatial mode separation is summarized, which is expected to provide guidance for the design of optical fibers with similar structures, and further provide a useful reference for the use of similarly structured optical fiber to achieve mode separation control. Therefore, this paper makes a comparison of the mode characteristics of these four kinds of fibers. The results are shown in Table 2.

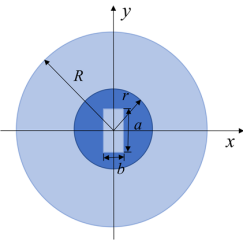
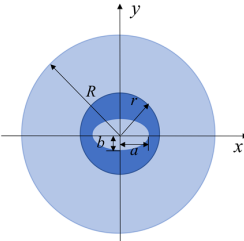
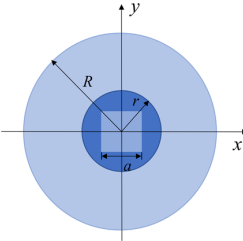
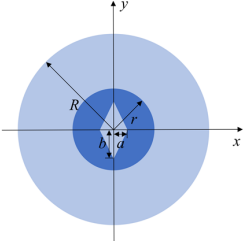
The four center-assisted ring-core fibers introduce rectangular, elliptical, square, and diamond regions in the core, respectively. The axisymmetric properties of the center-assisted structures break the circular symmetry of conventional step-index fibers. As mentioned earlier, the change in symmetry affects the birefringence properties of the fiber, causing degenerate separation of polarization modes, which is the design principle of many polarization-maintaining fibers. For the proposed center-assisted ring-core fibers, the change of symmetry increases the spacing between spatial modes and achieves degenerate separation of spatial modes, while the influence of birefringence characteristics is not significant. The size of the fiber is comparable to that of the current common FME, which reduces the difficulty of preparing this type of fiber to a certain extent. It is worth noting that the square-assisted ring-core fiber only supports the spatial degeneracy separation of the modes whose subscript m of LP_{mn} is an even number, such as LP_{21} , LP_{41} , LP_{61} , and LP_{22} modes. We consider this to be related to the numbers of symmetry axes of their cross-sections. For RRF, ERF, and DRF, the cross-section has two symmetry axes, while SRF has four. Combined with the mode characteristics of various fibers, we believe that the subscript m of the LP_{mn} mode that can support the degenerate separation of spatial

modes should satisfy an integer multiple of half the number of symmetry axes of the fiber cross-section, that is:

$$m = k \frac{s}{2}, k = 1, 2, 3 \dots \quad (1)$$

In the formula, s is the number of symmetry axes of the fiber cross-section, and k is an integer greater than 0.

Table 2. Performance comparison of four center-assisted ring-core fibers.

	Rectangle-Assisted Ring-Core Fiber (RRF) [15]	Ellipse-Assisted Ring-Core Fiber (ERF) [16]	Square-Assisted Ring-Core Fiber (SRF) [30]	Diamond-Assisted Ring-Core Fiber (DRF)
Schematic cross-section				
Core diameter (μm)	25	25	30.8	25
Assisted area parameters (μm)	$a = 19 \ b = 2$	$a = 12.5 \ b = 1$	$a = 16.6$	$a = 3.5 \ b = 11$
Core-clad refractive index difference	0.005	0.005	0.01	0.005
Number of symmetry axes	2	2	4	2
LP _{mn} mode supporting degenerate separation of spatial modes	LP ₁₁ LP ₂₁ LP ₃₁	LP ₁₁ LP ₂₁ LP ₃₁ LP ₁₂	LP ₂₁ LP ₄₁ LP ₆₁ LP ₂₂	LP ₁₁ LP ₂₁ LP ₃₁ LP ₁₂
Δn_{eff} between spatial modes	$> 2.2 \times 10^{-4}$	$> 3.16 \times 10^{-4}$	$> 1.13 \times 10^{-4}$	$> 2.25 \times 10^{-4}$
Δn_{eff} between polarization modes	$< 2.1 \times 10^{-6}$	$< 3.23 \times 10^{-6}$	$< 7.12 \times 10^{-6}$	$< 3.68 \times 10^{-6}$

The relationship between the spatial mode degeneracy separation and the number of symmetry axes of the fiber cross-section given here does not apply only to the fiber structures mentioned in Table 2. On a broader scale, the above relationship is still valid. To illustrate the general applicability of the relationship, the degeneracy of every mode is discussed when the central-assisted area is a regular hexagon, as well as more general concave and convex polygons with two symmetry axes, respectively. The results are shown in Tables 3–5 below. When the central-assisted region is a regular hexagon, meaning that the cross-section of the fiber has six symmetry axes, only LP₃₁ and LP₆₁ modes, whose subscript m is an integer multiple of 3, support spatial mode degenerate separation, while other modes remain their degeneracy. When the central-assisted area is a concave polygon or a convex polygon, the cross-section of the fiber has two symmetry axes, and every LP_{mn} mode with $m \neq 0$ presents degenerate separation, which is similar to the DRF proposed in this paper. It is worth noting that LP_{12b} has been cut off under this set of structural parameters when the central-assisted area is a convex polygon. Therefore, the Δn_{eff} between spatial modes of LP₁₂ is not given in Table 5. However, this does not affect our discussion of the fiber mode characteristics. The above results show that in a more general case, the relationship proposed in Equation (1) is still valid, that is, the subscript m of the LP_{mn} mode that can support the degenerate separation of spatial modes should satisfy an integer multiple of half the number of symmetry axes of the fiber cross-section. Similarly, all three fibers are comparable in size to conventional FMFs and have conventional core-clad refractive index differences. Additionally, the structural parameters given here are only

one of the sets of structural parameters that can satisfy this relationship. In the actual fiber structure design and application, the fiber structure parameters can be further optimized according to needs, to obtain a fiber structure with better performance.

Table 3. Mode properties when the central-assisted area is a regular hexagon (at the wavelength of 1550 nm).

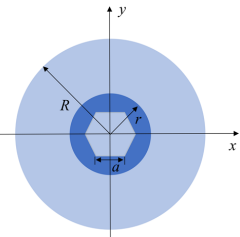
The Shape of the Central-Assisted Area: Regular Hexagon						
Schematic Cross-Section	Structural Parameters		Δn_{eff} between Spatial Modes (If Degenerated)			
	Core diameter (μm)	Assisted area parameters (μm)	LP ₀₁	LP ₁₁	LP ₂₁	LP ₃₁
	30	$a = 13$	-	-	-	6.21×10^{-4}
	Core-clad refractive index difference	Number of symmetry axes	LP ₄₁	LP ₅₁	LP ₆₁	
	0.01	6	-	-	1.76×10^{-4}	

Table 4. Mode properties when the central-assisted area is a concave polygon (at the wavelength of 1550 nm).

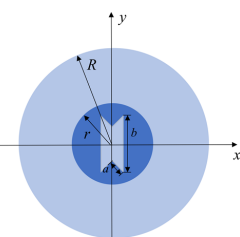
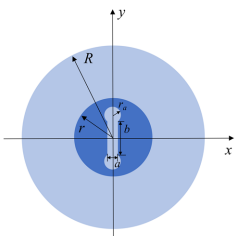
The Shape of the Central-Assisted Area: Concave Polygon						
Schematic Cross-Section	Structural Parameters		Δn_{eff} between Spatial Modes (If Degenerated)			
	Core diameter (μm)	Assisted area parameters (μm)	LP ₀₁	LP ₁₁	LP ₂₁	LP ₃₁
	25	$a = 8 \quad b = 18$	-	2.98×10^{-4}	1.44×10^{-4}	2.11×10^{-4}
	Core-clad refractive index difference	Number of symmetry axes	LP ₀₂			
	0.005	2	-			

Table 5. Mode properties when the central-assisted area is a convex polygon (at the wavelength of 1550 nm).

The Shape of the Central-Assisted Area: Convex Polygon						
Schematic Cross-Section	Structural Parameters		Δn_{eff} between Spatial Modes (If Degenerated)			
	Core diameter (μm)	Assisted area parameters (μm)	LP ₀₁	LP ₁₁	LP ₂₁	LP ₀₂
	25	$a = 2 \quad b = 13 \quad r_a = 1.5$	-	4.86×10^{-4}	3.58×10^{-4}	-
	Core-clad refractive index difference	Number of symmetry axes	LP ₃₁	LP ₁₂		
	0.005	2	1.98×10^{-4}	-		

In the above discussion, we compare the mode characteristics of DRF proposed in this paper and several previously published central-assisted ring-core fibers, and obtain the relationship between the symmetry of the fiber cross-section and the degeneracy separation of spatial modes. It is verified that this relationship is equally applicable on a broader scale. The discussion of these contents and the summary of the relationship provide new ideas

for the design of optical fiber structures for space division multiplexing systems. First of all, this kind of fiber with a special structure can realize the degeneracy separation of spatial modes, and these spatial modes can be more easily utilized in the SDM system to further tap the multiplexing potential of optical fiber. Secondly, by changing the number of symmetry axes of the fiber cross-section, the spatial mode degenerate separation can be manipulated, providing guidance for the design of similar fiber structures under different requirements.

5. Conclusions

In conclusion, this paper proposes a diamond-assisted ring-core few-mode fiber for space division multiplexing. This fiber can effectively separate two spatially degenerate modes with the introduction of a central low-refractive-index diamond-shaped region, while maintaining a low level of polarization separation. The simulation results show that in the whole C-band, the Δn_{eff} between all adjacent modes, including the spatial mode, is greater than 2.11×10^{-4} . The polarization separation level is lower than 3.68×10^{-6} , which is 2–3 orders of magnitude lower than the spatial mode separation. Such fiber structure caused the Δn_{eff} between adjacent modes to be greater than 10^{-4} , greatly reducing inter-mode crosstalk. The low level of polarization separation does not add additional difficulty to multiplexing and makes it easier to utilize these modes in SDM systems. The DRF also has a good process error tolerance, and the existing fiber preparation conditions can meet the processing requirements of DRF. By comparing with other center-assisted ring-core fibers, the mode characteristics and design method of this type of fiber are obtained, which can provide guidance for similar fiber structure design. The fiber structure proposed in this paper is expected to be a promising candidate for SDM systems.

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