Optics Communications 368 (2016) 27–33

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Invited Paper

A multi-orbital-angular-momentum multi-ring micro-structured fiber with ultra-high-density and low-level crosstalk

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ARTICLE INFO

Article history:
Received 26 October 2015
Received in revised form
3 January 2016
Accepted 5 January 2016
Available online 4 February 2016

Keywords:
Orbital angular momentum (OAM)
Multi-OAM multi-ring micro-structured fiber (MOMRMF)
Low crosstalk
Space-division multiplexing (SDM)

ABSTRACT

In this paper, a novel multi-orbital-angular-momentum multi-ring micro-structured fiber (MOMRMF) is proposed for the first time. This compact MOMRMF is presented with 19 rings, each ring supporting 36 modes (34 of them are OAM ones i.e., 684 channels in total) over the whole C wavelength band (1520–1580 nm). Due to the large refractive index difference between silica and air, the effective refractive index (n_{eff}) differences between the adjacent eigenmodes are all larger than 10^{-3}, which is practically impossible to gain in other traditional high-density OAM fibers fabricated by modified chemical vapor deposition (MCVD) method. Compared with the trench-assisted multi-OAM multi-ring fiber (TA-MOMRF), the lower-level inter-ring crosstalk in the designed MOMRMF also can be achieved by the air hole-assisted. It is believed that both the high-density and low-level crosstalk make such a fiber of great potential in the space-division multiplexing (SDM) system.

1. Introduction

Large capacity data transmission over the optical fiber communication system becomes more and more urgent due to the data explosion. Thus, the space-division multiplexing (SDM), which is developed as an alternative way for keeping up with the capacity demand over a single fiber, has been attracting great attention increasingly from the research community [1–3]. Among all the solutions, one promising option is to use the orbital angular momentum (OAM) of light, which includes a helical phase term of $\exp(il\varphi)$ in its wave-front, (where φ is the azimuth angle and l determines the OAM topological charge), that yield multiple orthogonal light paths [4–6]. The OAM modes, in theory, can have infinite values of topological charge, which opens up an additional degree of freedom for promoting the capacity of communication and facilitating flexible manipulation of data. The terabit free-space data transmission employing OAM multiplexing has already been reported [7]. Zeilinger et al. experimentally demonstrated the 3 km transmission in free space [8].

Although the adorable results have been achieved in free space, there is a significant interest in the potential to use OAM for MDM in the fiber. Thus, many special optical fibers are designed to support the OAM modes. However, the OAM beams are considered to be unstable owing to mode coupling and only employed in short-length fiber propagation [9,10]. The reliable transmission over km-length fiber without multiple-input multi-output (MIMO) techniques was demonstrated [11]. In this experiment, the fiber specially designed could support the fundamental mode and first order OAM modes. At present, the stable transmission over km-length was achieved in eight modes [12], and 36 states through sub-meter lengths were also reported [13]. It was also demonstrated that the SDM employing few mode multi-core fiber (FM-MCF) has boosted the density of information [14]. Thus, it is believed to be valuable to combine the OAM multiplexing with multi-core-like structure for ultra-high density SDM application. To some degree, the multi-OAM multi-ring fibers (MOMRF) multiplexing is akin to SDM using the FM-MCF, where both inter-mode crosstalk and inter-ring crosstalk should be considered [15].

In this paper, a novel multi-OAM multi-ring micro-structured fiber (MOMRMF) with the pure silica and solid core is firstly proposed for transmitting the higher topological charge OAM modes. Because no other doped materials are mixed, it is not necessary to deposit ring layer of SiO_2 and GeO_2 to gain high index contrast, and complex modified chemical vapor deposition (MCVD) process can be avoided. Compared with the previous

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http://dx.doi.org/10.1016/j.optcom.2016.01.009
0030-4018/

works [16,17], causing the air hole cladding assisted, both the inter-mode crosstalk and inter-ring crosstalk of this proposed fiber are much lower than that of the traditional OAM fibers. Due to the limit of appropriate materials and engineering feasibility, it is impossible to fabricate a ring fiber supporting large numbers of OAM modes by the technique of MCVD, whose n_{eff} difference of adjacent OAM modes are all on the order of 10^{-3}. However, the micro-structured fiber (MF) designed can achieve this goal. What's more, the inter-ring crosstalk can be suppressed effectively (< -56 dB with the propagation length of 100 km) owing to the air holes introduced between neighboring ring cores. This performance of the fiber is also better than that of TA-MOMRF. In total, this designed MOMRMF has 19 rings, where each ring supports 36 modes (34 OAM ones), i.e., 684 channels over the whole C wavelength band. Although the propagation loss of the MF is usually higher than that of traditional fiber, the level is acceptable for the possibly short-distance communication, e.g. broadband optical access network and indoor optical fiber communications to end users. Besides, it has already been reported that few mode MF was utilized in SDM system [18].

2. Fiber design

In order to avoid the modal coupling, the high effective refractive index (n_{eff}) contrast is adopted. A novel MOMRMF is proposed, whose 3D model is shown in Fig. 1(a). To compare the previous work [17], the same ring pitch Λ=25 and cladding diameter D=125 μm are adopted. Fig. 1(b) illustrates schematic cross-section of a single ring matching OAM beams, which are usually excited by spatial light modulator (SLM). For a common MF, since the fiber profile is an asymmetric circle, leading to the large difference of n_{eff} between the even and odd mode of $\mathrm{HE}_{l+1,1}$ or $\mathrm{EH}_{l-1,1}$, which will hinder the OAM modes comprised. So the air holes are arranged as a circle instead of a hexagon in our design for the first time. As well known, more air holes will lower the cladding index and give better circle symmetry as well. However, when a fiber is fabricated, the engineering process will be more complicated as the number of air holes increases. Thus, 21 air holes are arranged in each ring in this particular design. The large air-filling fraction will prevent the higher-order modes from leaking out through the gap, so four layers air hole-assisted cladding are used. Actually, the diameter of air-holes in the outermost ring d_4 has little influence on the modes confined in the ring core, but evident influence on suppressing the overlap integral of electric field distribution in each ring core, which can greatly reduce the inter-ring crosstalk. In Fig. 1, L_1, L_2, L_3, and L_4 represent the distances between the different air layers and central point. And there are five sizes of air holes, which are labeled by d_0, d_1, d_2, d_3, and d_4, respectively. The gray background and blue region represents the pure silica and air hole, respectively.

The redrawing technique can be used to fabricate this fiber, one viable method is. The single ring-core preform is obtained by stacking the silica capillaries, where d_{0o}, d_{1o}, d_{2o}, d_{3o}, and d_{4o} represent the diameters of capillary tube in different layers, respectively. Fig. 2 shows the geometrical relationship between L_2, d_{2o} and L_1, d_{1o} as the following equation:

$$L_2 = \left[2\left(L_1 \cos\theta + \frac{d_{1o}\sin\theta}{2} \right) + \sqrt{4\left[\left(L_1\cos\theta + \frac{d_{1o}\sin\theta}{2} \right)^2 - \left(L_1{}^2 - \left(\frac{d_{1o}}{2} \right)^2 \right)\cos^2\theta) \right]} \right] / 2\cos^2\theta$$

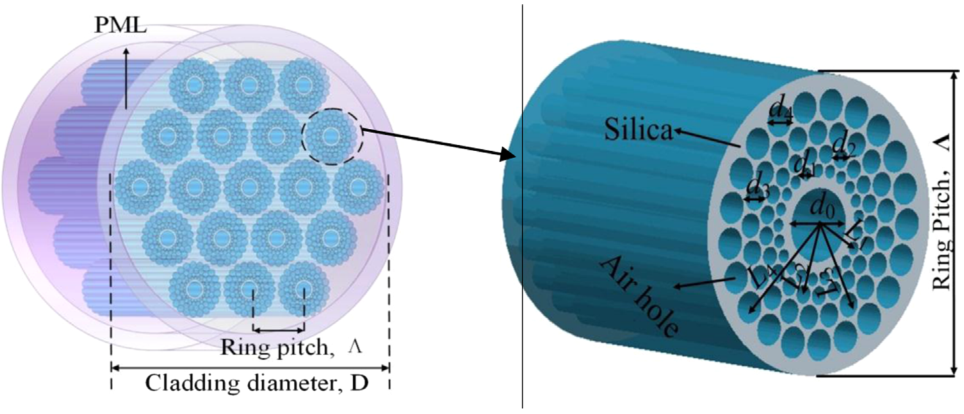
$$d_{2o} = 2 \times L_2 \sin\theta \tag{1}$$

where $L_1 = d_{1o}/2\sin\theta$ and $d_{1o} = d_{0o} \times \sin\theta/(1 - \sin\theta)$. Based on this principle, it presumes that if the number of the air holes (21) and value of d_{0o} are given, the other geometrical parameters (L_1, L_2, L_3, L_4, d_{1o}, d_{2o}, d_{3o}, d_{4o}) can be calculated. The design tools for the single ring-core fiber supporting OAM modes have been analyzed in detail, which can be also applied to design the special MF [19]. However, it is difficult to determine the parameters of the fiber to keep the balance between the number of states and separation of adjacent eigenmodes. To achieve our aim of supporting ten-order vector modes, meanwhile, the concentric intensity is single and n_{eff} differences of adjacent eigenmodes are all larger than 10^{-3}. According to the design tools, the ratio p and normalized frequency v_0 should be considered, which can be expressed by the following equation:

$$p = \frac{d_0/2}{L_1 - d_1/2} \tag{2}$$

$$v_0 = k_0 \times \left(L_1 - \frac{d_1}{2} \right) \times \sqrt{n_{co}^2 - n_{cl}^2} \tag{3}$$

where k_0 is the wave number in vacuum, n_{co} and n_{cl} are the effective refractive index of ring core and cladding. In order to suppress the higher radial order, defined as the number of the concentric intensity ring in a guided mode, the ratio p should be high. If the fiber would support ten-order vector modes with



(a) (b)

Fig. 1. (a) 3D structure of MOMRMF. (b) Cross section of a single ring. d_0, d_1, d_2, d_3, and d_4 are the diameters of air holes, L_1, L_2, L_3, and L_4 represent the distances between different air layers and central point.