Low bending loss square-core optical fiber for optical communication

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ABSTRACT

In this work, we propose and demonstrate a single-mode square-core optical fiber for optical communications. In the proposed square-core single-mode-fiber (SC-SMF), high bandwidth-distance product and low bending loss can be achieved. In this paper, first of all, we discuss the single mode condition of the SC-SMF theoretically and numerically. Then, we discuss the fabrication of the SC-SMF. We also characterize the performances of the proposed SC-SMF, such as the bending loss, and compare it with the standard single mode fiber (SSMF). A 10 Gb/s transmission experiment using 200 m, 500 m and 1 km SC-SMFs are performed. Negligible power penalty is observed.

Keywords: Square-core single-mode-fiber (SC-SMF), fiber design, optical communication

1. INTRODUCTION

In order to provide higher bandwidth to end-users, network operators are placing the optical fiber closer and closer to the user sides. Different fiber-to-the-x (FTTx) technologies have been proposed [1], such as fiber-to-the-building (FTTB), fiber-to-the-home (FTTH) and even fiber-to-the-desk (FTTD). Due to the low cost, low transmission loss and wide bandwidth, optical fibers are replacing the copper cables in home networks and data center networks [2]. Multimode fibers (MMF) and plastic optical fiber (POF) are traditionally used for these short-reach data center networks [2, 3] owing to lowing bending loss and high coupling tolerance. As the data center networks are expanding very rapidly, single-mode-fiber (SMF) is now considered to be applied to the data center optical networks to reduce the number of fiber port-counts per rack, and to increase the transmission distance. Another advantage of using SMF is that wavelength division multiplexing (WDM) can also be used in the data center optical networks to further increase the transmission capacity [4].

When optical fibers are deployed in home networks and data center networks, bending loss becomes an important issue. It is desired that these optical fibers can be handled similarly to typical electrical cables. Nowadays, several solutions have been proposed to decrease the bending loss of optical fiber, such as using depressed cladding, trench assisted, ring assisted and hole assisted schemes [5]. However, these schemes require complicate fabrication process. Recently, we have proposed and demonstrated using a 80 μm large core multimode fiber (LC-MMF) to reduce the bending loss [6, 7]. However, the 80 μm LCF could suffers from high modal dispersion and cannot be applied in long transmission distances for the next generation data center networks. Hence, SMF with high bend tolerance supporting relatively long transmission distance is needed.

Square-core optical fiber has been recently demonstrated for high optical power delivery in industrial processing [8]. Its core size is larger than 400 x 400 μm^2 for withstanding high optical power during the transmission. In this work, we propose and demonstrate a single-mode square-core optical fiber for optical communications. In the proposed square-core single-mode-fiber (SC-SMF), high bandwidth-distance product and low bending loss can be achieved.

The paper is organized as follow. First of all, we discuss the single mode condition of the SC-SMF theoretically and numerically. Then, we discuss the fabrication of the SC-SMF. We also characterize the performances of the

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proposed SC-SMF, such as the bending loss, and compare it with the standard single mode fiber (SSMF). A 10 Gb/s transmission experiment using 200 m, 500 m and 1 km SC-SMFs are performed. Negligible power penalty is observed. It is believed that the SC-SMF could be another alternative of low bending tolerance fiber for optical communication.

2. FIBER DESIGN

First of all, the single mode condition of the square-core fiber is studied. According to [9], the theoretical number of modes of a square-core optical waveguide is approximately equal to Eq. (1).

$$Number\_of\_MODE \approx \frac{\pi}{4}\left[\frac{\sin\left(\cos^{-1}\left(\frac{n_{cladding}}{n_{core}}\right)\right)}{\frac{\lambda}{2\cdot w}}\right]^2 \tag{1}$$

where $n_{cladding}$ is the refractive index of the fiber cladding, n_{core} the refractive index of the fiber core, λ the wavelength of the incident light, and w is the width of the square-core fiber.

In addition, beam propagation method (BPM) is used to get a more accurate relation between the number of modes and the core width. Fig. 1 shows the relationship between the number of modes and the core width obtained theoretically based on Eq. (1), and based on BPM numerical method. We can see that single mode requirement can be achieved while the square-core width is < 9 μm. As a result, the SC-SMF is fabricated with core with of 9 μm.

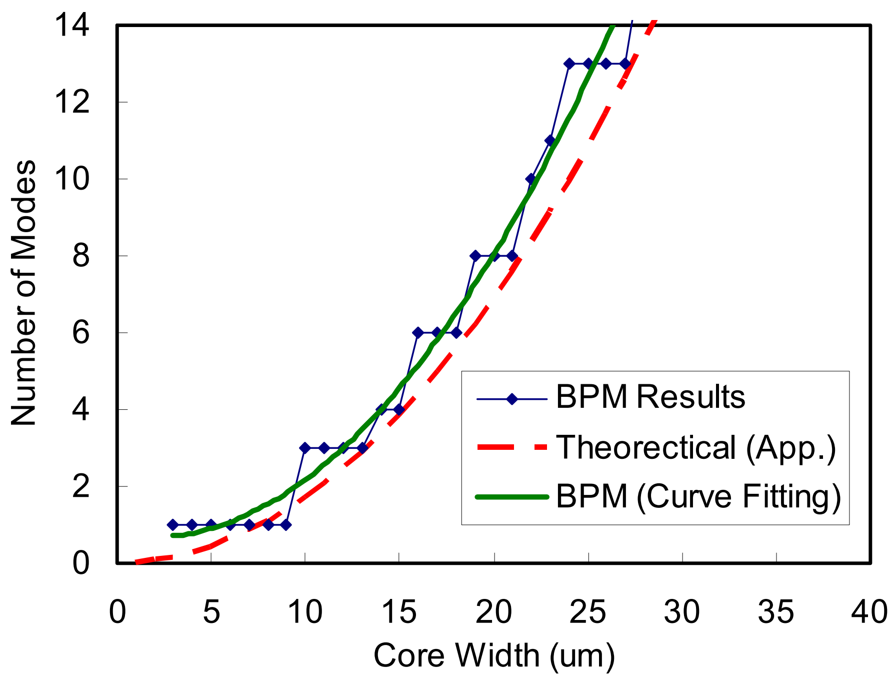

Figure 1. Relationship between number of modes and the core widths.

3. FABRICATION

The SC-SMF is fabricated using the same fiber drawing equipments as used in conventional SSMF. Fig. 2(a) shows the cross-section of the SC-SMF design, in which the SC-SMF center is a square preform with higher refractive index. The square preform is surrounded by several circular glass rods with lower refractive index. As shown in the photograph of Fig. 2(b), the square preform (silica rod) has the width of 21.2 x 21.2 mm^2 and length of 1000 mm. It is produced by milling the outside portion of a circular preform to produce the square preform. The square preform is then surrounded by several circular glass rods. Fig. 2(c) shows the photograph of the bundle of glass rods, which will then be put inside a hollow circular glass tube for holding them into position. Finally, the bundle of glass rods can be fabricated into the final SC-SMF preform. In the process of fiber drawing, a 9 μm x 9 μm square core and 125 μm diameter circular cladding SC-SMF fiber can be manufactured by proper controlling the drawing speed and temperature.

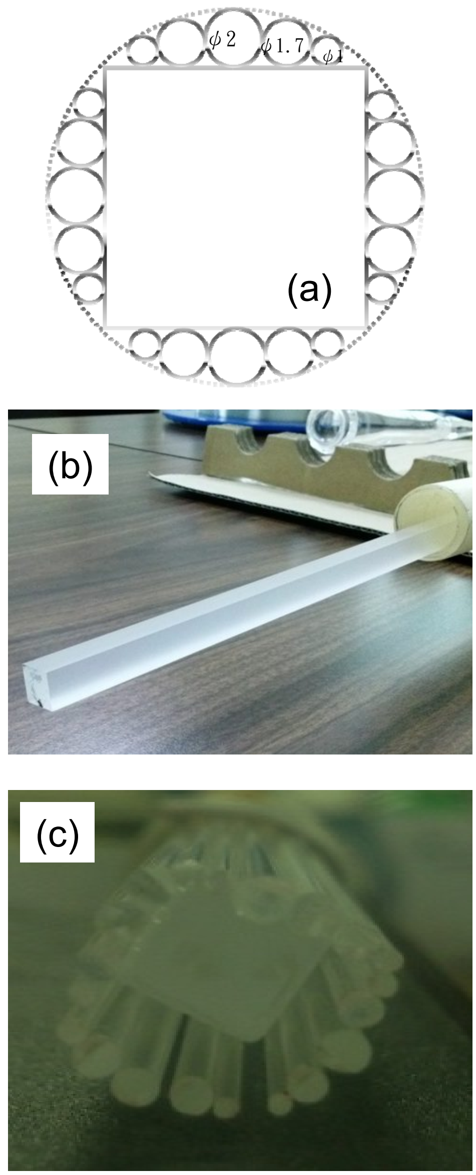

Figure 2. (a) Schematic of cross-section of the SC-SMF design; photographs of (b) square perform, and (c) bundle of glass rods.

4. EXPERIMENT AND RESULT

After the SC-SMF fabrication, we first study the field distribution of the proposed SC-SMF. Fig. 3(a) and 3(b) show the field distribution in the cross-sections of the SC-SMF calculated by using BPM and using experiment respectively. The SC-SMF end-face geometry shown in Fig. 3(b) is measured by the Photon Kinetics 2400 fiber geometry system. We observe the core and the cladding is very well distinguished, showing the single mode condition. It is worth to mention that since the optical signal is coupled from one fiber end and the fiber geometry is measured at the other fiber end, the fiber mode shown in Fig. 3(b) is slightly circular even though the fiber core is square. This can also be observed in the circular-shaped mode in the mode distribution profile obtained using BPM method shown in Fig. 3(a).

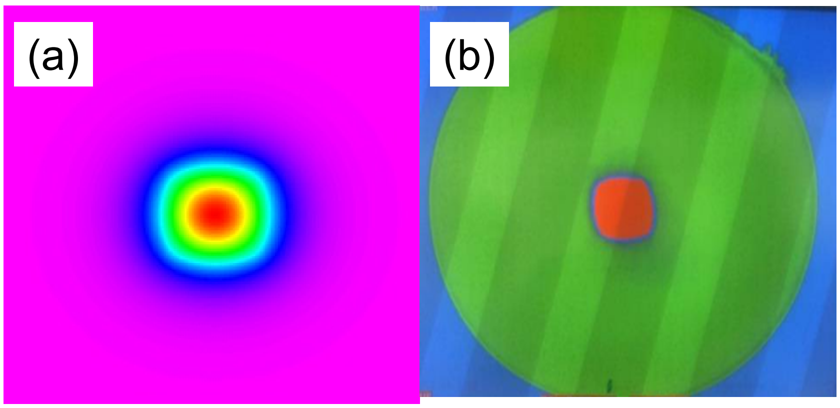

Figure 3. Field distribution of the (a) SC-SMF calculated by using BPM, and (b) measured SC-SMF end-face geometry by Photon Kinetics 2400 fiber geometry system.

Then we study the bending loss of the SC-SMF. A continuous-wave (CW) optical signal at wavelength of 1550 nm is coupled into the fiber, which is wrapped around steel rods with diameters of 20 mm and 15 mm respectively. The coupling loss of a SSMF with the SC-SMF is also measured, and it is < 0.18 dB. The coupling loss may come from the slightly mode mismatch between the SSMF and the SC-SMF. Fig. 4 shows the experimentally measured bending losses of the proposed SC-SMF and SSMF. When the bending turn increases, the SC-SMF shows significant lower bending loss when compared with the SSMF. We can observe from Fig. 4 that when the number of bending is 10, and using 15 mm diameter steel rod, a much higher bending tolerance of 15 dB can be achieved in the proposed SC-SMF when compared with the SSMF.

Finally, we evaluate the SC-SMF transmission performance in terms of bit-error-rate (BER). As the SC-SMF is used for data center optical networks, typical data center transmission length should be more than 300 m. A 10 Gb/s transmission experiments using 200 m, 500 m and 1 km SC-SMFs are performed using non-return-to-zero (NRZ) on-off keying (OOK) modulation. The transmission BER performance of 1 km SSMF is also included for comparison. In this experiment, a Mach-Zehnder modulator (MZM) is used to produce the 10 Gb/s NRZ OOK optical signal. After different fiber length transmission, a 10 GHz PIN photo-diode (PD) is used to capture the optical signal. A bit error rate tester (BERT) after the PD is used to measure the BER performance, which is shown in Fig. 5. We can observe that the SC-SMF shows negligible power penalty when compared with that of the SSMF; and at different transmission distances (200 m, 500 m and 1 km). The eye-diagrams after traveling 1 km of SC-SMF is also included in the insets.

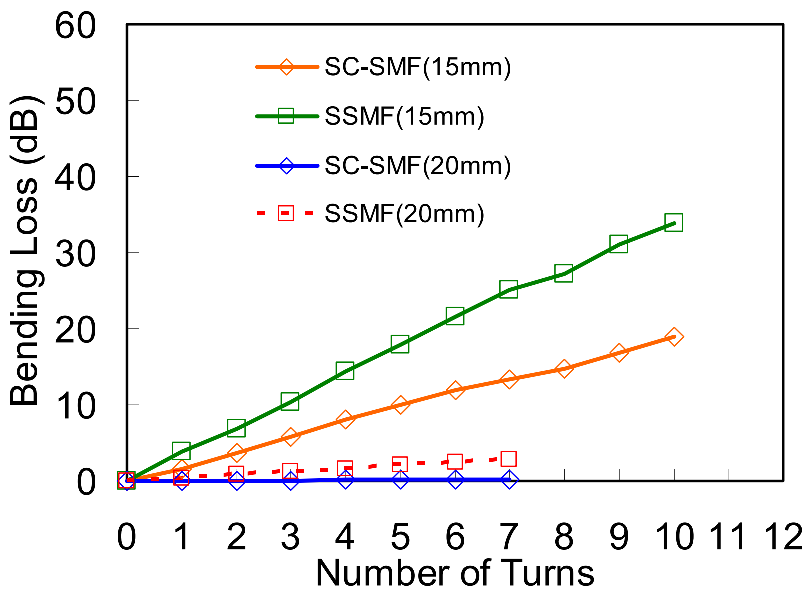

Figure 4. Measured bending loss characteristics of the proposed SC-SMF and SSMF.

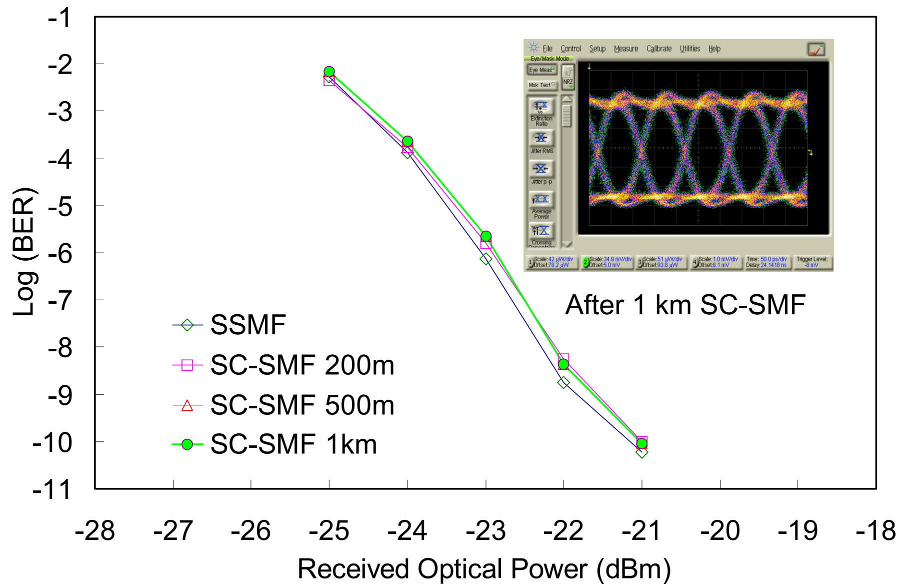

Figure 5. Measured BER using 10 Gb/s OOK signal traveling different lengths of SC-SMF.

5. CONCLUSION

In this work, we proposed and demonstrated a novel SC-SMF for optical communications. It had high bandwidth-distance product and low bending loss. We discussed the single mode condition of the SC-SMF theoretically and numerically. Then, we discussed the fabrication of the SC-SMF. We also characterized the performances of the proposed SC-SMF, such as the bending loss and coupling loss, and compare it with the SSMF. Finally, a 10 Gb/s transmission experiment using 200 m, 500 m and 1 km SC-SMFs were performed. Negligible power penalty was observed.

6. ACKNOWLEDGMENT

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