Small-Silica-Core Polymer-Clad Fiber for Optical Interconnection

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A polymer-clad silica-core fiber (PCF) with a small core diameter that is suitable for an optical interconnection is studied and experimentally manufactured. Error-free transmission over 2.5 Gbps in a 20-m link can be supported by manufactured fibers with VCSEL excitation. Large tolerance for a fiber connection and small bending loss for a small bending radius are experimentally confirmed.

1. Introduction

Electrical interconnections using twisted pair, coaxial cables, flexible printed circuit, and so on are widely known as short-reach transmission media for an industrial network, a car network, an in-building network, and an in-house network. However, limitations on high-speed and large-capacity transmission especially in terms of electrical noise resistance for the electrical interconnections have been pointed out. An optical interconnection using a polymer-clad silica-core fiber (PCF) or a plastic optical fiber (POF) has attracted attention as a system that enables high-speed transmission beyond the limit of the transmission rate of the electrical interconnection. The optical interconnection has been highly demanded for the use of gigabit-class transmission in short-reach applications of up to several 10 m [1)2)]. Easy connection, easy handling, and high-speed transmission are recognized as issues for the practical use of the optical interconnection.

In this paper, small-core PCFs for optical interconnection are presented. The PCFs show the capability of high-speed transmission over 1 Gbps up to several 10 m, the allowance of bending with a small radius, and flexibility for splice. First, we describe characteristics of the PCFs. Then, we show bandwidths and bending losses of the PCFs. Finally, we demonstrate high-speed transmission using the PCFs with restricted excitation by vertical-cavity surface-emitting laser (VCSEL).

2. Characteristics of small-core PCF

Table 1 shows the typical characteristics of PCF, POF, and graded index glass optical fiber (GI-GOF), which are used in optical interconnections. The typical POFs that have a large-core diameter of 1 mm have an advantage of easy connection. Since relative refractive index difference Δ_1 between core and clad of the POFs is designed to be much larger than those of the other fibers, the POFs are less capable for high-speed transmission. In addition, since both core and clad of the POFs are usually composed of polymer resins that are softened over 85 degree, the POFs are not suitable for use in an environment of high temperature.

Both core and clad of the GI-GOFs are composed of silica glass. The GI-GOFs are most flexible because typical clad diameter of 125 μm is the smallest among optical fibers for optical interconnections. The GI-GOFs are suitable for high-speed transmission in comparison to the POFs and PCFs. However, precise alignment is required for the connection of the GI-GOFs because of its small core diameter of 50 μm.

The PCFs are composed of silica core and polymer clad. The PCFs can be used under temperature higher than 85 degrees at which the clad becomes softer but the core has the same stiffness. Since the typical core diameter of the PCF is 200 μm, the PCF cannot be applicable, in terms of mechanical reliability, for situations where a fiber is bent in a small radius. The relative refractive index difference Δ_1 of the PCFs is a moderate value between that of the POF and the GI-GOF. The transmission speed of the PCFs is slower than that of the GI-GOFs, whereas the PCFs are capable for more high-speed transmission than the POFs.

As a result of the above consideration, we propose a small-core PCF for the optical interconnection. The mechanical reliability of the proposed PCF for a bending of small radius is assured by the small core diameter. The relative refractive index difference Δ_1 of the PCF is optimized to achieve a small bending loss and

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Table 1. Characteristics of optical fibers for optical interconnections.

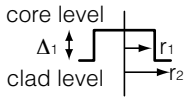
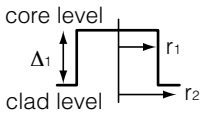
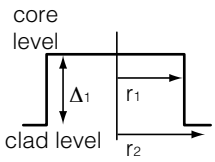
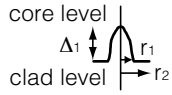
Items	Small-core PCF	PCF	POF	GI-GOF
Core diameter (μm)	125	200	980	50
Clad diameter (μm)	170	230	1000	125
Heat-resistent temperature	+120°C	+120°C	+85°C	depends on coating material
Tolerance for fiber connection	○	○	◎	×
Flexibility	○	△	×	○
Refractive index profile				

Table 2. Conditions of simulation.

Wavelength (nm)	850
Silica-core refractive index @ 850 nm	1.453
Polymer-clad refractive index @ 850 nm	1.4 ~ 1.45
Silica-core diameter $2r_1$ (μm)	125
Polymer-clad diameter $2r_2$ (μm)	170

Table 3. Measured characteristics of manufactured PCFs.

Items	fiber A	fiber B	fiber C
Silica-core refractive index @ 850 nm	1.453	1.453	1.453
Polymer-clad refractive index @ 850 nm	1.435	1.43	1.425
Relative refractive index difference Δ_1 (%)	1.2	1.6	1.9
Theoretical numerical aperture	0.23	0.26	0.28
3-dB overfilled bandwidth at 20 m (MHz·20 m)	588	553	428

a high bandwidth simultaneously. The theoretical bandwidth of a fiber depends on the relative refractive index difference Δ_1 between the core and clad, and the dependence of the core diameter on the bandwidth is almost negligible. The small Δ_1 is preferable to increase the bandwidth because higher order propagation modes are limited. On the contrary, large Δ_1 is preferable to suppress the bending loss of the PCF. The bandwidth is inversely proportional to the bending loss.

3. Fiber design and manufacture

We simulated the bandwidth of small-core PCFs and manufactured PCFs based on the simulation. The WKB method [3] was employed for the 3-dB bandwidth simulation of the PCFs. Overfilled excitation [4], which corresponded to LED excitation, was assumed for the bandwidth simulation. Table 2 shows the condition of the simulation. In the simulation, the refractive index of polymer clad was varied from 1.400 to 1.450. We experimentally manufactured small-core PCFs to confirm the simulation results. The polymer clad of manufactured PCF was coated with a polymer resin around the silica core that was drawn in the drawing process. The refractive indices of the polymer resins of the PCFs were lower than that of silica glass: 1.425, 1.430, and 1.435, respectively. The silica-core diameter of manufactured PCFs was set to be 125 μm in terms of mechanical reliability and flexibility for connection. Table 3 shows the measured characteristics of the manufactured PCFs. The overfilled bandwidth was measured by pulse method [5] at 850 nm wavelength. The lengths of the PCFs for the simulation and the measurement of the overfilled bandwidth were 20 m. Figure 1 shows the simulated and the measured results of the overfilled bandwidth as a function of theoretical NA calculated from the relative refractive index difference Δ_1. The measured overfilled bandwidths are similar to the simulated ones. The overfilled bandwidth of fiber A is 588 MHz 20 m, which is the maximum value in the manufactured fibers.

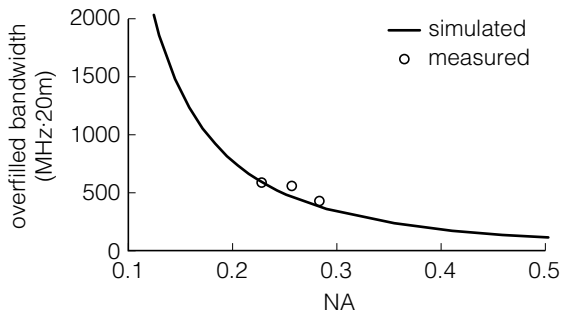


Fig. 1. Simulated and measured bandwidths as a function of NA.

Figure 2 shows the measured bending losses with overfilled excitation for fiber A as a function of the number of turns. The manufactured PCFs show a large bending loss for a small bending radius. The

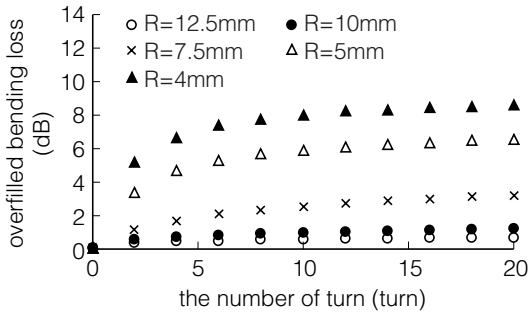


Fig. 2. Bending losses as a function of the number of turns.

bending losses of the PCFs drastically increase in the first several turns. There is a little increase in the bending losses of the PCFs after the first several turns, especially over five turns. Since higher order propagation modes in the PCFs are sensitive to bending, most of higher order propagation modes are radiated in the first several turns. Several lower order propagation modes, which are insensitive to bending, are left and are hardly radiated after first several turns.

4. Transmission experiment results

In optical interconnection systems over 1 Gbps, a VCSEL is used as a light source. Launching mode conditions excited by the VCSEL are more restricted than that of LED; the overfilled bandwidth of small-core PCFs discussed in the previous section may underestimate the transmission performance of a fiber with VCSEL excitation. We investigated the ability of high-speed transmission for the manufactured fibers by demonstrating transmission experiment for the VCSEL excitation conditions.

Figure 3 shows the setup for the transmission experiment for the VCSEL excitation conditions. An 850-nm multimode VCSEL module, which was not commercial, was modulated by the pulse pattern generator (PPG), which generated NRZ PRBS 2^{23}-1 signals. The VCSEL was coupled into the manufactured fiber using a precision mechanical stage to adjust coupling conditions. The transmission distance was 20 m. The output signals from the fiber were detected by the photo detector (PD). After the detected signals were amplified by an electrical amplifier, the amplified signals were fed into a digital sampling oscilloscope or an error analyzer (EA) to measure the eye diagram or BER.

Figure 4 shows the measured eye diagrams at 2.5 Gbps after 20-m transmission through fibers A, B, and C. The eye diagram of fiber A for 2.5 Gbps shows sufficient large eye openings, as shown in Fig. 4a. Figure 4b and 4c shows that the eye openings of fibers B and C are smaller than that of fiber A. The jitter of the signals that transmit over fibers B and C is

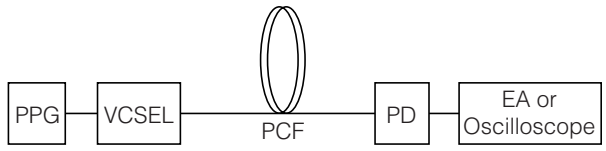


Fig. 3. Setup for transmission experiment.

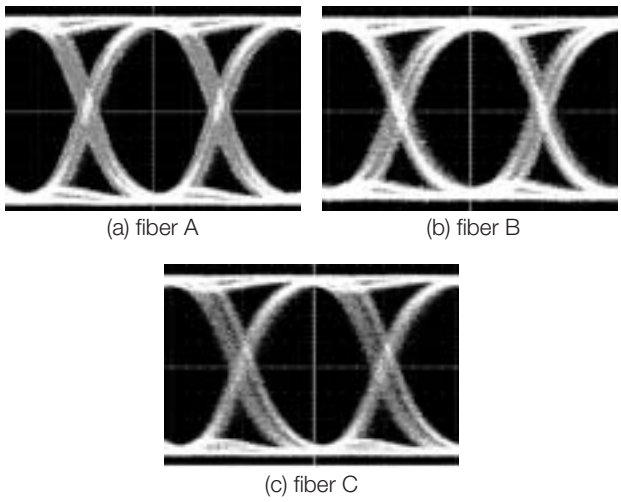


Fig. 4. Measured eye diagrams at 2.5 Gbps after 20-m transmission for fiber A, B, and C.

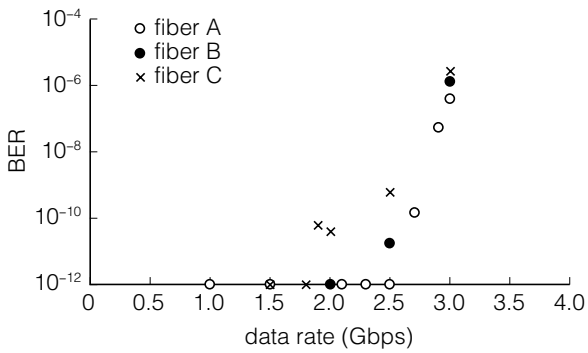


Fig. 5. Measured BERs after 20-m transmission.

larger than that of fiber A. Figure 5 shows the measured BER curves after 20-m transmission for fibers A, B, and C. The measured BERs are lower than 10^{-12} for bit rates of up to 2.5 Gbps for fiber A, up to 2.0 Gbps for fiber B, and up to 1.8 Gbps for fiber C. Moreover, we also evaluated eye diagrams and BERs in the case of lateral offset between the fibers. One of the cleaved fiber A at the middle of transmission distance of 20 m was coupled into the other cleaved fiber after 10-m transmission using the precision mechanical stage to adjust the lateral offset, and then the output signals from the fiber after 10-m transmission were detected by the PD. We confirmed that eye diagram and BER did not vary at 100-μm lateral offset as long as the transmitted signals were detected by the

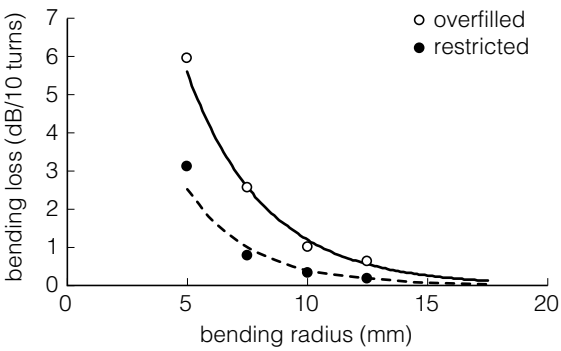


Fig. 6. Measured bending losses as a function of bending radius for different launch conditions.

PD. The PCFs are sufficiently tolerant for a fiber connection. Consequently, the manufactured small-core fiber A potentially has the ability of high-speed transmission for the optical interconnection.

Figure 6 shows the measured results of bending losses for fiber A under overfilled and restricted excitation as a function of the bending radius. The number of turns was 10. A GOF with a core diameter of 10 μm and NA of 0.18 was used for restricted excitation to simulate the VCSEL excitation. The spot size and NA of the GOF were similar to those of the VCSEL. The restricted-bending loss is about one third of the overfilled-bending loss. The estimated bending loss of fiber A for a bending radius of 15 mm is almost equivalent to the bending loss of a bend-insensitive GI-GOF [6]. Fiber A, which is designed to have the smallest Δ_1 and has the largest overfilled bandwidth, is the most sensitive in bending among the manufactured PCFs. As a result, fiber A is available for use in the optical interconnection in terms of bending loss as well as bandwidth.

5. Conclusion

We have simulated the bandwidth of small-core PCFs and have manufactured three small-core PCFs based on the simulation. The measured overfilled bandwidths of the fibers are similar to the simulated ones. The measured bending losses with overfilled excitation for the PCF (fiber A) are very large for a small bending radius. We have evaluated the overfilled and VCSEL-excited bandwidths of the manufactured PCFs. The VCSEL-excited bandwidths are higher than the overfilled ones. Fiber A with an overfilled excitation of 588 MHz has achieved 20-m error-free transmission of up to 2.5 Gbps under restricted excitation condition of VCSEL. We have evaluated the VCSEL-excited bandwidth at lateral offset connection for fiber A whose relative refractive index difference between the core and clad has been optimized in terms of high-speed transmission. Fiber A has achieved an error-free transmission of less than 2.5 Gbps under the condition of 100-μm lateral offset. Furthermore, the bending loss of fiber A under restricted excitation is equivalent to that of a bend-insensitive GI-GOF. Since small-core PCF has the features of heat resistance, ability of high-speed transmission, easy connection and bent insensitiveness, the PCF is a strong candidate for optical interconnections.

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