A design strategy of the circular photonic crystal fiber supporting good quality orbital angular momentum mode transmission

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ABSTRACT

Based on 5 requirements which are essential for stable OAM mode transmission, we propose an OAM fiber family based on a structure of circular photonic crystal fiber (C-PCF). The proposed C-PCF in the family is made of pure silica, with a big round air hole at the center, several rings of air-hole array as the cladding, and a ring shaped silica area in between as the core where the OAM modes propagate. We also provide a design strategy with which the optimized C-PCF can be obtained with optimum number of high quality OAM modes (up to 42 OAM modes), large effective index separation for corresponding vector modes over a wide bandwidth, relative small and flat dispersion, and low nonlinear coefficient compared with a conventional single mode fiber. The designed fiber can be used in MDM communications and other OAM applications in fibers.

1. Introduction

A light beam with the spiral phase front $\exp(il\varphi)$ carries an orbital angular momentum (OAM), where, l is a integer called as topological charge, φ is azimuthal angle [1,2]. OAM beam has recently spurred tremendous interests because of its wide potential applications, in the field of optical manipulation [3], quantum information [4], imaging [5] and communications [6,7]. The orthogonality between different OAM states provides another dimension (mode division multiplexing, MDM) to be multiplexed to solve the currently urgent requirements for data capacity [7–10]. Terabit data transmission in a fiber carrying OAM modes has been demonstrated [7]. Since OAM modes in fibers can be properly constituted by the even and odd modes of a vector mode with the identical propagation constants, they will not undergo intermodal work-off effect. But the mode degeneracy between corresponding HE and EH eigenmodes will lead to strong modal coupling (couple into LP modes), subsequently break the stability of OAM modes transmission, and hence cause the serious crosstalk. To handle these problems, a specially designed optical fiber is required to possess high effective refractive index separation ($> 10^{-4}$) between different vector modes in the fiber [11,12] to avoid modal coupling and to be free from complex multi-input multi-output (MIMO) treatment at the receiver. Recently, a

ring shaped or annular shaped fiber was designed with a high index ring area as the ring core to hold OAM modes, and its central circle area and cladding are with lower indices [13–22]. The high index contrast between the ring core and cladding is achieved by up-doping in ring core area. So far, ring fibers can support 9 orders of OAM (34 OAM modes) or 36 information bearing states [18]. However, heavily up-doping may result in higher fiber loss [21].

Compared with the conventional fibers, photonic crystal fibers (PCFs) [23,24] have more flexible structure design to provide unique fiber properties such as endlessly single mode [25], controllable nonlinearity and confinement loss [25,26], tailorable chromatic dispersion [26,27]. The structure of PCF used to realize the OAM modes transmission has potential application prospects in fiber communications. In Ref. [28] the ring photonic crystal (ring-PCF) with hexagonal air hole array as cladding was proposed which can only support less number of OAM modes (4 OAM modes) with bad mode quality. We find that the hexagonal structure of air holes is not a good design for its not good OAM mode quality and higher confinement loss. The reason is that hexagonal structure with noncircular symmetry is not consistent with ring shaped intensity of OAM modes.

In order to gain more numbers of OAM mode and better mode field quality, we presented a new structure of circular shaped PCF (C-PCF)
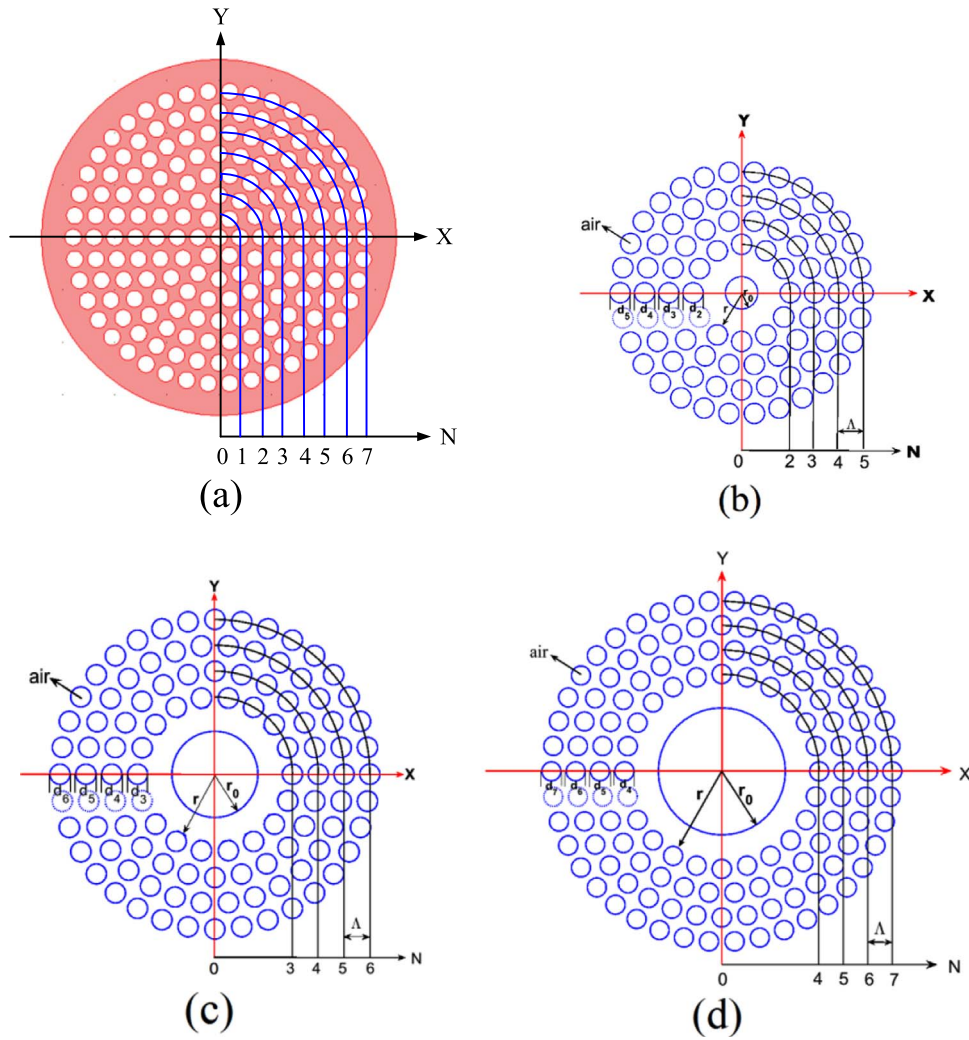
Fig. 1. Cross-section and main parameters of the designed C-PCFs for (a) the fiber base, (b) C-PCF 1#, (c) C-PCF 2#, (d) C-PCF 3#.

[29] with circular symmetry which has a large air-hole in the center, and a circular shaped air-hole array rather than the hexagonal air holes as cladding. Compared with the ordinary ring fibers, the C-PCF has more advantages such as getting high index contrast without up-doping, larger fiber bandwidth, good mode quality, lower confinement loss, and larger fabrication tolerance [30]. Recently, Ref. [31] presented a microstructure ring fiber (MRF) with the equally number of air holes in three different cladding rings to obtain the circular symmetry. The hole size of the proposed fiber is different in every ring. And the proposed MRF has narrow bandwidth and higher confinement loss. Ref. [32] adopted the similar fiber structure with that of Ref. [31], but the material of the fiber is the As$_2$S$_3$ glass. This kind of fiber has larger loss and high nonlinearity which is not suitable for the OAM mode transmission, while suitable for supercontinuum generation.

In this paper, we summarize 5 essential requirements to ensure the OAM modes stable transmission in optical fiber, and based on which an OAM fiber family with the structure of ring circular PCF are proposed to realize MDM in optical communication systems. A detail fiber design strategy is presented under which the C-PCFs are designed to possess good features. Comparing the properties of three C-PCFs, we can find that C-PCF 3# has the maximum number of high quality OAM modes (11 OAM orders or 42 OAM modes), the relative wide bandwidth (460 nm from 1.25 μm to 1.71 μm) with large effective index separation of different vector modes, relative small and flat dispersion, low confinement loss and low nonlinear coefficient compared with a

conventional single mode fiber. Furthermore, it is proved that the ring thickness of the presented C-PCF has a relative large fabrication tolerance about 0.6 μm both to guarantee the good mode quality and suppress the high order radial modes. So this kind of fiber is suitable to be used in MDM systems for long distance.

2. Design strategy of the C-PCF supporting OAM modes

OAM modes in fibers are defined as OAM$_{l,m}$, where m is the number of concentric rings of the intensity profile of the mode in radial direction, l(l∈Z) is the topological charge. OAM modes in fibers can be regarded as the superposition of the vector eigenmodes by following relations:

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

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

where the sign in superscript '±' denotes the right or left circular polarization, and the sign of ±l denotes the right or left wave front rotation direction, odd and even modes of HE or EH denotes a π/2 azimuthal rotation, j presents a π/2 phase shift. HE mode has the same directions of spin angular momentum (SAM) and OAM, while EH mode has the opposite directions of SAM and OAM. The OAM$^{\pm}_{0,m}$ mode composed by HE$_{1,m}$ with two circular polarizations can not be used as OAM mode for it carries no OAM. Moreover, the OAM$^{\mp}_{\pm\ 1,m}$ mode composed by azimuthally polarized TE$_{0,m}$ and radially polarized TM$_{0,m}$