Unique Bending Loss Properties and Design Consideration for Coupled Multi-core Fiber

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Abstract: We reveal the unique bending angle and coupled core count dependence of bending loss in a coupled multi-core fiber and demonstrate adequate core design conditions can be derived by considering the average bending loss property.

1. Introduction

Space division multiplexing (SDM) optical fiber technologies such as few-mode fiber (FMF) and multi-core fiber (MCF) have been developed to overcome the capacity crunch of the conventional single-mode fiber. Coupled multi-core fiber (C-MCF) [1] has recently attracted interest due to its potential for higher spatial channel density, thanks to core pitches designed to be smaller than uncoupled MCF. C-MCF is also a promising candidate for achieving ultra-long-haul SDM optical transmission, since distributed random mode coupling in C-MCF suppress spatial mode dispersion (SMD), thus helping to reduce the multi-input multi-output (MIMO) processing complexity. Several studies have investigated the relationships between SMD and fiber design, bend, and twisting effect [2]–[4]. However, the relationship between the fiber design of C-MCF and its basic optical properties, such as bending loss and cut-off wavelength, has not been clarified.

In this paper, we numerically and experimentally investigate the unique bending angle and core pitch dependence in a C-MCF. Our findings demonstrate that an adequate core design for a C-MCF with 4–12 cores can be derived by considering the average bending loss property.

2. Unique bending loss property in C-MCF

We numerically investigated the modal bending loss in a C-MCF using eigenmode analysis with a 2-D full vector finite element method (FEM). Figure 1 shows the calculated bending loss in a two-core C-MCF with the bending radius R of 30 mm and the wavelength of 1625 nm. Each core has a step-index profile with the core radius a of 4.8 µm and the relative index difference Δ of 0.35%, and are placed horizontally in the bending direction. Figure 1(a) and (b) show the core pitch Λ and bending angle θ dependence, respectively. Red and blue lines represent the bending loss of fundamental modes (FM) propagating the outer core and higher-order modes (HOM) propagating the inner core, and solid and dotted lines represent x- and y-polarization modes, respectively. The green bold line represents the average loss of all propagation modes. The black dash-dotted line represents the bending loss of an SMF with the same core structure. We can see in (a) that the bending loss of HOM increases dramatically as Λ decreases, while that of FM decreases. On the other hand, there is no significant polarization dependence in each mode. Thus, the modal loss difference increases as Λ is decreased, and the bending loss tends to degrade compared with the single-core situation. As for (b), we can see that HOM exhibits a larger bending loss than FM, and that the

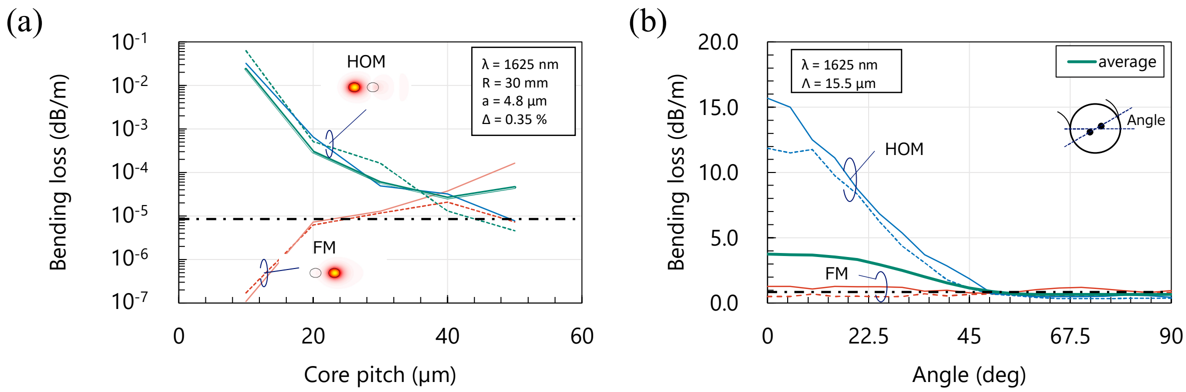

Fig. 1. Calculated bending loss of two-core C-MCF with R = 30 mm and 1625 nm. (a) Core pitch Λ dependence with $\theta = 0°$. (b) Bending angle θ dependence with Λ = 15.5 µm.

bending loss and modal loss difference is significantly degraded at smaller θ. These results indicate that C-MCF contains a unique Λ and θ dependence of bending loss, and that the bending loss tends to degrade compared to the single-core condition.

3. Effective bending loss property and design consideration of C-MCF

Figure 2 shows the experimental setup we used to measure the bending loss. Continuous-wave laser light was input to one of the cores of the fiber under test (FUT) through the SMF with offset splicing. The output light from the C-MCF was directly detected using an integrating sphere-based power meter for suppressing the power fluctuation due to power coupling between cores. Two different bending conditions were examined. In the first, a half-turn bent with the radius of 15 mm was applied to the FUTs using two metal plates, where the bending angle θ was varied using a fiber rotator. In the second, we used a 100-turn spooled bobbin with radii ranging from 15 to 25 mm. The properties of the three FUTs we measured are listed in Table 1. The core counts were 4, 8, and 12, and the core layouts were square with Λ = 14.8 μm, circular with Λ = 15.5 μm, and square with Λ = 15.5 μm, respectively. All FUTs had the same core structure with a = 4.8 μm and Δ = –0.35% (pure-silica core).

Figure 3(a) and (b) show the measured bending loss as a function of θ and R, respectively. Here, the θ and R dependence was measured at a half-turn and at 100 turns, respectively. The symbols and lines show the measured and calculated results, where blue, orange, and gray respectively represent the results of the 4-, 8-, and 12-core C-MCFs. The simulation results are the average values of all propagation modes for θ. As we can see in (a), the measured and calculated results have a similar θ dependence when a half-turn bending is added. Moreover, (b) shows that the bending loss at 100 turns is in good agreement with the calculated average values. We also found that the bending loss tends to degrade as the number of coupled cores increases. These results indicate that non-uniform multiple bending averages the Λ and θ dependence of the bending loss in a C-MCF, while a half-turn bending confirms the existence of a unique bending loss property in the C-MCF.

Finally, we numerically investigated the optimal core design for a C-MCF with different core numbers by

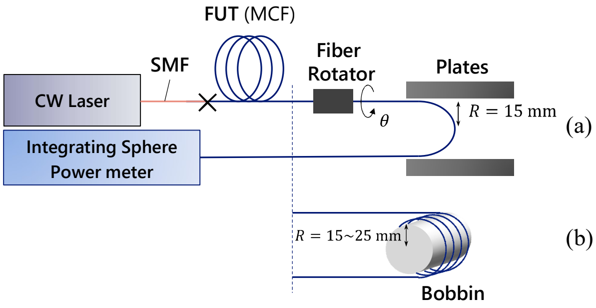

Fig.2. Experimental setup for measuring bending loss at (a) half-turn and (b) 100-turn on the bobbin.

Table 1. Properties of fabricated pure silica-core step-index C-MCFs

Parameters	4core	8core	12core
Cross section			
Core pitch	14.8 μm	15.5 μm	15.5 μm
Core radius	4.8 μm		
Core Δ	− 0.35 %		
Length	3 km		

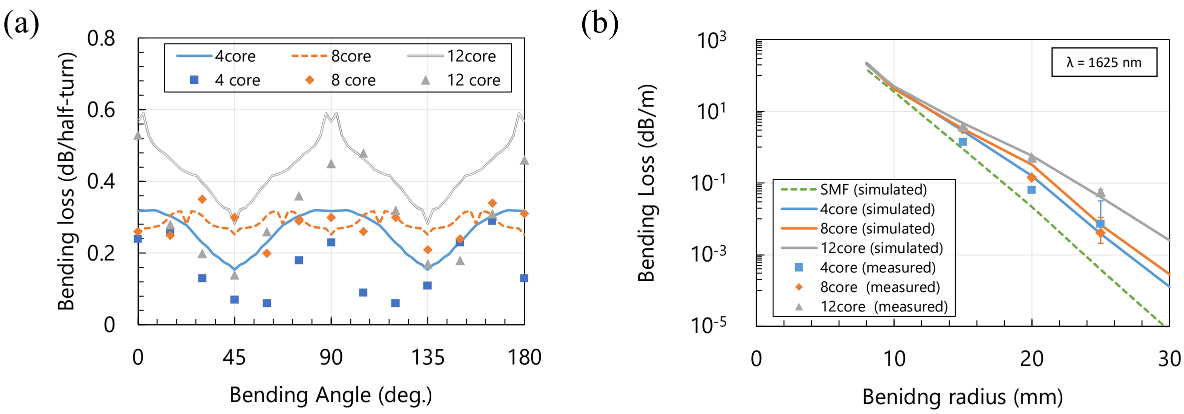

Fig. 3. Measured and calculated bending loss as a function of (a) θ and (b) R.

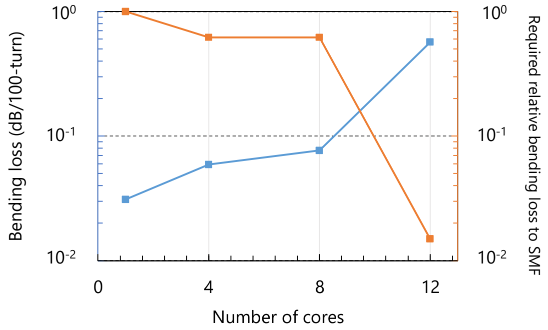

Fig. 4. Calculated bending loss and required relative bending loss to SMF as a function of number of cores

Table 2. Calculated properties of redesigned C-MCFs

Properties	SMF	4core	8core	12core
MFD (μm)	9.2			
Bending loss (R = 30 mm)	0.03 dB/100turns			
Cut-off wavelength (μm)	1.18	1.20	1.20	1.23

considering the average bending loss. An earlier study reported that the optimal Λ of C-MCF to induce random mode coupling and suppress group delay spread (GDS) is around 16 to 25 μm [2]. As discussed in Section 2, a larger Λ is preferable since the bending loss increases as Λ decreases. On the other hand, the upper limits of Λ in 8- and 12-core fibers with the standard 125-μm cladding diameter are 20 and 16 μm to suppress the leaky losses to less than 10^{-2} dB/km at 1625 nm. Therefore, we assume that the optimal Λ values of 4-, 8- and 12-core C-MCF are 25, 20, and 16 μm, respectively. The left-hand axis in Fig. 4 shows the calculated bending loss with R = 30 mm and λ = 1625 nm in 4-, 8-, and 12-core C-MCF with Λ of 25, 20, and 16 μm, respectively. Their core had a step-index structure with a = 4.2 μm and Δ = 0.35%. (We set a and Δ of the step-index core to 4.2 μm and 0.35% as an example structure to satisfy the conventional G.652.D fiber property [5].) We can see in Fig. 4 that the bending loss gradually degrades as the number of cores increases, and it becomes larger than 0.1 dB/100 turns for the 12-core structure. The right-hand axis in Fig. 4 shows the required relative bending loss, which we define as ratio of the bending loss in dB unit between those assuming the single-core and C-MCF structure when we design the C-MCFs with the same bending loss as the SMF. We found that about 2–100-time bending loss reduction in single-core is necessary for 4–12 core C-MCFs.

Based on the above results, we then re-designed the core structure of 4, 8, and 12 core C-MCFs so that the bending loss at the single-core condition satisfies the required relative bending loss property while keeping the mode-field diameter of 9.2 μm at 1310 nm. Table 2 lists the properties of these C-MCFs with the modified core structure. We can confirm here that the bending losses of all C-MCFs are suitably designed at 0.03 dB/100 turns, as expected. The cut-off wavelength also satisfies the requirement of less than 1.26 mm, although there is a slight dependence on the core numbers. Here, the cut-off wavelength is defined as a wavelength when the averaged bending loss of LP_{11} modes is larger than 1.0 dB/m with R = 140 mm. These results indicate that 4–12 core C-MCFs with optical compatibility to conventional SMFs can be designed by considering the average bending loss property and core number dependence.

4. Conclusion

We demonstrated the unique bending angle and core pitch dependence in a C-MCF. We also showed how to design a C-MCF that has a comparable optical property to a conventional SMF by considering the average bending loss property in a C-MCF.

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