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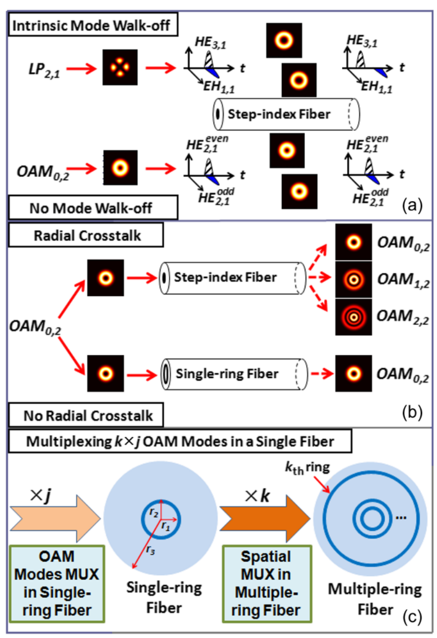


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# Mode Properties and Propagation Effects of Optical Orbital Angular Momentum (OAM) Modes in a Ring Fiber

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**Abstract:** We simulate and analyze the mode properties and propagation effects of orbital angular momentum (OAM) modes in a ring fiber. A ring fiber with 0.05 up-doping is designed in simulation to support up to 10 OAM modes while maintaining single-mode condition radially. With a multiple-ring fiber, tens of OAM modes can be potentially multiplexed to greatly enhance the system capacity and spectral efficiency. The mode index difference can be maintained above $10^{-4}$ over hundreds of nanometers optical bandwidth. Higher order OAM modes' azimuthal intensity and odd-order OAM modes' azimuthal phase show better tolerance to the fiber ellipticity. Moreover, higher order OAM modes also have longer $2\pi$ and 10-ps walk-off length. After 600-km propagation, $OAM_{0,4}$ mode shows $<$ 10-ps mode walk-off, even in a ring fiber with 1% ellipticity. Also, in such an elliptical fiber, the well-aligned OAM modes with different charges have $<-20$ dB intermode crosstalk. The improvement of the circularity for the ring fiber is expected to reduce the crosstalk and increase the demultiplexing efficiency.

**Index Terms:** Fiber optics systems, multiplexing, optics, orbital angular momentum, waveguides.

## 1. Introduction

Optical fiber communication, as the backbone of today's telecommunications infrastructure, supports voice, video, and data transmission through global networks. A critical issue in optical communications research is the challenge of meeting the needs of the inevitable growth in data transmission capacity. Dense wavelength-division multiplexing (DWDM) has been proven to be an efficient solution that provides a multiplicative-factor (on the order of 100) increment. Fueled by emerging bandwidth-hungry applications, much work has focused on increasing the data spectral efficiency by utilizing polarization, amplitude, and phase manipulations of the optical field [1], [2]. Another potentially complementary approach that has gained much attention recently is to transmit independent data streams, each in a different core using multicore fibers (MCF) or each on a different spatial linearly polarized (LP) mode using few-mode fibers (FMF) [3]–[6]. Increasing the number of spatial modes in the optical fiber can increase the capacity and the spectral efficiency of the communication link simultaneously.

It is known that photons can carry orbital angular momentum (OAM), which is associated with azimuthal phase dependence of the complex electric field. Light beams carrying OAM can be described in the spatial phase form of $\exp(il\phi)$ $(l = 0, \pm 1, \pm 2, \ldots)$. As OAM has an infinite number of orthogonal eigenstates, it provides another degree of freedom to manipulate the optical field [7]. OAM based free-space and fiber optical communication systems have been proposed for spectral and energy efficient communication links, which can meet the latest trend in the field of optical communications [8]–[12]. In free-space optical communication links, multiplexing Laguerre–Gaussian (LG) modes carrying OAM has been demonstrated to be an efficient way to increase the spectral efficiency and data capacity [13], [14]. Moreover, the OAM modes based optical communication system can potentially provide improved security [15]. There are many other applications of optical OAM modes beyond data communications, including microscopy, laser cutting of metals, and optical tweezers [7]. Consequently, efficiently maintaining the OAM modes in an optical fiber, which can potentially facilitate many applications, is of great importance [16], [17]. Some recent research has shown the capability of OAM excitation and transmission (1-km) in fiber [18]–[20]. Though the reach and stability of OAM mode propagation in the ring fiber needs further investigation, it can potentially open the door to a host of different applications.

In this paper, we simulate and analyze the mode properties and propagation effects of OAM modes in the ring fiber. A ring fiber with 0.05 up-doping is designed in simulation to support up to 10 OAM modes while maintaining single-mode condition radially. Using optical OAM modes in a multiple-ring fiber for space- and mode-division multiplexing systems, this scheme can potentially transmit tens of modes in a single fiber and, thus, greatly enhance the system capacity and spectral efficiency. In the ring fiber, the mode index difference can be maintained above $10^{-4}$ with different ring fiber parameters over hundreds of nanometers optical bandwidth and, thus, reduce the effect of mode degeneracy to avoid the modal coupling. Azimuthal intensity and phase changes of the OAM modes with respect to fiber eigenmodes misalignment and fiber ellipticity are studied. For azimuthal intensity, higher order OAM modes are more tolerant to the fiber variations, while odd-order OAM modes have better azimuthal phase tolerance. Because of the more azimuthal periods of the higher-order OAM mode, its modal index difference (between even and odd fiber eigenmodes) induced by the fiber ellipticity is smaller. Consequently, higher order OAM modes also have longer $2\pi$ and 10-ps walk-off length. $OAM_{0,4}$ mode shows < 10-ps mode walk-off after 600-km propagation distance, even in a ring fiber with 1% ellipticity. For the well-aligned OAM modes with different charges in a $\varepsilon = 1\%$ ring fiber, their crosstalk with other channels is less than $-20$ dB. The enhancement of the circularity for the ring fiber is expected to reduce the crosstalk and increase the demultiplexing efficiency.

## 2. Concept of Multiplexing Optical OAM Modes in a Ring Fiber

The block diagram of multiplexing OAM modes in a ring fiber is conceptually shown in Fig. 1. As shown in Fig. 1(a), higher order LP modes are composed of two fiber eigenmodes with different propagation constants (i.e., $LP_{2,1} = HE_{3,1} + EH_{1,1}$). While propagating along the fiber, these two modes walk off, resulting in a highly distorted mode profile at the detection end. In contrast, fiber OAM modes can be obtained by properly combining two fiber eigenmodes (i.e., $OAM_{0,2} = HE_{2,1}^{even} + i \times HE_{2,1}^{odd}$). Since these eigenmodes have the same propagation constant, they will not undergo any intrinsic mode walk-off. Therefore, compared with LP modes, OAM modes can better maintain the mode profile after propagating through a certain length of fiber. However, in multimode step-index fiber, unwanted radially higher order modes can easily be excited, thus posing a strict restriction to the mode coupling. A small change in the launching condition, such as variation of angle, mode spot size, or deviation from the center, can excite higher order modes in radial direction, resulting in serious crosstalk, as shown in Fig. 1(b). On the other hand, a properly designed high-index single-ring fiber

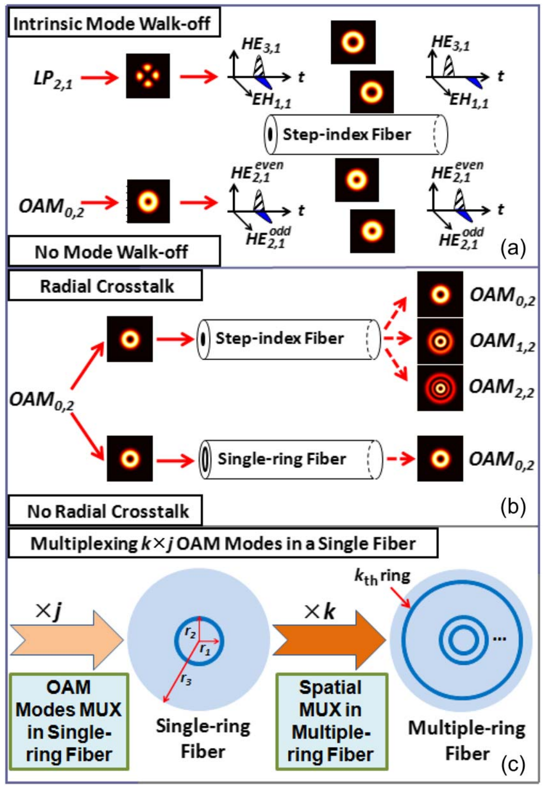


Fig. 1. Comparison of different schemes for multiplexing multiple optical spatial modes for fiber transmission. (a) Higher order LP modes are composed of two fiber eigenmodes ($LP_{2,1} = HE_{3,1} + EH_{1,1}$) having different propagation constants. The two fiber eigenmodes walk off as they propagate along the fiber. OAM modes are composed of two fiber eigenmodes with same propagation constant ($OAM_{0,2} = HE_{2,1}^{even} + i \times HE_{2,1}^{odd}$), and thus, there is no walk-off after propagation. (b) To multiplex multiple OAM modes into multimode step-index fiber, a small change of launching condition can excite radially higher order modes and results in the crosstalk. With proper design, single-ring fiber can support only radially fundamental modes with reduced crosstalk. (c) $j$ OAM modes with different azimuthal phase order can be multiplexed into the single ring fiber. Using a multiple-ring fiber with $k$ rings can increase the multiplexed mode number with another factor of $k$. This can potentially transmit $k \times j$ OAM modes in a single fiber.

can support only the radially fundamental modes [21] and, thus, potentially reduce the crosstalk induced during mode excitement. In order to multiplex multiple OAM modes simultaneously, the number of the eigenmodes supported by the fiber should be increased by increasing either the core radius or the refractive index difference between the core and cladding. In this scheme, a single-ring fiber can provide 1-D mode-division multiplexing of the optical OAM modes. Similar to the concept of multiple-core fiber [3], [4], by using a multiple-ring fiber with small inter-ring crosstalk and launching OAM modes with different azimuthal phase into the high-index ring regions, one can potentially achieve multiplexing of the optical OAM modes in another spatial dimension. Consequently, this scenario might provide a promising way for spatially multiplexing more stable modes in a single optical fiber.

## 3. Mode Properties and Propagation Effects

In this section, we study the OAM mode properties and propagation effects in single-ring fiber. The ring's inner radius ($r_1$), ring's outer radius ($r_2$), and the fiber cladding radius ($r_3$) are 4, 5, and 62.5 $\mu$m, respectively. The fiber cladding is made of silica with a refractive index ($n_{clad}$) of 1.444 at 1550 nm. The refractive index of ring region ($n_{ring}$) can have a 0.05 refractive index increment ($\Delta n$) by

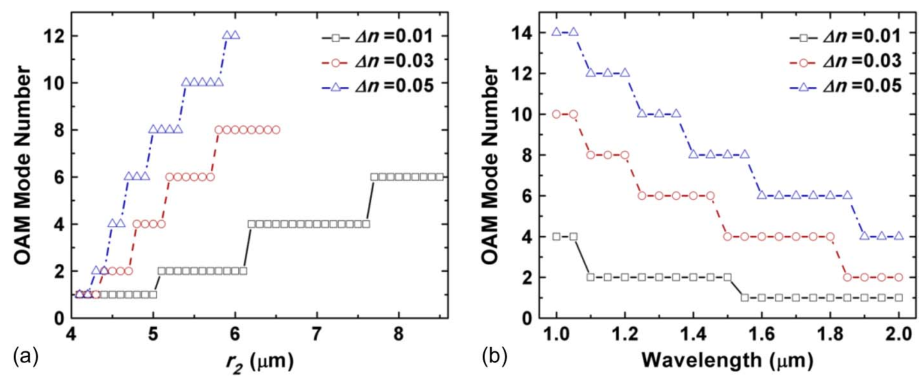


Fig. 2. (a) OAM mode number supported in the single-ring fiber as a function of the ring outer radius ($r_2$) with different ring-cladding index difference ($\Delta n$). (b) OAM mode number as a function of the wavelength with different ring-cladding index difference ($\Delta n$).

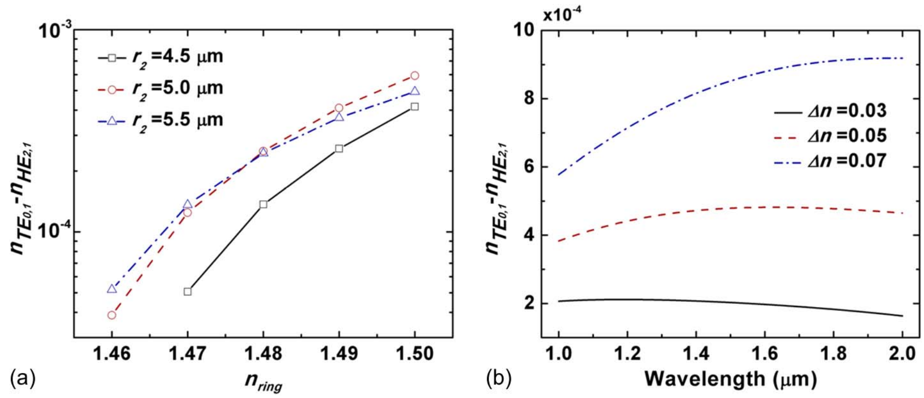


Fig. 3. Effective refractive index difference of $TE_{0,1}$ and $HE_{2,1}$ modes as a function of (a) the refractive index in the fiber ring region with different ring outer radius ($r_2$) and (b) wavelength with different ring-cladding index difference ($\Delta n$).

up-doping [22]. Using a commercial full-vector finite-element mode solver (COMSOL), we can obtain the electromagnetic field distributions and effective refractive indices of the eigenmodes in the ring fiber. By maintaining the radially single-mode condition [21], we first investigate the OAM mode number ($HE_{m,1}^{even} + i \times HE_{m,1}^{odd}$ and $EH_{n,1}^{even} + i \times EH_{n,1}^{odd}$) that can be supported in the ring fiber. From Fig. 2, one can see that the OAM mode number increases with $r_2$ and $\Delta n$, while decreases with the wavelength. A ring fiber ($r_1 = 4\ \mu$m, $r_2 = 5.5\ \mu$m) with 0.05 up-doping can support 10 OAM modes. Compared with single-mode fiber, this already shows an order of magnitude increment in the number of multiplexed fiber modes. Moreover, this number can be further increased with larger ring fiber parameters, such as $r_2$ and $\Delta n$. As shown in Fig. 2(b), a large number of OAM modes can be supported over a broad bandwidth, which can cross hundreds of nanometers, in the ring fiber. This further shows the great potential for increasing the link capacity by utilizing more wavelength-division multiplexing channels.

With the increase of the supported OAM modes number, enlarging the ring-cladding index difference is a feasible way to reduce the modal coupling in the ring fiber [16]. We further study the mode index difference between the eigenmodes in the ring fiber with $r_1 = 4\ \mu$m at 1550 nm. As shown in Fig. 3(a), the effective index difference between $TE_{0,1}$ and $HE_{2,1}$ modes increases with $n_{ring}$ and $r_2$, indicating higher index-contrast and larger ring outer radius are preferred. The effective refractive indices of the eigenmodes in the ring fiber, such as $TE_{0,1}$ and $HE_{2,1}$, always increase with $n_{ring}$ and $r_2$.

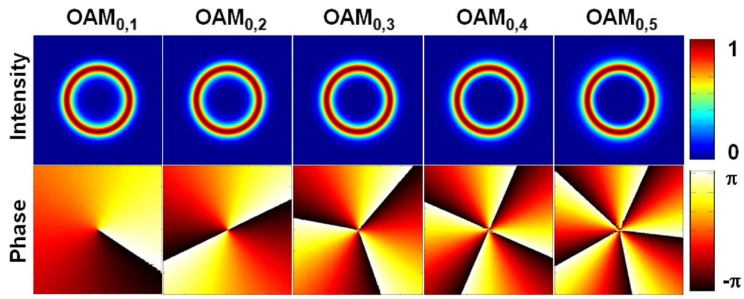


Fig. 4. Intensity and phase distribution of the supported $OAM_{0,m}$ modes ($HE^{even}_{m,1} + i \times HE^{odd}_{m,1}$, $m = 1 \sim 5$) in the ring fiber ($r_1 = 4\ \mu$m, $r_2 = 5\ \mu$m, and $\Delta n = 0.05$).

However, the mode index difference does not follow this trend due to the different increment rate of the effective indices for different modes, especially at high index-contrast case ($n_{ring} = 1.50$). Moreover, we investigate the wavelength dependence of the index difference between $TE_{0,1}$ and $HE_{2,1}$ modes ($r_1 = 4\ \mu$m, $r_2 = 5\ \mu$m), as shown in Fig. 3(b). The mode index difference can be maintained above $10^{-4}$ over hundreds of nanometers optical bandwidth.

For the ring fiber with $r_1 = 4\ \mu$m, $r_2 = 5\ \mu$m, and $\Delta n = 0.05$, eight OAM modes can be supported by $HE_{m,1}$ and $EH_{n,1}$ ($m = 1 \sim 5, n = 1 \sim 3$). Fig. 4 shows the intensity and phase distribution of the OAM modes, which are from the proper combination of the even and odd $HE_{m,1}$ ($m = 1 \sim 5$) modes. For these OAM modes with different charge orders, the field distributions are well controlled within the high-index ring region. The shape of the ring-like intensity distribution remains, while its size gradually increases with the OAM mode order. Moreover, the phase distribution of the $OAM_{0,m}$ mode has a $2m\pi$ change azimuthally and provides us a chance to efficiently demultiplex these modes with a conjugate phase pattern.

Controlling the alignment of two fiber eigenmodes is critical to form an OAM mode with high purity. Fig. 5 shows the intensity and phase variation of $OAM_{0,3}$ modes azimuthally along the center of the ring region with different mode walk-off ($\theta$). Note that $\theta = 90^\circ$ provides a perfect OAM mode. $OAM_{0,3}$ has 3 periods of phase change ($-\pi$ to $\pi$) for each azimuthal circle. A 360° mode walk-off repeats the mode period. From Fig. 5(b), one can see that the intensity distribution is quite flat azimuthally for the well-aligned case ($\theta = 90^\circ$) and the average of maximum intensity variation for the misaligned case ($\theta = 180^\circ$) is around 5%. As shown in Fig. 5(d), for $\theta = 90^\circ$, the phase changes linearly along the azimuthal circle. A 30° extra mode walk-off ($\theta = 120^\circ$) still gives a relatively smooth phase change, while it changes with a sharp step when $\theta = 180^\circ$.

## 4. Tolerance to Fiber Ellipticity

The nonperfect circularity (ellipticity) of optical fibers can give rise to polarization mode dispersion (PMD) on the fundamental Gaussian mode. It can also affect the mode profile or purity of the OAM modes as it induces a difference in the propagation constants of the decomposed two fiber eigenmodes. In the following, we study the impact of the ring fiber ellipticity ($\varepsilon$) on the supported OAM modes. In Fig. 6(a), the standard deviation (SD) of the azimuthal intensity increases with fiber ellipticity. The higher order OAM modes show more tolerance to the ellipticity variations as they have more azimuthal periods, and thus mitigate the effect from fiber ellipticity. From the phase SD as shown in Fig. 6(b), odd-order OAM modes have a stronger tolerance than that of even-order modes. This is mainly because the ellipticity brings a two-fold symmetry to the ring fiber. Such an effect enhances the phase distribution separation for the OAM modes with even order. For the odd-order OAM modes, one of its azimuthal $2\pi$ phase period can cross the symmetry axis and, thus, mitigate this effect.

As fiber ellipticity induces an effective refractive index difference to the two eigenmodes (even and odd) that form the OAM mode, this gives mode walk-off upon propagation. Here, we use two

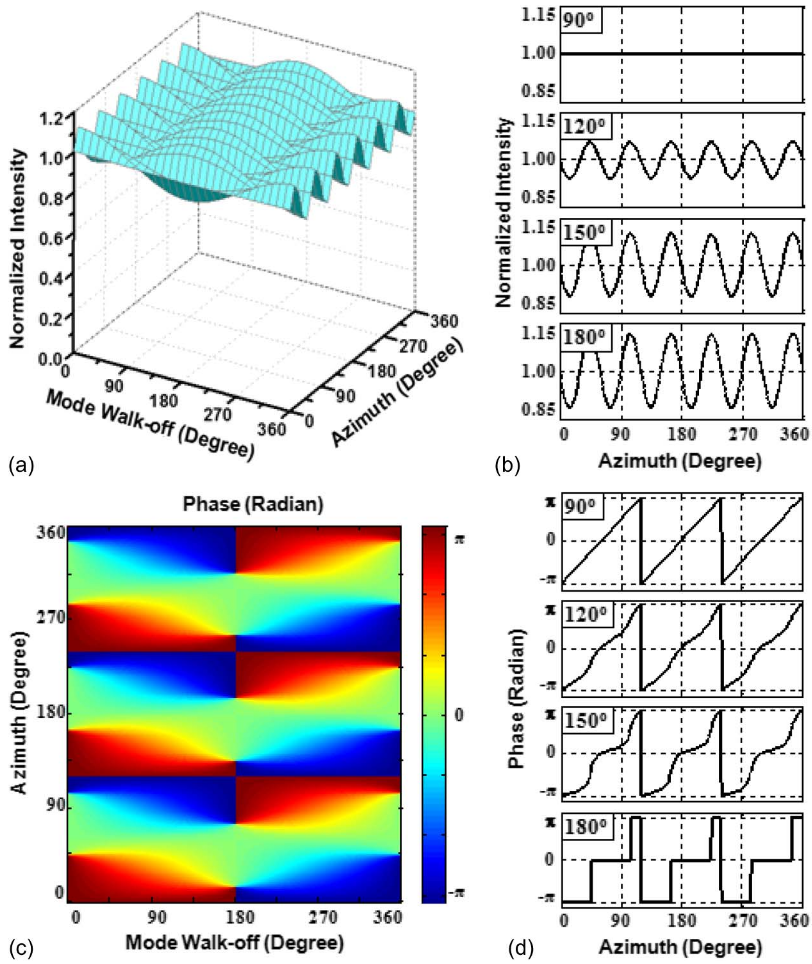


Fig. 5. Intensity and phase variation of $OAM_{0,3}$ $(HE_{3,1}^{even} + e^{i\theta} \times HE_{3,1}^{odd})$ modes azimuthally along the center of ring region with different mode walk-off $(\theta)$ ($\theta = 90°$ provides a perfect OAM mode). (a) Normalized intensity variation with different mode walk-off and azimuth. (b) Azimuthally normalized intensity variation for $\theta = 90°$, 120°, 150°, and 180°. (c) Phase variation with different mode walk-off and azimuth. (d) Azimuthal phase variation for $\theta = 90°$, 120°, 150°, and 180°.

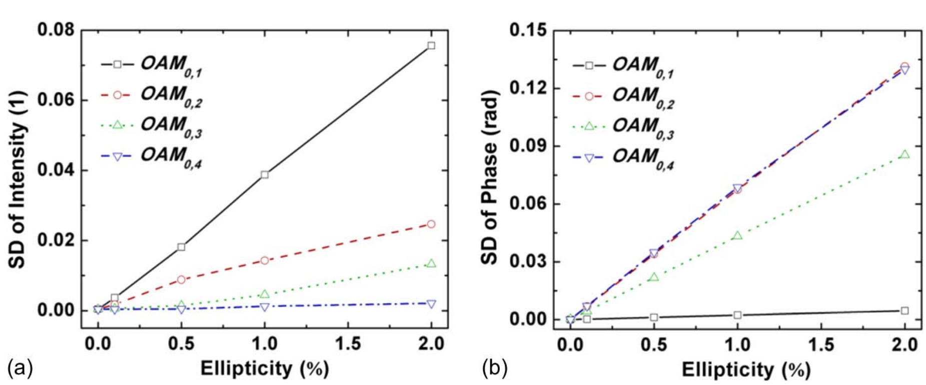


Fig. 6. Standard deviation of (a) intensity, and (b) phase azimuthally along the center of ring region as a function of fiber ellipticity for different OAM modes.

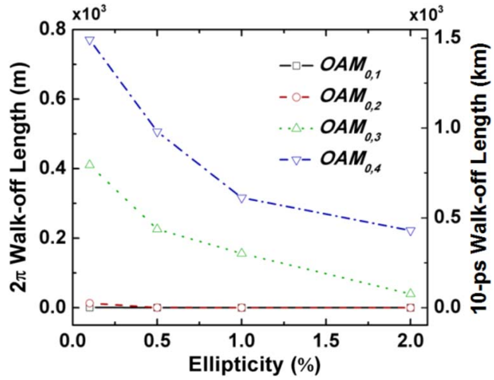


Fig. 7. $2\pi$ and 10-ps walk-off length as a function of fiber ellipticity for different OAM modes.

parameters, i.e., $2\pi$ walk-off length $(L_{2\pi})$ and 10-ps walk-off length $(L_{10\ \text{ps}})$, to characterize the intramode walk-off of the OAM modes in a noncircular ring fiber at 1.55 $\mu$m

$$L_{2\pi} = \frac{\lambda}{n_{\text{HE}^{\text{even}}_{m,1}} - n_{\text{HE}^{\text{even}}_{m,1}}} = \frac{1.55 \times 10^{-6}}{n_{\text{HE}^{\text{even}}_{m,1}} - n_{\text{HE}^{\text{even}}_{m,1}}}(m) \tag{1}$$

$$L_{10\ \text{ps}} = \frac{c \times \Delta t}{n_{\text{HE}^{\text{even}}_{m,1}} - n_{\text{HE}^{\text{even}}_{m,1}}} = \frac{3 \times 10^{-3}}{n_{\text{HE}^{\text{even}}_{m,1}} - n_{\text{HE}^{\text{even}}_{m,1}}}(m) \tag{2}$$

where $\lambda$, $c$, and $\Delta t$ are the wavelength, speed of light in a vacuum, and walk-off time, respectively. $L_{2\pi}$ denotes the propagation length when the two eigenmodes walk off to each other with a $2\pi$ optical cycle, while $L_{10\ \text{ps}}$ means the propagation length after the two eigenmodes has a 10-ps walk-off. Here, we can see that $L_{10\ \text{ps}}$ is around 2000 times larger than $L_{2\pi}$. For a 10-Gbit/s signal, 10-ps intramode walk-off is only 10% of one bit length (100 ps). Such a walk-off will not affect the quality of the detected signal much. One can see from Fig. 7, as higher order OAM modes have more azimuthal periods, its modal index difference $(n_{\text{HE}^{\text{even}}_{m,1}} - n_{\text{HE}^{\text{even}}_{m,1}})$ induced by the ellipticity is smaller. This leads to a longer $2\pi$ and 10-ps walk-off length. $\text{OAM}_{0,4}$ can propagate more than 600 km with $<$ 10-ps mode walk-off, even in a ring fiber with 1% ellipticity. One can see that the modal index difference increases with fiber ellipticity and results in a shorter walk-off length.

To effectively demultiplex multiple OAM modes for data communications, we need to provide channels with small crosstalk. The charge weight of OAM modes is defined as the electric field overlap integral of the optical field and the eigenmodes in the ring fiber [23]. Fig. 8(a)–(h) show the crosstalk among well-aligned OAM modes with different charges in a $\varepsilon = 1\%$ ring fiber. All these OAM modes have $< -20$ dB crosstalk with other channels. Furthermore, we study the crosstalk of $\text{OAM}_{0,3}$ modes after 0, 5, 10, and 15-m propagation in a $\varepsilon = 1\%$ ring fiber, which is shown in Fig. 8(i)–(p). With the increase of mode misalignment, the crosstalk with the other channels also increases. Here, the property of crosstalk is periodic with the $2\pi$ walk-off length of the mode.

As mentioned above, we can demultiplex these transmitted OAM modes with a conjugate phase pattern using a phase plate or a spatial light modulator. The demultiplexing efficiency of $\text{OAM}_{0,3}$ mode as a function of propagation length is shown in Fig. 9. One can see that it decreases with the ring fiber ellipticity. With the increase of the ellipticity, the effective index difference between the even and odd eigenmodes increases, and thus the $2\pi$ walk-off length decreases. The larger walk-off induces a more severe OAM mode distortion and, thus, gives rise to a lower demultiplexing efficiency. The demultiplexing efficiency of $\text{OAM}_{0,3}$ mode can be greater than 50% after 300-m-long propagation in a ring fiber with 0.5% ellipticity. Consequently, a more circular fiber is preferred to boost the demultiplexing efficiency and the propagation length of the OAM modes. Moreover, with the multiple-input–multiple-output (MIMO) signal processing technique, which is widely employed in

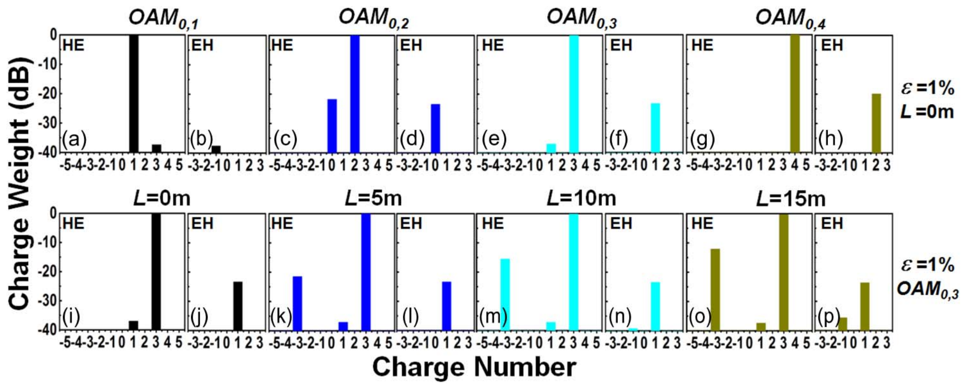


Fig. 8. Charge weight of (a)–(h) different well-aligned OAM modes in a $\varepsilon = 1\%$ fiber. (i)–(p) $OAM_{0,3}$ modes after 0, 5, 10, and 15-m propagation in a $\varepsilon = 1\%$ fiber.

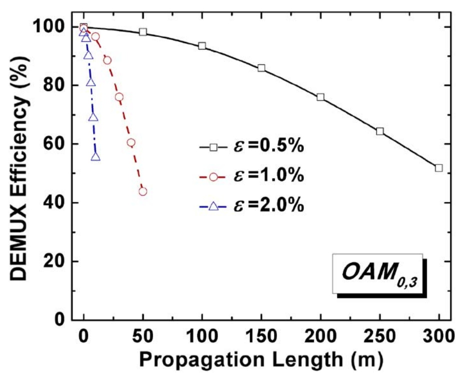


Fig. 9. Demultiplexing efficiency of $OAM_{0,3}$ mode as a function of the propagation length in the ring fiber with different *fiber ellipticity* (periodic versus $2\pi$ walk-off length).

currently proposed mode-division multiplexing systems, OAM modes long-haul transmission is very promising [5], [6]. Here, as the mode walk-off will recover after $2\pi$ period, the demultiplexing efficiency is also periodic with the $2\pi$ walk-off length.

## 5. Conclusion

In conclusion, we analyze the mode properties and propagation effects of OAM modes in the ring fiber and propose to use the optical OAM modes in a multiple-ring fiber for space- and mode-division multiplexing systems. Tens of different modes can be potentially multiplexed in a single fiber and, thus, enhance the system capacity and spectral efficiency. Simulation shows, higher order OAM modes' azimuthal intensity, and odd-order OAM modes' azimuthal phase have better tolerance to the fiber ellipticity. Moreover, higher order OAM modes also have longer $2\pi$ and 10-ps walk-off length because of their more azimuthal periods for their spatial distribution. Even in a ring fiber with 1% ellipticity, $OAM_{0,4}$ mode shows $<$ 10-ps mode walk-off after 600-km propagation. A ring fiber with small ellipticity is expected to greatly reduce the intermode crosstalk, enlarge the demultiplexing efficiency, and increase the propagation distance. Furthermore, the loss, chromatic dispersion, nonlinearity, tolerance to temperature variation, and amplification technique of ring fiber need further investigation and optimization through design and fabrication. Long-haul transmission of the OAM modes is promising with the help of MIMO signal processing techniques.

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