Demonstration of a Rectangular Core Few-mode Fiber with Ultra-low Differential Group Delay

Ruihuan Zhang(1, 3), Gang Chen(2), Yuanhang Zhang(3), Liangming Xiong(2), Haoshuo Chen(3), Nicolas K. Fontaine(3) and Yikai Su(1, *)

(1) State Key Lab of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

(2) State Key Laboratory of Optical Fiber and Cable Manufacture Technology, Yangtze Optical Fiber and Cable Joint Stock Limited Company (YOFC), Wuhan, 430073, China

(3) Nokia Bell Labs, 791 Holmdel Rd, Holmdel, NJ, 07733, USA

**E-mail: yikaisu@sjtu.edu.cn*

Abstract: We design and experimentally demonatrate a rectangular core few-mode fiber that can support the transmission of TE_{00}/TM_{00}, TE_{10}/TM_{10} and TE_{20}/TM_{20} modes with ultra-low differential group delays. © 2022 The Author(s)

1. Introduction

Driven by the exponential growth of data traffic in recent years, the transmission capacity supported by the conventional standard single-mode fiber (SMF) has already approached its theoretical limit, which is set by the Shannon's information theory and fiber nonlinear effects. Few-mode fibers (FMFs) have been proposed for years to guide several orthogonal transverse fiber modes in a single core to increase the transmission capacity. However, modes transmitted in an FMF tend to mix after a long distance, requiring a multiple-input and multiple-output (MIMO) digital signal processing algorithm to recover the original information [1]. To avoid the complex MIMO processing, weakly coupled FMFs have been proposed, such as elliptical core fibers (ECFs) [2], and rectangular core fibers (RCFs) [3]. The RCF can break the spatial degeneracy, thus eliminating the rotational symmetry of the fiber. The mode groups in the RCF are regularly distributed along the long side of the fiber core, which can significantly reduce the crosstalk among the modes. However, detailed properties of the RCF have not been experimentally demonstrated yet.

In this work, we designed and experimentally demonstrated an RCF that can support the transmission of TE_{00}/TM_{00}, TE_{10}/TM_{10} and TE_{20}/TM_{20} modes simultaneously. Ultra-low differential group delays (DGDs) are achieved with the designed RCF among the three modes on two polarizations. This work may open up a new window towards ultra-compact, high density, low cost, low computation complexity optical interconnects [4].

2. Design of the rectangular core few-mode fiber

The cross section of the proposed RCF is schematically shown in Fig. 1(a), where R is the cladding radius, a and b are the short and long side lengths of the rectangular fiber core, respectively. The cladding radius R is designed to be 62.5 μm, which is a typical value for the FMFs [5]. The dimensions of the rectangular core are designed according to the normalized frequency (V parameter) of the fiber.

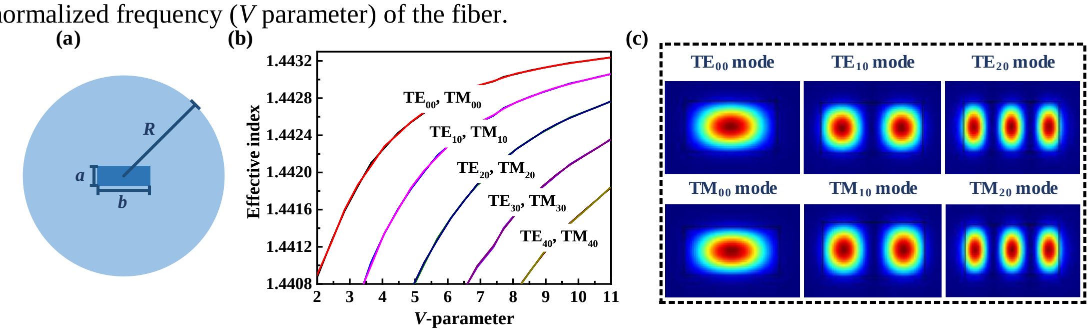

Fig. 1. (a) The cross section of the proposed RCF. (b) The dispersion curves of the RCF. (c) The calculated modal fields in the RCF, respectively.

In a standard step-index circular core fiber with a core radius r, and core and cladding indices of n_{co} and n_{cl}, the normalized frequency (V) can be defined as [6]:

$$V = \frac{2\pi r}{\lambda}\sqrt{n_{co}^2 - n_{cl}^2}\ . \tag{1}$$

The V parameter can be used to calculate the supported guided modes in step-index fibers. The V parameter should be smaller than 2.405 to ensure a single mode propagation for a SMF [7]. In this work, we choose $V = 3$ for the fiber to support two or more modes. In order to employ the concept of V parameter to RCF, we use half of the short side length of the core as the corresponding core radius of the RCF ($r = a/2$). The core and cladding indices of n_{co} and n_{cl} are chosen as 1.4435 and 1.44, respectively, to ensure its compatibility with the conventional fabrication technology of FMFs. Then, the corresponding core radius (r) of the RCF can be obtained according to Eq. (1), which is r = 7.5 μm. The short side length of the fiber core is $a = 2r = 15$ μm. The long side length of the fiber core is set as $b = 2a$ = 30 μm. Then, a finite-difference method (FDM) mode solver is used to characterize the RCF. Figure 1(b) shows the dispersion spectra of different modes with the increase of the V parameter. It can be noted that the curves are regularly spaced, indicating low crosstalk among these modes in the RCF. Figure 1(c) shows the supported modes in the RCF simulated at the wavelength of 1550 nm.

3. Fabrication and testing of the rectangular core few-mode fiber

The designed fiber was fabricated and tested. The numerical aperture (NA) of the fabricated fiber is 0.089. The fabricated dimensions of the rectangular fiber core are tested to be 13.70 nm and 30.40 nm, respectively. The cladding diameter of the fiber is 110 μm. Figure 2(a) shows the cross-section index profile of the fabricated RCF captured by a CCD. The modes that transmitted in the fiber are also tested as shown in Fig. 2(e). It can be obtained that there are three modes existing in the fiber, which are TE_{00}/TM_{00}, TE_{10}/TM_{10} and TE_{20}/TM_{20} modes, respectively. The DGDs of the three modes are also tested as shown in Fig. 2(b) and 2(c). The DGD values are ultra-low, which are 0.04 ps/m for TE_{10}-TE_{00}, and 0.12 ps/m for TE_{20}-TE_{10} modes, respectively. The transmission loss of the fiber is tested to be 7.8 dB/km at the wavelength of 1550 nm, as shown in Fig. 2(d), which is mainly due to the scattering loss induced by the fiber core imperfection and the light leaking loss in the high-index region of the cladding. The loss can be significantly decreased by optimizing the fabrication.

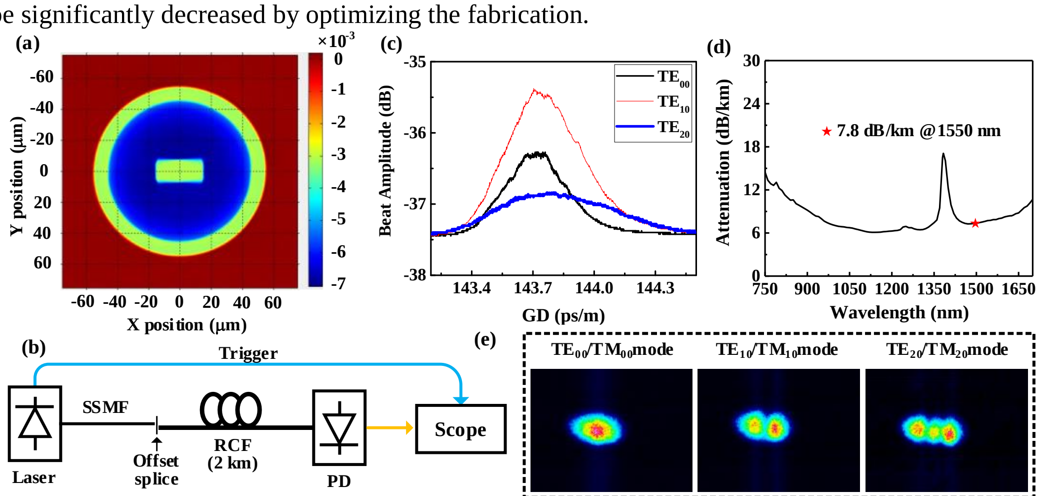

Fig. 2. (a) The cross-section index profile of the fabricated RCF. (b) Experimental setup for DGD testing. (c) DGD curves for TE_{00}, TE_{10} and TE_{20} modes. (d) Tested attenuation of the RCF.

4. Conclusion

We designed and experimentally characterized a step-index rectangular core FMF that can support the transmission of three spatial modes on two polarizations, which are TE_{00}/TM_{00}, TE_{10}/TM_{10} and TE_{20}/TM_{20} modes. The experimental results demonstrate that the fiber shows ultra-low DGDs, which are 0.04 ps/m for TE_{10}-TE_{00}, and 0.12 ps/m for TE_{20}-TE_{10} modes, respectively. This RCF can potentially meet the demand for low-crosstalk mode division multiplexing transmission in short reach systems.

5. References

[1] N. K. Fontaine, et al., "30 × 30 MIMO Transmission over 15 Spatial Modes," Proc. OFC 2015, Post-Deadline Paper Th5C.1.
[2] E. Ip, et al., "SDM transmission of real-time 10GbE traffic using commercial SFP + transceivers over 0.5km elliptical-core few-mode fiber," Opt. Express. 23(10), 17120-17126, 2015.
[3] L. Rechtman and D. M. Marom, "Rectangular versus circular fiber core designs: New opportunities for mode division multiplexing?", Proc. OFC 2017, Paper Th2A.10.
[4] Y. Su, et al., "Perspective on mode-division multiplexing," Applied Physics Letters, 118(20), pp. 200502(1-9), 2021.
[5] https://www.yofc.com/view/2133.html
[6] M. Koshiba, "Full-Vector Analysis of Photonic Crystal Fibers Using the Finite Element Method," IEICE Trans. Electron. 85(4), 881-888, 2006.
[7] J. A. Buck, Fundamentals of Optical Fibers, Wiley, Hoboken, New Jersey (2004).