Optics and Laser Technology 107 (2018) 162–168

Contents lists available at ScienceDirect

Optics and Laser Technology

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

Full length article

Hole-assisted polarization-maintaining few-mode fiber

Han Xiao, Haisu Li *, Shuisheng Jian

Key Laboratory of All Optical Network and Advanced Telecommunication Network of EMC, Institute of Lightwave Technology, Beijing Jiaotong University, Beijing 100044, China

ARTICLE INFO

Article history:
Received 23 March 2018
Received in revised form 29 April 2018
Accepted 23 May 2018

Keywords:
Optical fibers
Few mode
Polarization maintaining
Optical fiber communications

ABSTRACT

We propose a novel polarization-maintaining few-mode fiber by introducing four identical circular side-holes surrounding an elliptical ring core. In addition to the parameters of ring core, this kind of fiber endows new degrees of freedom to adjust the modal birefringence of guided modes. Numerical simulations indicate that such fiber could support 10 distinct polarization modes, including the effectively separated fundamental modes. The influences of side-hole size and positions on the polarization-maintaining property are investigated for the 10-mode fiber. With appropriate parameters of side-holes, the minimum effective refractive difference (Δn_{eff}) between adjacent modes is 1.65×10^{-4} at 1550 nm. Compared with the fiber excluding side-holes, the modal effective refractive indexes are decreased while most Δn_{eff} values are enlarged in the proposed fiber. Moreover, all the Δn_{eff} values could be higher than 1.52×10^{-4} over a bandwidth ranging from 1510 nm to 1630 nm. The chromatic dispersion covering the broadband is analyzed subsequently. Furthermore, 16 vector modes could be guided in the proposed fiber structure with modified parameters. The proposed fiber is capable of supporting extended modes and might be a promising candidate toward high–capacity spatial-division-multiplexing communications.

1. Introduction

The ever-increasing consumer demand and machine-to-machine network traffic are now creating big challenges for the optical communication capacity [1]. Spatial-division-multiplexing (SDM), as a promising technique to break the coming capacity crunch, has currently inspired great interests [2]. Multi-core fibers (MCFs) [3,4] and few-mode fibers (FMFs) [5,6] are intensely investigated and developed as two efficient approaches to realize high-density SDM. Generally, MCF integrates multiple independent cores for parallel signal transmission [4,7]. In order to integrate more independent cores in a single fiber, the fiber cross-section area enlarges, which would increase the fabrication complexity. Another approach for SDM system is using the FMF, wherein the guided modes are spatially overlapped. Up to date, numerous FMFs have been proposed and demonstrated [8–13]. Regarding FMF based SDM transmission link, multi-input and multi-output (MIMO) digital signal processing (DSP) is generally performed as an essential requirement to compensate the crosstalk between optical modes [8,14]. Nevertheless, the system complexity and energy consumption increase dramatically as the number of guided modes in FMF increases. To simplify or even eliminate the implementation of MIMO DSP, an efficient solution is enlarging the difference of effective refractive index (Δn_{eff}) between adjacent modes via novel fiber design. In previous reports, it has been experimentally confirmed that with Δn_{eff} beyond 10^{-4}, modal crosstalk could be suppressed in MIMO-free transmission systems [9,10].

Currently, ring core FMFs [15,16], elliptical core FMFs [10,12,17], elliptical ring core FMFs [9,18] and PANDA FMFs [11,19] have been proposed and demonstrated as candidates for separating spatial modes and reducing mode coupling. The ring core fiber has been achieved to support higher-order vector modes with Δn_{eff} beyond 10^{-4} towards orbital angular momentum modes transmission [16]. In 2012, Riesen has proposed a polarization-maintaining FMF (PM-FMF) featuring an elliptical core with step-index profile [12]. Nevertheless, a trade-off between high Δn_{eff} values and the cut-off of higher-order modes occurs. The elliptical ring core PM-FMF avoids the trade-off and eight higher-order vector mode channel transmission over 0.9 km without MIMO DSP has been achieved experimentally [9]. However, the two fundamental polarization modes are still degenerate in this FMF. Recently, a PM-FMF comprised of an elliptical ring core and a concentric circular hole has been reported to separate all guided modes. The two fundamental polarization modes are separated and Δn_{eff} values between all adjacent guided modes are above 1.32×10^{-4} over C + L band [13].

* Corresponding author.
E-mail address: lihaisu@bjtu.edu.cn (H. Li).

https://doi.org/10.1016/j.optlastec.2018.05.043
0030-3992/© 2018 Published by Elsevier Ltd.

Meanwhile, optical fibers with side-holes in cladding have found intriguing applications. For example, single-mode fibers with side-holes have been realized and applied in birefringence-based and interference-based sensing systems [20–23]. Very recently, dual side-holes have been introduced in circular-ring core fiber to support PM few-mode transmission [19]. In this paper, we propose a novel PM-FMF combining an elliptical ring core with four circular side-holes. The size and positions of side-holes could be adjusted to obtain Δn_{eff} values between all adjacent modes higher than 10^{-4}. With appropriate optical and structural parameters, 10 vector modes are supported in the PM-FMF. The modal properties in the proposed fiber are compared with those in elliptical ring core fiber with the same parameters. The wavelength dependence over 1510–1630 nm is studied, indicating a relatively low chromatic dispersion. Furthermore, by modifying structural parameters of ring core and side-holes, the number of guided modes can be extended to 16, making it a potential structure in dense SDM applications.

2. Fiber structure and simulation parameter

The schematic cross-section and defined parameters of the proposed PM-FMF are shown in Fig. 1, where four circular side-holes are added to an elliptical ring core fiber. The diameter of fiber cladding is assumed to be 125 μm. The refractive index values of fiber cladding and air are set to be 1.444 and 1, respectively. The radii along x-axis and y-axis are denoted as b_x and b_y for the outer core edge, and as a_x and a_y for the inner core edge, respectively. The ellipticity is represented as $\eta = b_x/b_y = a_x/a_y$. Four identical side-holes locate symmetrically with respect to the fiber core. The distances between the center of fiber and the center of side-holes along x-axis and y-axis are denoted as d_x and d_y, respectively. The radius of each hole is denoted as h. The refractive index of ring core is denoted as n_{ring}. The n_{ring} value is assumed to be 1.478 for 10-mode guidance in the proposed fiber. Such a high n_{ring} value can be realized with GeO_2 doping rate of 23.75% [13]. The structural parameters of elliptical ring core are from Ref. [18], which are $\eta = 1.4$, $\rho = 0.67$ and $b_x = 5.06$ μm, locating at their optimal regions in the context of enlarging Δn_{eff} (note that under this condition the Δn_{eff} value between fundamental modes are less than 10^{-4}). The fiber characteristics are numerically simulated with finite element method, where a perfectly matched layer is implemented surrounding the cladding.

3. Modal properties

According to the perturbation theory, modal birefringence can be introduced in waveguides with geometrical anisotropy [24]. Because of the elliptical deformation of ring core and the non-circular symmetrical distribution of side-holes, the modal profiles of vector modes supported in the proposed PM-FMF become linearly polarized (LP) distribution. Therefore, all guided modes are considered as LP modes in following discussions. The modes are named as the same as those in Ref. [25], where the superscripts represent polarization directions and the subscripts show the intensity patterns, respectively.

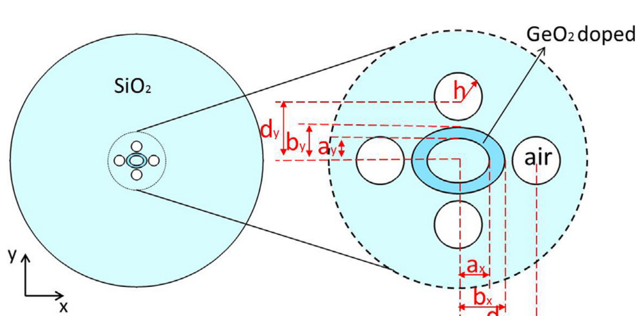

Fig. 1. Schematic cross-section and parameter definitions of the proposed PM-FMF with a GeO_2-doped elliptical-ring core and four side-holes.

To explore the impact of side-hole size on polarization-maintaining property, we first consider fiber with fixed positions of four side-holes. Fig. 2 (a) shows the effective refractive index (n_{eff}) curves of 10 guided vector modes as a function of side-hole radius h with $n_{ring} = 1.478$, $\eta = 1.4$, $\rho = 0.67$, $b_x = 5.06$ μm, $d_x = 8.5$ μm and $d_y = 7.0$ μm at 1550 nm. The dashed line indicates the refractive index of fiber cladding. With $d_x = 8.5$ μm and $b_x = 5.06$ μm, the radius of side-holes cannot be larger than 3.44 μm to prevent side-holes touching the ring core. Similarly, the h value should be smaller than 3.38 μm for the consideration in y-direction. Therefore, h is ranging from 0 μm to 3.3 μm with a step of 0.1 μm in simulations here. From Fig. 2 (a), n_{eff} values of all guided modes decrease gradually as side-hole size increasing. Moreover, the two

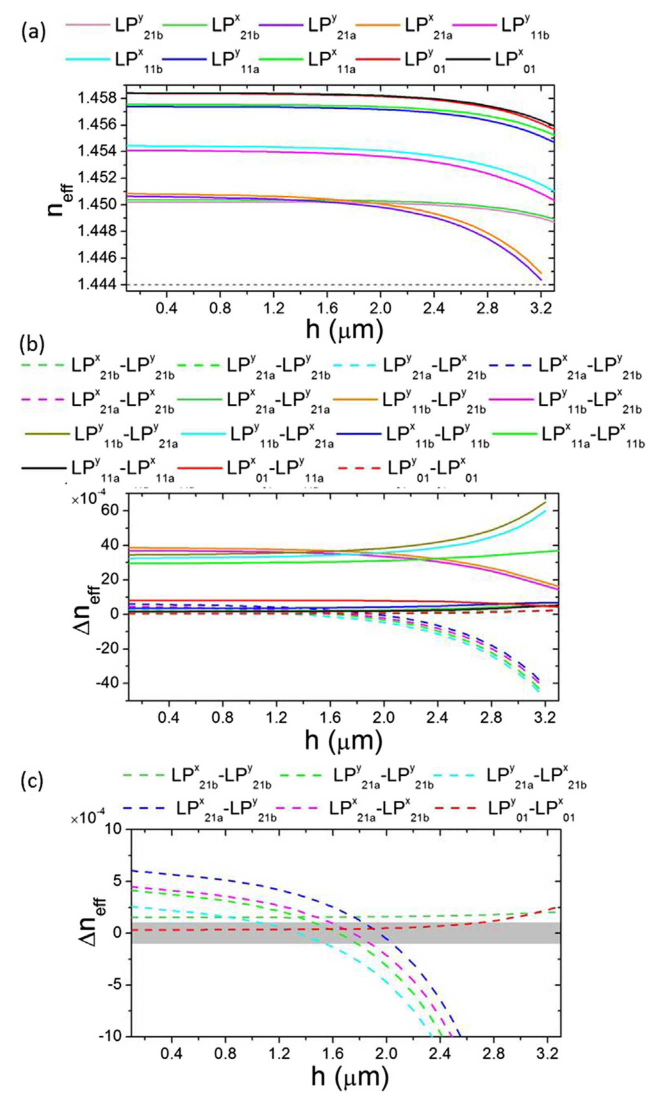

Fig. 2. (a) n_{eff} curves of all guided modes and (b) Δn_{eff} curves between all adjacent modes as a function of side-hole radius h for 10-mode PM-FMF at 1550 nm, (c) magnified image for the dashed curves of Δn_{eff} in (b). Parameters are $n_{ring} = 1.478$, $\eta = 1.4$, $\rho = 0.67$, $b_x = 5.06$ μm, $d_x = 8.5$ μm and $d_y = 7.0$ μm.