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Spiral photonic crystal fiber structure for supporting orbital angular momentum modes

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ABSTRACT

We propose a spiral photonic crystal fiber structure for supporting orbital angular momentum modes. The structure has 12 arms, arranged in a spiral shape in the cladding region, and a big air hole at the center of the structure. It can support 14 well-separated OAM modes with a mode index difference of 10^{-4}. Our numerical results show a nonlinear coefficient of 2.78 W^{-1} Km^{-1} for the HE_{21} mode at 1550-nm wavelength. The fiber shows a dispersion difference over a 600 nm bandwidth for HE_{21} mode is 12.1 ps/km-nm, and the structure shows a low confinement loss. We have also calculated the effect of ellipticity on the mode's effective index. Numerical results suggest that, this structure can be utilized in high-capacity communication systems for multiplexing fiber-based OAM.

1. Introduction

Space division multiplexing (SDM) has been the subject of significant recent attention because of its potential application in scaling network capacity [1–3]. Few-mode fiber communication system technologies use the multiple-input multiple-output (MIMO) signal processing method to recover the information [3] from multiplexed systems. However, MIMO is not the only available system applicable in higher-order mode fiber systems. Orbital angular momentum (OAM) beams with a helical phase are advantageous for higher order mode fiber communication systems [4,5]. As the modes of OAM are orthogonal to each other, no coupling exists between the modes. The OAM beam is expressed by $exp(il\varphi)$, where φ represents the azimuthal angle and l is the topological charge number [5,6]. Due to these properties, OAM modes in specialty fiber show a variety of dimensions for multiplexing. Since an OAM beam comprises ring-shaped intensity distributions with a particular angular momentum, the beams can be used for several applications including super resolution imaging [7], optical communication [8–10], entanglement of photons [11], and particle trapping [12]. Generally, OAM beams are generated using spatial phase plates [13], computer generated holograms [14], ring resonators [15], and birefringent elements [16,17]. Compared to the free space OAM communication, propagation and generation of OAM beams in a fiber have considerable significance. In free space, OAM beams are enlarged with increasing propagation distance, but in the case of fiber, the beams can propagate over large distances with low crosstalk. Recently, a considerable amount of work has been carried out in the field of fiber-based OAM, in which, ring core fibers, air core fibers, and fiber couplers were reported to support the propagation of the OAM modes [18–22]. However, on the one hand, when crosstalk is reduced by the fibers, the number of OAM modes is restricted, and this number is vitally important in high-capacity communication systems. Therefore, it is necessary to investigate fiber structures having a large number of OAM modes. Over the years, photonic crystal fibers (PCFs) have been of great significance in communication [23,24]. Yue et al. showed that the transmission of OAM modes was supported by a PCF structure with As_2S_3. The PCF design reported the two OAM modes [25]. Zhang et al. numerically demonstrated the generation of OAM modes in a circular PCF

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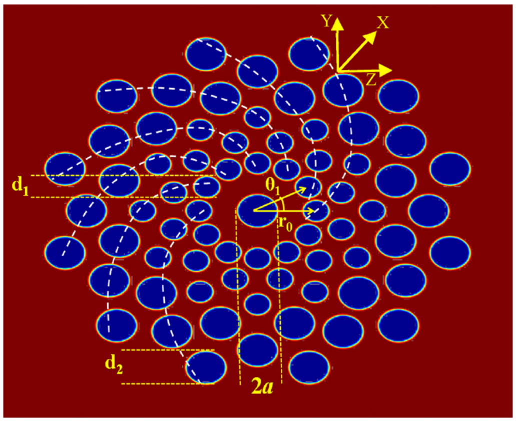

Fig. 1. Cross-section of the proposed PCF.

[4]. In the present work, our aim is to design an optical fiber that can support several OAM modes with specialty fiber.

In this paper, we propose a novel spiral PCF structure with spirally arranged air holes in the cladding, which can support 14 OAM modes. Numerical simulations suggest that the use of suitable PCF parameters will permit the accommodation of many OAM modes. Our study illustrates a low dispersion variation of 10.35 ps/km-nm for the TE_{01} mode, and 12.1 ps/km-nm for the HE_{21} mode with a 600 nm bandwidth.

2. Proposed spiral design

The schematic of Fig. 1 illustrates our proposed spiral PCF structure with the given design parameters to support the propagation of OAM modes. The present PCF structure consists of 12 spiral arms, where each spiral arm contains 6 air holes, in addition a big air hole arranged at the center. The optical fiber is made of silica. In each arm, the first three air holes have a diameter d_1, and the next three air holes have a diameter d_2. The distances between the center to the first air hole is r_0 and the distance between center to second air hole is $r_1 = (0.48 \times \Lambda) + r_0$ respectively, where Λ is the distance between two adjacent holes. The angular displacement is $\theta_1 = 180/N_a$, where N_a is the number of arms in the PCF [26,27]. The distance between the center to the n^{th} hole is $r = (0.48 \times \Lambda) + r_{n-1}$, and the n^{th} angular displacement is $\theta_n = (n \times 180)/N_a$. Lumerical eigen-mode solver has been used to analyze the mode fields [28], and modes' effective indices are calculated from propagation constants [29]. The structure supports TE_{01}, TM_{01}, and 14 OAM modes, in which the azimuthally polarized and radially polarized modes do not carry the OAM. The OAM modes in the fiber can be described as being combinations of even and odd modes of HE and EH [4].

$$\left.\begin{array}{lll} OAM^{\pm}_{\pm l,m} & = & HE^{even}_{l+1,m} \pm i\, HE^{odd}_{l+1,m} \\ OAM^{\mp}_{\pm l,m} & = & EH^{even}_{l-1,m} \pm i\, EH^{odd}_{l-1,m} \end{array}\right\} \tag{1}$$

The 14 OAM modes supported by the structure are $OAM^{\pm}_{\pm 1,1}$ (HE_{21}), $OAM^{\pm}_{\pm 2,1}$ (HE_{31}, EH_{11}), $OAM^{\pm}_{\pm 3,1}$ (HE_{41}, EH_{21}), and $OAM^{\pm}_{\pm 4,1}$ (HE_{51}, EH_{31}). We achieved a large effective index difference for the HE group modes (and EH group modes) as a result of which the PCF achieves stable OAM modes. Adjusting the design parameters, the structure allows the accommodation of a large number of OAM modes with low dispersion variation. A design of this sort would have value in high-capacity communication systems where mode division multiplexing is required.

3. Numerical results and discussions

The proposed structure has been investigated numerically for the following fiber parameter values. The arms have air holes with two diameters: diameter 'd_1' (small air holes) is 2.2 μm and diameter 'd_2' (big air holes) is 3.4 μm. The diameter of the center air hole ($2a$) is 3.4 μm. Commercial software was used to calculate the effective indices of the following supported modes: TE_{01}, TM_{01}, HE_{11}, HE_{21}, HE_{31}, EH_{11}, HE_{41}, EH_{21}, HE_{51}, and EH_{31}. The structure contributes four OAM order modes with different topological charges l, and the $l = 0$ mode, or HE_{11} mode, has not been considered in the 14 OAM modes. Fig. 2 shows the plot of the intensity distribution for the OAM modes at a wavelength of 1550 nm. The figure shows that the OAM modes are largely restricted to the annular region. Next, we calculated the vector plots of the OAM modes, and the results are plotted in Fig. 3, which shows the vector notations of the OAM modes. As seen in the figure, similar values of m have different vector notations, which means that the same value of m results in different polarization patterns. The modal field distribution for the OAM modes along with their radius is illustrated in Fig. 4. As the mode number increases, the width of the annular intensity distribution slightly decreases. This figure also shows that the mode distribution has a good confinement in the high index region, and it can be concluded that the proposed design will overcome the coupling of multiple OAM modes into the annular index fiber system. In Fig. 5 we have plotted the propagation of HE_{21} even mode in