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A new designed dual-guided ring-core fiber for OAM mode transmission

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ABSTRACT

We propose and analyze a design of multi-OAM-modes ring-core fiber with two guided modes regions which possess relatively large effective index separations required for the vector modes transmission. The proposed fiber can support up to 28 information states bearing OAM spanning 8 OAM orders in the ring region, and two degenerate fundamental polarization modes in the core region across the whole C bands. Fiber features such as dispersion, differential mode delay, effective mode area, power isolation between two guided regions and modal birefringence have been analyzed in this paper. For the reason that the proposed fiber possess the relatively good features, it has potential applications in the next generation fiber communication systems either in the quantum domain or in the classical domain.

1. Introduction

Space division multiplexing (SDM) is a new milestone in the evolution of fiber optic communication which is considered as a promising solution to scale the capacity of future networks [1–3]. SDM is potential to solve the capacity crunch of single mode fiber transmission. There are different technical directions to realize SDM, such as multimode (or few mode) fibers, multicore fibers and the combination of the both.

It is well known that each photon can carry both spin angular momentum (SAM) associated with beam's polarization and orbital angular momentum (OAM) associated with beam's spiral phase front $\exp(il\varphi)$, where l is the topological charge [4].

Recently, OAM beams were introduced into optical communication as a new degree of freedom for data multiplexing in optical communication links as a new kind of SDM, based on the fact that the different OAM eigenstates form a complete and orthogonal basis [5]. Together with wavelength division multiplexing (WDM) and polarization division multiplexing (PDM) techniques, the total transmission capacity can be dramatically increased [6,7].

OAM has also stimulated an increasing research hotspot in the development of quantum cryptography technique in which we can use the properties of multi-dimensional photons to provide unconditional secure communication. Conventional quantum key distribution (QKD) systems usually adopted the polarization or the phase encoding scheme. Although significant advances have been achieved in QKD both for free-space and fiber channel, the secure key rates in two-dimensional QKD are still low and the secure transmission distance is limited. OAM based QKD structure is a promising candidate for the next generation of high-speed QKD system [8,9].

OAM fiber is a critical device for the OAM-based fiber transmission systems. Several types of special fibers to support OAM mode transmission have been proposed, such as ring fiber [10], ring fiber with air center [11–13], trench-assisted ring fiber [14] and the inverse-parabolic graded-index profile [15]. The class of ring fiber designs has shown much promise for enabling the km-length stable OAM modes propagation and this design concept has been exploited adequately including the OAM scalability problem in Ref. [16]. The ring fiber structure also has the advantage of being easy to fabricate compared with that of multi-core fiber (MCF) and its concentric-ring structure is helpful to realize optical signal amplification [17,18].

Most previous OAM fiber designs have only one guided regions. In 2009, Ramachandran proposed a kind of ring fiber with an additional monomode core in the center, the OAM modes with $l = \pm 1$ order can propagate in the ring region [19]. In this work, we propose another kind of dual-guided ring-core fiber (DG-RCF) with two guided regions. By carefully designing the refractive index profile (RIP) of the fiber, the central-core of the fiber enables the fundamental mode transmission as it usually does in a conventional single mode fiber (SMF), while the ring area can support the multi-OAM modes transmission. Besides, the simulation result shows that the power crosstalk between the two guided regions is almost negligible in the proposed fiber.

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2. The principle of vector modes and the OAM modes in fibers

The full-vector finite-element method (FEM) with perfected matched layer (PML) at the outer boundary is used as the analysis tool to compute the effective refractive index and the electromagnetic field distribution of the exact vector solution (true eigenmodes) of the designed fiber [20]. Commercial software COMSOL Multiphysics provides the FEM mode solver. For a given fiber, once the RIP is determined, the supported vector modes of the fiber are also fixed.

The azimuthally polarized TE mode and radially polarized TM mode do not carry OAM. Each mixed mode (HE or EH) has two degenerate modes (even and odd modes). OAM modes are formed by these two basis of vector modes through coherent combinations. OAM modes can be regarded as superposition of the exact vector modes based on the following formation rules:

$$\mathrm{OAM}^{\pm}_{\pm l,m} = \mathrm{HE}^{\mathrm{even}}_{l+1,m} \pm j\mathrm{HE}^{\mathrm{odd}}_{l+1,m} \tag{1a}$$

$$\mathrm{OAM}^{\mp}_{\pm l,m} = \mathrm{EH}^{\mathrm{even}}_{l-1,m} \pm j\mathrm{EH}^{\mathrm{odd}}_{l-1,m} \tag{1b}$$

To support stable OAM modes transmission, the minimum effective index separation (Δn_{eff}) between two constituent HE or EH modes should be larger than the threshold of 1×10^{-4}, in order to reduce the possibility of mode coupling and avoid degeneration into "LP modes". This criterion is demonstrated by [12,19]. In theory, as the Δn_{eff} increases, the number of supported OAM modes also increases, but at the cost of other undesirable effects such as dispersion, differential mode delay, modal birefringence, etc. Therefore, there must be a trade-off between the maximum number of OAM modes and the fiber performance metrics.

3. Design of the proposed fiber

The cross-section of the proposed DG-RCF is shown in Fig. 1. The proposed fiber is made up of Schott glasses within the standard telecom single mode fiber dimensions (diameter of 125 μm). The geometric structure is characterized by a center-core of radius a, a ring with the inner and outer radii of b and c. The refractive index profile is determined by three refractive indices, n_1 the index of the center-core (Schott BK7), n_2 the index of the inner-cladding and the outer-cladding (Schott K7) and n_3 the index of the ring (Schott BAK1). The specific parameters of the fiber used in our simulation are listed in Table 1.

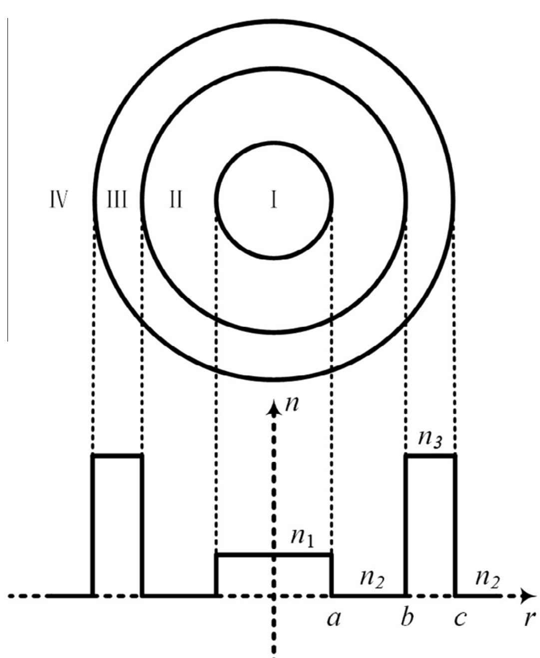

Fig. 1. Cross-section of the designed fiber: (top) geometric structure; (bottom) refractive index profile.

The refractive index (RI) of these glasses varies with wavelength can be calculated by using the Sellmeier equation with a three-oscillator form [21].

$$n_1^2(\lambda) = 1 + \frac{1.03961212\lambda^2}{\lambda^2 - 0.00600069867} + \frac{0.231792344\lambda^2}{\lambda^2 - 0.0200179144} + \frac{1.01046945\lambda^2}{\lambda^2 - 103.560653} \tag{2a}$$

$$n_2^2(\lambda) = 1 + \frac{1.1273555\lambda^2}{\lambda^2 - 0.00720341707} + \frac{0.124412303\lambda^2}{\lambda^2 - 0.0269835916} + \frac{0.827100531\lambda^2}{\lambda^2 - 100.384588} \tag{2b}$$

$$n_3^2(\lambda) = 1 + \frac{1.12365662\lambda^2}{\lambda^2 - 0.00644742752} + \frac{0.309276848\lambda^2}{\lambda^2 - 0.0222284402} + \frac{0.881511957\lambda^2}{\lambda^2 - 107.297751} \tag{2c}$$

The relative refractive index difference (RRID) of the DG-RCF is defined as follows

$$\Delta_1 = \frac{n_1^2 - n_2^2}{2n_1^2} \tag{3a}$$

$$\Delta_2 = \frac{n_3^2 - n_2^2}{2n_3^2} \tag{3b}$$

The relationship between the relative refractive index difference and wavelength is given in Fig. 2. We note that the design of n_1 and n_2 satisfies the weakly guiding approximation (WGA) condition where $\Delta_1 = 3.48 \times 10^{-3} \ll 1$ at 1550 nm. We also note that the radius of center-core is 3.5 μm which satisfies single mode condition. Therefore the center-core supports the fundamental HE_{11} modes, as it does in the telecom single mode fiber. Whereas, the high-contrast-index ring structure ($\Delta_2 = 3.77 \times 10^{-2}$ at 1550 nm) can support OAM modes transmission.

4. The features of the proposed fiber

In this paper, the modal properties of the DG-RCF are analyzed by using numerical simulation within the wavelength range from 1520 nm to 1580 nm (according to the standard of ITU-Grid C-band wavelengths from 1520.25 nm to 1579.52 nm).

By sweeping the wavelength, we can obtain the effective index of each vector mode as a function of wavelength and the results are illustrated in Fig. 3. Here the suffix "c" represents the guided modes in the central-core. The $\mathrm{OAM}_{\pm 4,1}$: {HE_{51}, EH_{31}}, $\mathrm{OAM}_{\pm 3,1}$: {HE_{41}, EH_{21}}, $\mathrm{OAM}_{\pm 2,1}$: {HE_{31}, EH_{11}} and $\mathrm{OAM}_{\pm 1,1}$: {HE_{21}} mode

Table 1
Fiber parameters at 1550 nm.

Wavelength	λ	1550 nm
Center-core	n_1	1.5007
Claddings	n_2	1.4954
Ring	n_3	1.5552
Core radius	a	3.5 μm
Inner radius of the ring	b	7.0 μm
Outer radius of the ring	c	7.5 μm