

## Regular Articles

## A circular photonic crystal fiber supporting 26 OAM modes

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## ABSTRACT

A new design of a circular photonic crystal fiber, which can support 26 OAM modes, is proposed. The numerical analysis shows that the proposed fiber possesses very good values of the fiber parameters, such as low confinement loss which is lower than 0.003 dB/m at wavelength of 1.55  $\mu\text{m}$ , flat chromatic dispersion whose dispersion variation for the OAM modes with the order number  $|l| \leq 4$  is within 39.84 ps/nm/km over a 750 nm bandwidth from 1.25 to 2  $\mu\text{m}$ , and small nonlinear coefficient which is less than 2.08  $\text{W}^{-1}/\text{km}$  for all modes at 1.55  $\mu\text{m}$ . In addition, the influence of geometric deformation on the modal birefringence of the proposed fiber has also been discussed. It is proved that the modal birefringence caused by the geometric deformation is different for different vector modes, and most of the higher order modes have a smaller modal birefringence than the lower order modes when the ellipticity is less than 1.08.

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## 1. Introduction

Orbital angular momentum (OAM) can be another dimension for multiplexing. The orthogonality between any two OAM modes and its theoretically infinite states of the modes (its topological charge  $l$  can take any positive and negative integers except 0) make OAM multiplexing to be one of the promising candidates of space division multiplexing [1–5]. Unfortunately, the traditional step-index multimode fiber cannot well support stable OAM mode transmission. So, it is important to design the special optical fibers which can support OAM mode transmission.

So far, many kinds of special fibers which can support the transmission of OAM modes have been proposed, such as spun fiber [6], ring fiber [7–10], air-core fiber [11], twisted air-core fiber [12], inverse-parabolic graded-index profile fiber [13], trench-assisted ring fiber [14] and the new multi-orbital-angular-momentum multi-core supermode fiber (MOMCSF) [15], and so on.

The fibers in which the OAM modes can propagate should possess low loss, relatively flat dispersion coefficient, large effective area, and especially the high refractive index contrast between the mode transmission region and cladding to ensure the transmitting OAM modes not to couple into LP modes [10]. The OAM fibers

proposed in the literature mentioned above do not have enough parameters to be adjusted to ensure the good features for OAM modes mentioned above, and most of them need to be doped accurately [10,11,16,17]. In 2012, Yang Yue et al. firstly proposed that we can use the photonic crystal fiber to support the transmission of the OAM modes [18]. The designed ring PCF uses  $\text{As}_2\text{S}_3$  and air holes to realize the large material index contrast, but it can only support 2 OAM ( $l = \pm 1$ ) modes and has a larger dispersion. In addition, there are also other kinds of PCF which can be used to support OAM modes, such as multicore photonic crystal fiber [19] and twisted photonic crystal fiber [20]. In this paper, we propose a new circular photonic crystal fiber (C-PCF) whose shape has a central air hole and several outer air-hole rings with a ring region to hold 26 OAM modes working at the wavelength range from 1.25 to 1.9  $\mu\text{m}$  (650 nm). The new C-PCF needs no doping and it has more adjustable parameters.

In [21] Gai Zhou et al. independently proposed a microstructure ring fiber whose structure seems similar to the structure proposed in this paper at first glance, but actually they are quite different. The fiber structure in [21] seems to be too much pursuit of the circular symmetry. For the fiber structure proposed in [21], the sizes of the air-holes in the ring structure of the cladding area are different in order to keep the same number of air-holes in different rings, so the air-holes in the inner ring are much smaller than those in the outer ring. Such structure with different hole size is more difficult to be fabricated than the structure we proposed and does not show better performance than the one proposed in this paper. We

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find that the proposed C-PCF in this paper possesses enough circular symmetry to ensure the stable transmission of OAM modes. The all-silica Bragg fibers which have been successfully fabricated in [22] proved that the fabrication of our new C-PCF is possible.

In Section 2, the structure of proposed C-PCF will be described. In Section 3, the mode features such as mode distribution, effective refractive index, chromatic dispersion, confinement loss, effective mode area, nonlinear coefficient, and modal birefringence will be discussed.

## 2. Design of the proposed circular photonic crystal fiber

The idea that C-PCF could be chosen as an OAM mode transmission fiber is as follows. The original base of the PCF is shown in Fig. 1(a). With the idea that OAM modes can propagate in a ring area, we change the core and the first air-hole ring into a large air hole in the center, and remove the second air-hole ring as the transmission region of OAM modes, leaving the rest air-hole rings as the part of the cladding. The final designed C-PCF is shown in Fig. 1(b). The background material of the designed fiber is silica with a refractive index of 1.444. The adjustable parameters of this structure include: the radius of the center air hole  $r$ , the inner radius of the cladding  $R$ , the diameters of the outer air holes  $d_n$  ( $n = 3, 4, 5, \dots$ ), the distance between two consecutive circles  $\Lambda$  and the number of outer air hole rings  $N$ . In this paper, we set that  $r = 4.4 \mu\text{m}$ ,  $R = 6 \mu\text{m}$ ,  $\Lambda = 2.2 \mu\text{m}$ ,  $N = 4$ ,  $d_n/\Lambda = 0.8$  and  $d_3 = d_4 = d_5 = d_6 = 1.76 \mu\text{m}$ .

## 3. The OAM modes supported and their features

### 3.1. The OAM modes supported

The OAM states are formed by the linear combinations of the conventional vector eigenmodes of a fiber, and the formulas are [10]

$$\begin{cases} \text{OAM}_{\pm l, m}^{\pm} = \text{HE}_{l+1, m}^{\text{even}} \pm j\text{HE}_{l-1, m}^{\text{odd}} \\ \text{OAM}_{\pm l, m}^{\mp} = \text{EH}_{l-1, m}^{\text{even}} \pm j\text{EH}_{l+1, m}^{\text{odd}} \end{cases} \quad (1)$$

In this paper, we have analyzed the mode properties of the proposed C-PCF by using numerical simulation (COMSOL). And the fiber can support 26 OAM modes over a 650 nm bandwidth from 1.25 to 1.9  $\mu\text{m}$ , including  $\text{OAM}_{\pm 1, 1}^{\pm}\{\text{HE}_{21}\}$ ,  $\text{OAM}_{\pm 2, 1}^{\pm}\{\text{HE}_{31}, \text{EH}_{11}\}$ ,  $\text{OAM}_{\pm 3, 1}^{\pm}\{\text{HE}_{41}, \text{EH}_{21}\}$ ,  $\text{OAM}_{\pm 4, 1}^{\pm}\{\text{HE}_{51}, \text{EH}_{31}\}$ ,  $\text{OAM}_{\pm 5, 1}^{\pm}\{\text{HE}_{61}, \text{EH}_{41}\}$ ,  $\text{OAM}_{\pm 6, 1}^{\pm}\{\text{HE}_{71}, \text{EH}_{51}\}$  and  $\text{OAM}_{\pm 7, 1}^{\pm}\{\text{HE}_{81}, \text{EH}_{61}\}$ . Fig. 2 shows the

intensity distributions of the vector eigenmodes supported by the proposed C-PCF. We can see that all the modes are well limited in the annular region.

### 3.2. Effective refractive index

The effective index of each vector mode as a function of wavelength by numerical simulation is shown in Fig. 3(a). We can see that the cut-off frequencies of  $\text{HE}_{91}$  and  $\text{EH}_{71}$  modes are about 1.5  $\mu\text{m}$  (indicated by the open circle marks), so we ignore these two modes. To support OAM modes, the effective index separation between the vector modes must be larger than  $1 \times 10^{-4}$ , otherwise they will couple into LP modes. Fig. 3(b) shows the absolute value of effective index difference between HE and EH modes in the designed C-PCF. At the same time, we make a reference line of  $1 \times 10^{-4}$  in the same figure. From Fig. 3(b) we can see that the effective index differences of all HE and EH mode groups are larger than  $1 \times 10^{-4}$ , so all those modes can exist in the C-PCF in a stable manner.

### 3.3. Dispersion properties

The chromatic dispersion can be described as [23]

$$D = -\frac{\lambda}{c} \frac{d^2 \text{Re}[n_{\text{eff}}]}{d\lambda^2} \quad (2)$$

In this work, the material dispersion is also taken into account. Fig. 4 shows the dispersion as a function of wavelength for different modes in the designed C-PCF. The figure shows that the dispersion variation for the OAM modes with  $|l| \leq 4$  ( $l$  is the order of OAM mode) is within 39.84 ps/nm/km over a 750 nm bandwidth from 1.25 to 2  $\mu\text{m}$ , which is much more flattened than the results shown in [18]. And we can see that the dispersion variation of EH modes is less than HE modes. The dispersion variations of  $\text{EH}_{41}$ ,  $\text{EH}_{51}$  and  $\text{EH}_{61}$  are: 36.68 ps/nm/km, 43.53 ps/nm/km and 46.1 ps/nm/km, and they are also less than the results shown in [18].

### 3.4. Confinement loss

The confinement loss for the proposed fiber structures has been calculated through [23]

$$L = \frac{2\pi}{\lambda} \frac{20}{\ln(10)} 10^6 \text{Im}(n_{\text{eff}}) (\text{dB/m}) \quad (3)$$

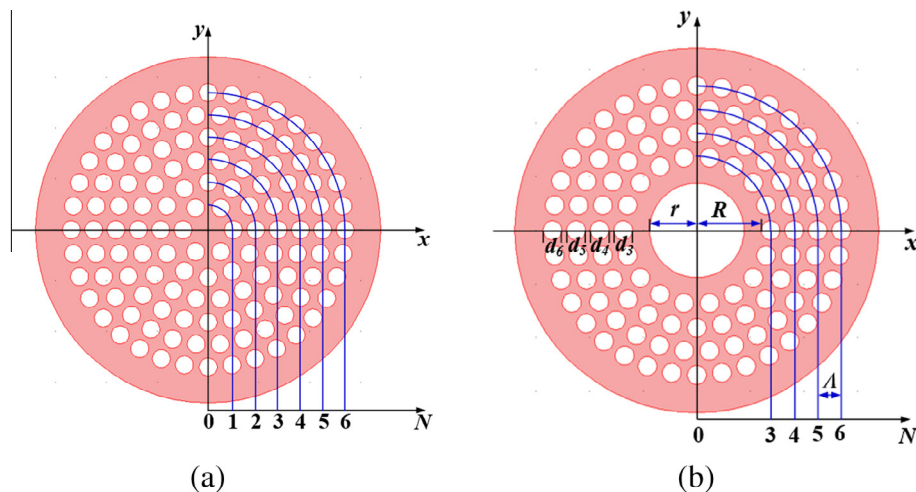


Fig. 1. (a) Cross-section of the original base of the PCF and (b) the new designed C-PCF.

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