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# Hollow Ring-Core Photonic Crystal Fiber With >500 OAM Modes Over 360-nm Communications Bandwidth

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**ABSTRACT** We propose and design a hollow $As_2S_3$ ring-core photonic crystal fiber (PCF) with 514 radially fundamental orbital angular momentum (OAM) modes over 360 nm communications bandwidth across all the O, E, S, C, and L bands. The designed PCF with 40 $\mu$m-radius air core and 150 nm-width $As_2S_3$ ring can support eigenmodes up to $HE_{130,1}$ and $EH_{128,1}$. The numerical analysis shows that the designed ring PCF has large effective refractive index contrast, and can transmit up to 874 OAM modes near 1.55 $\mu$m. Simulation results show that in the C and L bands, the PCF with a hollow-core radius of 40 $\mu$m and a ring width of 0.15 $\mu$m can retain an $2.5 \times 10^{-3}$ effective refractive index difference between the two highest order OAM modes, which achieves effective mode separation, thereby achieving stable OAM mode transmission. The $n_{eff}$ difference between the even and odd fiber eigenmodes and the intra-mode walk-off are also carefully studied under different bending radii. The results show that higher-order OAM modes has better tolerance to the fiber bending, compared with the lower-order modes. The fiber has the potential to support ultra-high capacity OAM mode division multiplexing in the optical fiber communication systems.

**INDEX TERMS** Orbital angular momentum, fiber optics, mode division multiplexing, photonic crystal fiber.

## I. INTRODUCTION

Over the past several decades, the optical communication industry has been developing rapidly. Pushing the optical fiber transmission systems towards large capacity for different emerging applications has become more and more urgent [1]. Optical communication systems need to use more degrees of freedom of the photon to carry more information, such as wavelength division multiplexing (WDM), polarization division multiplexing (PDM) and spatial division multiplexing (SDM) [1]–[4]. Orbital angular momentum (OAM), which is a compelling candidate for a modal basis of SDM, has attracted extensive attention [5]–[7]. It could potentially overcome the problem of insufficient capacity in the current optical fiber communications infrastructures [8].

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Unfortunately, traditional step-index fiber cannot support stable OAM mode transmission. Therefore, it is of great significance to design a dedicated optical fiber that supports OAM mode transmission in an efficient and stable manner.

Correspondingly, the optical fibers that can transmit OAM mode have also been proposed and demonstrated extensively, including single-mode, multi-mode, single-core, and multi-core optical fibers [9]–[16]. As one of these innovative designs, the concept of photonic crystal fiber (PCF) was first proposed by J. C. Knight *et al.* [17] in 1996. PCF allows light to be guided within a lower refractive index core [18], [19], far exceeding the possibility of traditional single-mode fiber (SMF), which has now been well proven. Since then, the research on PCFs has made dramatical progress, such as modifying the structural parameters including core and cladding diameters, using different materials including $SiO_2$ or other polymers with different refractive indices, and changing the arrangement of air holes, etc.

Compared with traditional optical fibers, one of the important advantages of PCF is that the cladding holes of optical fibers can be filled with new functional optical materials, thereby creating a new branch of research area, called hybrid PCFs. An extensive review article written by C. Markos *et al.* reviewed the recent progress in the field of hybrid PCF [20]. He showed the ability to adjust the cladding mode resonance by simply changing the external temperature of the solid fiber with polymer injection holes. Since the concept of ring-shaped PCF was proposed, there have been more researches on hybrid PCF [21]–[23], in which hollow ring-core PCFs are combined with advanced materials to achieve target performance in a way that is not possible in traditional standard optical fibers.

The circular photonic crystal fiber supporting OAM modes is first proposed in [24]. In 2016, C. Chen *et al.* proposed a novel multi-orbital-angular-momentum multi-ring micro-structured fiber (MOMRMF) which can transmit 34 OAM modes in the wavelength band from 1.52 to 1.56 $\mu$m [9]. In 2017, H. Zhang *et al.* proposed a ring-shaped PCF made of pure silica material, with a ring-shaped silica region in the middle as the core of OAM mode propagation [25]. They also provided a design strategy through which the best number of high-quality OAM modes (up to 42 OAM modes) can be obtained. In 2018, Y. Lei *et al.* proposed a PCF structure with semicircular pores [26] that can support 66 OAM modes for wavelength from 1.1 $\mu$m to 1.7 $\mu$m. The confinement loss of most modes can be kept at $10^{-9}$dB/m level. The designed structure has good communication performance and material availability. In 2018, L. Zhang *et al.* proposed a new type of circular photonic crystal fiber (CPCF), which can support up to 110 orbital angular momentum (OAM) modes in the C and L bands [27].

In this paper, we propose and design an air-core thin-ring $As_2S_3$ PCF to support hundreds of OAM modes, which is systematically modeled and numerically studied by the finite element method (FEM). According to the results, the proposed PCF structure with a 40-$\mu$m air-core radius could potentially support more than 500 radially fundamental OAM modes across all O, E, S, C, and L bands from 1260 nm to 1625 nm. Furthermore, it can support 546 radially first-order OAM modes at 1550 nm. To show the robustness of the designed fiber, we calculate the effective refractive index difference between the even and odd fiber eigenmodes when the fiber suffers bending and find that the high-order OAM modes feature satisfying capability of bending tolerance. This designed fiber can be potentially used for the OAM-WDM optical communication system to dramatically increase the transmission capacity.

## II. PROPOSED PCF STRUCTURE

We propose a design of an air-core thin-ring $As_2S_3$ PCF [28]. Figure 1 shows the structure and material profile of the air-core thin-ring $As_2S_3$ photonic crystal fiber. There is a

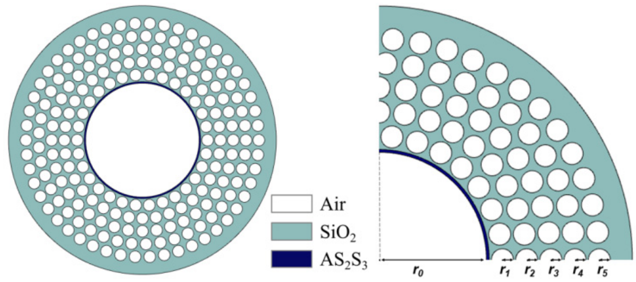


**FIGURE 1. Structure and material profile of the air-core thin-ring $As_2S_3$ PCF.**

large air hole in the center, and it is surrounded by an $As_2S_3$ high-index ring, of which the width is $\Delta r$. Five well-ordered air hole rings are arranged evenly in the outer cladding layer. $SiO_2$ ($n = 1.444$ at a wavelength of 1.55 $\mu$m) is selected as the background material. The embedded material between the large air holes and the outer $SiO_2$ cladding is $As_2S_3$ ($n = 2.4373$ at a wavelength of 1.55 $\mu$m). To consider the material dispersion, the material refractive indices of $SiO_2$ and $As_2S_3$ are obtained using the Sellmeier equations in the simulation [29], [30]. According to the $As_2S_3$ material loss [31], [32], the optical loss is several times larger than 0.03 dB/m at 1550 nm. Furthermore, previous experiment result has shown that relatively low loss 0.012 dB/m at 3000 nm and 0.014 dB/m at 4800 nm can be achieved in $As_2S_3$ multimode fibers. Moreover, we add a 7.5-$\mu$m perfectly matched layer (PML) in the FEM model to absorb the incident electromagnetic waves at the outer boundary of cladding, which could be used to calculate the confinement loss. The size of PML is determined according to the size of the standard single-mode optical fiber (SMF), which is 62.5-$\mu$m. And we tested the influence of the PML thickness around 7.5 $\mu$m on the real and imaginary parts of the refractive index. The results of the complex refractive indices are very stable and show good convergence.

From the perspective of fiber manufacturing, the selection of materials and the design of fiber structure are feasible [33], and fibers composed of silica and chalcogenide have been manufactured in practice. The detailed manufacturing process has been described in several papers [34]–[36].

From the perspective of fiber structure, it can be seen that compared with the structure of the conventional optical fiber, the parameters in the novel air core fiber structure have more degree of freedoms to adjust the structure parameters. This potentially provides more possibilities for performance optimization of the supported optical OAM modes.

## III. OAM MODE PROPERTY

Figure 2(a) shows that the simulated distributions of the normalized intensity and the phase for $OAM_{l,1}$ mode ($l = 2, 6, 27, 57$) in the designed fiber ($r_0 = 10$ $\mu$m, $r_1 = r_2 = r_3 = r_4 = r_5 = 1$ $\mu$m, $\Delta r = 0.25$ $\mu$m). OAM modes can be formed from fiber eigenmodes according to the

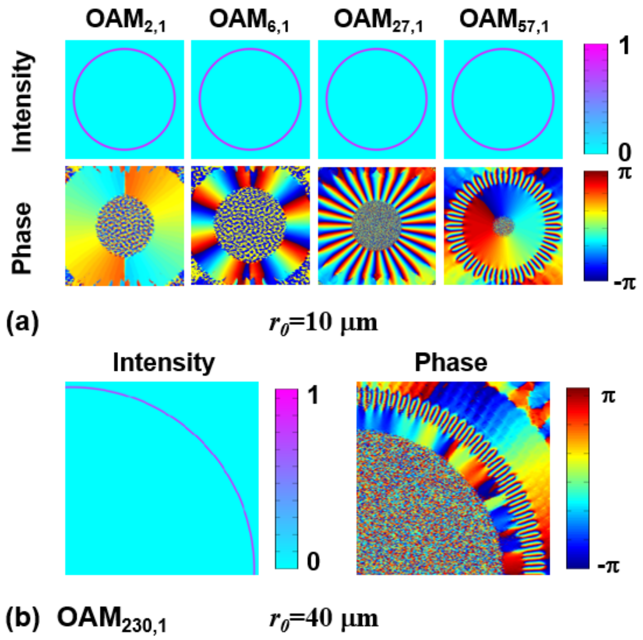


**FIGURE 2.** (a) Intensity and phase distributions of the supported OAM modes in the air-core $As_2S_3$ ring fiber ($r_0 = 10$ $\mu$m, $\Delta r = 0.25$ $\mu$m). (b) Intensity and phase distributions of the $OAM_{230,1}$ mode in the air-core $As_2S_3$ ring fiber ($r_0 = 40$ $\mu$m, $\Delta r = 0.25$ $\mu$m).

following formulas [35]

$$OAM^{\pm}_{\pm l,m} = HE^{even}_{l+1,m} \pm jHE^{odd}_{l+1} \quad (1\text{-}1)$$

$$OAM^{\mp}_{\pm l,m} = EH^{even}_{l-1,m} \pm jEH^{odd}_{l-1} \quad (1\text{-}2)$$

In the design of the central air core size and the thickness of the $As_2S_3$ high-index ring region, we also have to pay attention to avoid the radial high-order mode. It would be highly desirable for the fiber not to support the radially higher-order OAM modes ($m > 1$), in which unwanted radially higher-order modes can be totally eliminated. Accordingly, the thickness of the $As_2S_3$ region should be appropriately selected under certain value to suppress the OAM modes with m > 1. Nevertheless, to maximize the number of the supported OAM modes, the thickness of the $As_2S_3$ region should be chosen as large as possible. Therefore, there is a trade-off between obtaining a large quantity of OAM modes and avoiding radially high-order modes. This design choice on fiber material and structure can better support and conserve OAM modes. First of all, the symmetric structure and large material refractive index, can lead to the large difference of $n_{eff}$ between the even and odd mode of $HE_{l+1,1}$ or $EH_{l-1,1}$ mode of the same $|l|$ family, which can hinder decomposition of OAM modes. Moreover, the thin-ring make it suitable for preserving OAM modes due to the similarly annular intensity profile of OAM beams [37].

As displayed in Figure 2(b), the air-core ring fiber with $r_0 = 40$ $\mu$m and $\Delta r = 0.25$ $\mu$m can support 874 OAM modes ($m = 1$, $l = 219$) at 1550 nm, in which the highest order eigenmodes are $HE_{231,1}$ and $EH_{229,1}$ respectively.Considering the fundamental mode $HE_{1,1}$ ($x$ and $y$ polarization), $TE_{01}$ and $TM_{01}$ modes, 878 modes (874 OAM ones) in total are supported in the single ring. Several multiplexing and demultiplexing techniques have been demonstrated [38], [39], including the use of an inverse helical phase hologram to convert the OAM into a Gaussian-like beam, a mode sorter, free-space interferometers, a photonic integrated circuit, and q-plates. Optical fiber with 8 OAM mode channels and 10 WDM channels for transmission distances of 50 kilometers has been achieved [40], providing low fiber loss and low crosstalk. Ingerslev *et al.* [41] developed an optical fiber that can carry more multiplexed OAM modes in short distances. 12 multiplexed OAM modes can be achieved at a distance of about 1 km. The technology of multiplexing and demultiplexing of such large number of OAM modes is not yet mature and still needs time to develop. Compared with other geometric parameters, enlarging the core radius is a much more efficient way to increase the number of OAM modes supported.

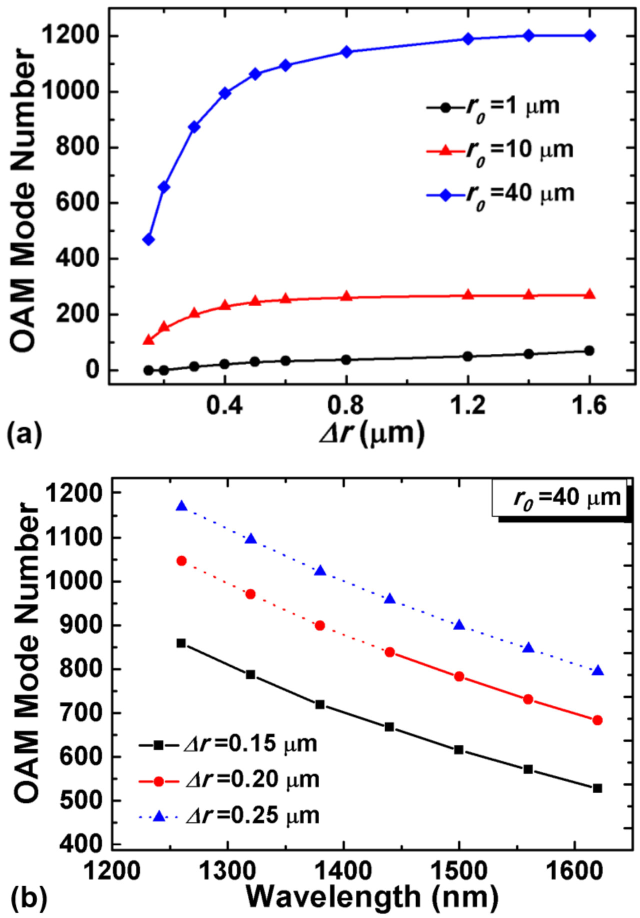


**FIGURE 3.** (a) OAM mode number supported in the air-core thin-ring $As_2S_3$ PCF with three different air-core radii ($r_0$) as a function of the ring width ($\Delta r$). (b) OAM mode number with three different ring widths ($\Delta r$) as a function of wavelength at $r_0 = 40$ $\mu$m.

We calculate the total OAM mode number supported in the designed fiber with different $As_2S_3$ ring width ($\Delta r$) and air-core radii ($r_0$) as shown in Figure 3(a). It can be found that more OAM modes are supported with the increase $\Delta r$ and $r_0$, which is mainly due to the larger radial space for the modes. Furthermore, the designed fiber with larger air-core radius contributes to the higher increase rate of OAM modes number as a function of $\Delta r$ due to the faster increase of ring area. Figure 3(b) illustrates the supported OAM mode number as a function of wavelength under three different fiber ring width. Noted that the dotted line means the existence of radially high-order mode, while the solid line represents that only first-order radial modes exist in the fiber. (De)multiplexing techniques cannot efficiently separate OAM modes with different radial order, thus, it is meaningful for design fiber to support only the first radial order modes, using a narrow ring region [42]. We can see that the supported OAM mode number decreases as the increase of wavelength. Here, the thickness of the $As_2S_3$ ring region should be suitably chosen to suppress the OAM mode with $m > 1$. The proposed PCF with larger ring width can support more OAM modes, but radially first-order mode will maintain narrower bandwidth. Up to 514 first-order OAM modes can be supported in the designed fiber with $\Delta r = 0.15\ \mu$m across O, E, S, C and L bands from 1260 nm to 1625 nm and it can support 546 OAM modes ($m = 1, l = 137$) at 1550 nm, where the highest order HE and EH eigenmodes are $HE_{138,1}$ and $EH_{136,1}$ respectively.

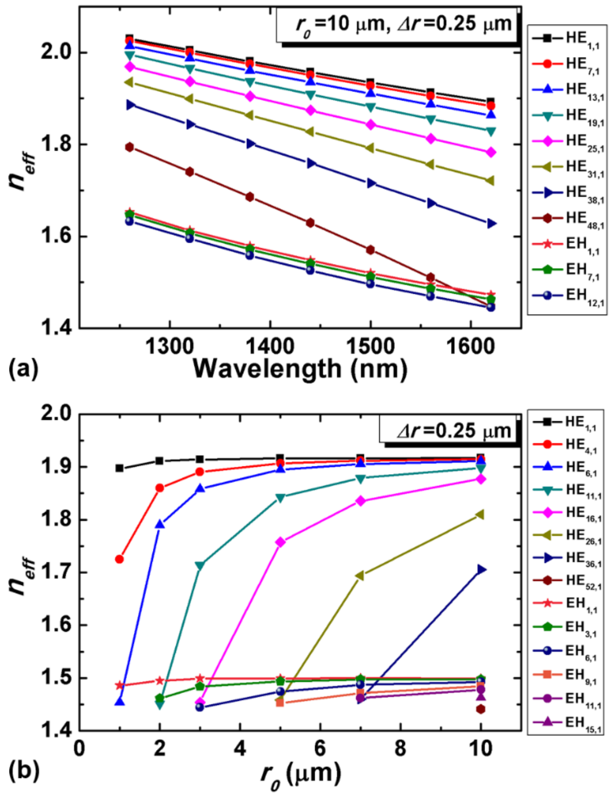


**FIGURE 4.** **(a) Effective refractive index as a function of wavelength for different fiber eigenmodes ($r_0 = 10\ \mu$m and $\Delta r = 0.25\ \mu$m). (b) Effective refractive index as a function of air-core radius ($r_0$) at $\Delta r = 0.25\ \mu$m for different vortex modes.**

Figure 4(a) illustrates the effective refractive indices ($n_{eff}$) of various OAM modes supported in the fiber as a function of wavelength with fiber parameters of $r_0 = 10\ \mu$m and $\Delta r = 0.25\ \mu$m. As shown in the figure, the effective refractive index decreases as the order of each vector mode increases. At the same time, the $n_{eff}$ of each vector mode of the same order increases and the EH mode appears later as the radius of the central air hole increases. It can be seen from these two figures that the refractive index difference decreases with the increase of the air-core radius and the decrease of the wavelength, thus assure good modal separation and avoid the crosstalk.

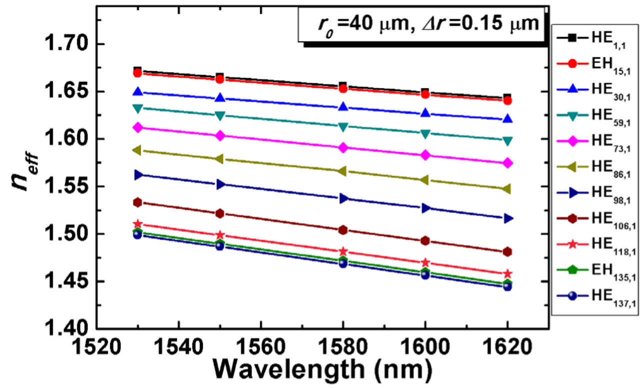


**FIGURE 5.** **Effective refractive indices as a function of wavelength for vortex modes with fiber parameters of $r_0 = 40\ \mu$m and $\Delta r = 0.15\ \mu$m.**

Figure 5 illustrates the effective refractive indices of the supported OAM modes as a function of wavelength with fiber parameters of $r_0 = 40\ \mu$m and $\Delta r = 0.15\ \mu$m. We can see that the effective refractive indices decrease as the wavelength increases and the fiber can support modes up to $HE_{137,1}$ and $EH_{135,1}$ across C and L bands. Over the optical bandwidth in hundreds of nanometers, the effective refractive index differences between the eigenmodes should be more than $10^{-4}$, which can ensure good separation between eigenmodes. According to the simulation results, the refractive index differences of the nearest fiber eigenmodes increases with the mode order. Among them, $\Delta n_{eff}$ between the $HE_{137,1}$ and $EH_{135,1}$ modes reaches about $2.5 \times 10^{-3}$. Consequently, the OAM modes in this designed PCF structure can maintain stable transmission in the optical communications bands.

## IV. FIBER BENDING

In general, fiber bending induced by external force is one of the major reasons to cause the non-perfect circularity of the fiber. Considering that the OAM modes are composed of fiber eigenmodes, i.e. the combination of even and odd modes of $HE_{m,1}$ or $EH_{n,1}$ with a $\pm\pi/2$ phase shift, fiber bending will affect the modal profile and purity of the OAM modes. Eventually, this will lead to modal coupling and crosstalk, and further impact the performance of optical communication systems when it comes to practice. Therefore, we further study the effect of fiber bending radius on the characteristics of the OAM modes.

We find that the fiber bending has most significant impact on the $n_{eff}$ of the low order HE modes. Figure 6 illustrates the

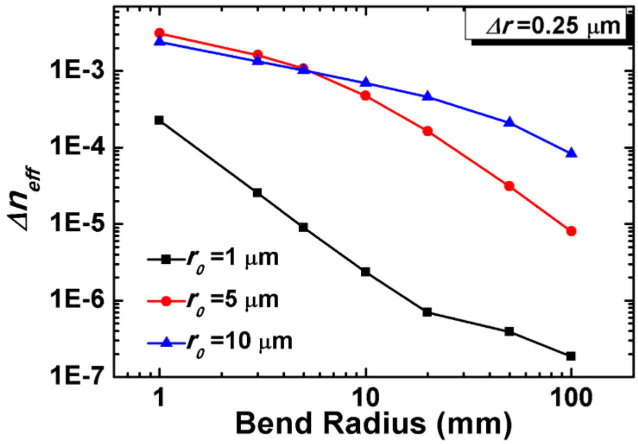


**FIGURE 6.** Effective refractive indices of $HE_{1,1}$ mode as a function of the fiber bend radius with different high-index ring's inner radius ($r_0$).

$n_{eff}$ difference between the even and odd fiber eigenmodes of $HE_{1,1}$ as a function of the fiber bend radius with different high-index ring's inner radius. It is shown that the refractive index difference increases as bend radius decreases, and the smaller air-core radius ($r_0$), the greater tolerance to fiber bending effect.

Figure 7(a) shows the $n_{eff}$ difference between the even and odd fiber eigenmodes as a function of the fiber bend radius. As the bend radius reduces from 100 to 1 mm, high-order OAM modes feature stronger tolerance to the fiber bending effect, while the $n_{eff}$ difference between the even and odd fiber eigenmodes of the low-order modes increases significantly. This is because high-order OAM modes have more azimuthal periods in their transverse field distribution [43]. The maximum $n_{eff}$ difference is $2.5 \times 10^{-3}$ for the $HE_{1,1}$ under a fiber bend radius of 1 mm.

Figure 7(b) demonstrates $2\pi$ walk-off length and 10-ps walk-off length for different OAM modes as a function of fiber bend radius. Here, we use two parameters, $2\pi$ walk-off length ($L_{2\pi}$) and 10-ps walk-off length ($L_{10ps}$), to characterize the intra-mode walk-off of the OAM modes in the ring-core PCF at 1.55 $\mu$m. They can be expressed as [44], [45]

$$L_{2\pi} = \frac{\lambda}{n_{eff}^{even} - n_{eff}^{odd}} \tag{2-1}$$

$$L_{10ps} = \frac{c \times \Delta t}{n_{eff}^{even} - n_{eff}^{odd}} \tag{2-2}$$

where $\lambda$, $c$ and $\Delta t$ are the wavelength, light velocity in vacuum, and the temporal walk off time, respectively. Here, $n_{eff}^{even}$ and $n_{eff}^{even}$ are the effective refractive indices of the even and odd eigenmodes, respectively. The $2\pi$ walk-off length and 10-ps walk-off length of $HE_{1,1}$ to $HE_{9,1}$ modes decrease about $10^4$ times when the fiber bending radius reduces from 100 to 1 mm. According to the simulation results, the high-order OAM modes feature longer walk-off length than that of lower-order modes. Consequently, high-order

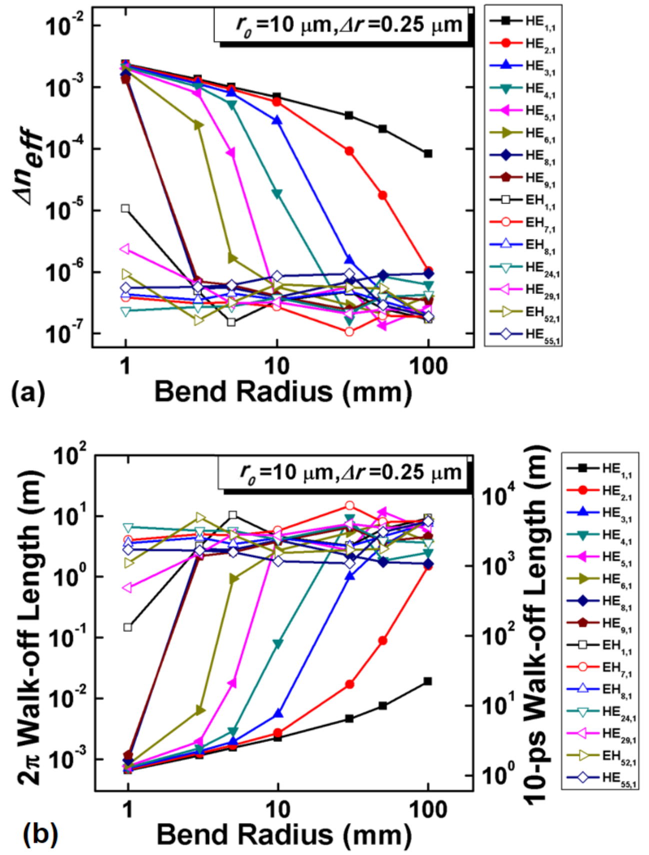


**FIGURE 7.** (a) Effective refractive indices of the fiber eigenmodes as a function of fiber bend radius. (b) $2\pi$ walk-off length and 10-ps walk-off length as a function of fiber bend radius.

OAM modes can ensure stability and robustness suffering environmental perturbation.

## V. CONCLUSION

We propose a new design strategy for a large mode count OAM ring-core PCF with over 360-nm communications bandwidth across all the O, E, S, C, and L bands. The fiber with 40-$\mu$m air core radius and 150-nm $As_2S_3$ high-index ring thickness can support eigenmodes up to $HE_{130,1}$ and $EH_{128,1}$. The numerical analysis shows that the designed ring PCF can accommodate 874 OAM modes near 1.55 $\mu$m, and has the characteristics of high effective refractive index contrast. Furthermore, we analyze the effective refractive index difference between the even and odd fiber eigenmodes in the curved hollow ring-core PCF. It is found that higher-order OAM modes are more tolerant to the fiber bending [42]. It has potential application prospects in large capacity OAM mode division multiplexing optical fiber communication systems.

## ACKNOWLEDGMENT

*(Yingning Wang and Yao Lu contributed equally to this work.)*

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