Bending Radius Dependence of Power Coupling Coefficient and Spatial Mode Dispersion in Coupled Multi-Core Fibers

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Abstract: We experimentally investigated the dependence of the power coupling coefficient (PCC) on the bending radius in coupled multi-core fibers for the first time. We also discuss the relationship between the PCC and spatial mode dispersion. © 2022 The Author(s)

1. Introduction

Randomly coupled multi-core fibers (C-MCFs) are attractive transmission media for achieving long-haul and large-capacity transmission [1,2]. They intentionally introduce random and frequent mode coupling to suppress spatial mode dispersion (SMD) [3], mode-dependent loss (MDL) [4], and nonlinear impairments [5]. Since these important characteristics are directly related to the strength of the mode coupling, understanding how the power coupling coefficient (PCC) between cores changes with external factors such as bending is important. Several studies have investigated the mode coupling behavior under bending conditions theoretically [6,7], but, to the best of our knowledge, the bending dependence of the PCC and the relationship between the PCC and other important characteristics have not yet been investigated experimentally.

In this paper, we experimentally investigate the bending radius dependence of the PCC in C-MCFs for the first time. We also discuss the relationship between the PCC and the SMD in C-MCFs based on the experimental results.

2. Method of investigating PCC of C-MCFs

Some previous studies have proposed methods using an optical time domain reflectometer (OTDR) for measuring the PCC between two cores in uncoupled MCFs [8,9]. These methods inject the probe pulse into a core and simultaneously or sequentially measure the backscattered power from both the input and adjacent cores. The PCC between the cores can be obtained as

$$h = \frac{1}{2z}\tanh^{-1}\left[\frac{P_{bs2}(z)}{P_{bs1}(z)}\right], \tag{1}$$

where h represents the average value of the PCC from the input end of the probe pulse to a distance z. P_{bs1} and P_{bs2} indicate the backscattered power from the input and adjacent cores, respectively. This method can in principle be used to measure the PCC between two cores in C-MCFs provided that P_{bs2} is smaller than P_{bs1}. It must be noted that light traveling in C-MCFs often fully coupled with other cores before it propagates several meters or so. Thus, to obtain the PCC of C-MCFs, we need to measure the backscattered power with high spatial resolution, for example, by using an optical frequency domain reflectometer (OFDR).

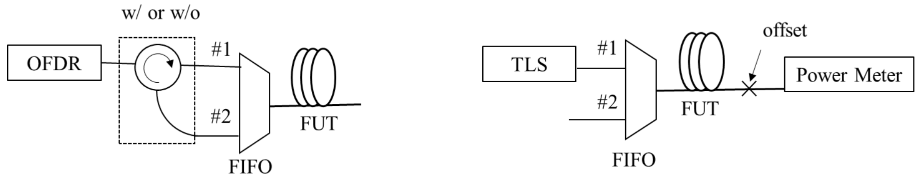
3. Experiments

3.1 Experimental Setup

We used two kinds of two-core fibers (2CFs) as the fibers under test (FUTs) and wrapped them around bobbins with different radii of 30 mm, 80 mm, and 145 mm. One of the FUTs had homogeneous cores, and the other had heterogeneous cores. We refer to the former and the latter as homogeneous and heterogeneous 2CFs, respectively. Although the 2CF with heterogeneous cores might not be a practical transmission medium, we used it as the FUT for understanding the PCC characteristics depending on the bending radius. The structural parameters of the FUTs were described in [10]. The lengths of the FUTs were about 100 m.

Figure 1(a) shows the experimental setup for measuring the PCC of the FUTs. We used a commercially available OFDR (LUNA OBR4600) for measuring the backscattered power from the FUT. The wavelength sweeping range was 0.4 nm, which corresponds to a spatial resolution of 2 mm. The center wavelength was 1566 nm. We first measured the backscattered power from the input core (core #1) by injecting the test light into core #1 via a fan-in/out device (FIFO) without using an optical circulator (OC). We next measured the backscattered power from the adjacent core (core #2) the FIFO and OC. The PCC was obtained by the method described in Section 2. We measured the PCC 50 times while changing the bending state of the FUT. This is because the amount of the power coupling between the cores strongly depends on the slight changes in the bending and twisting states [6,7].

Figure 1(b) shows the experimental setup based on the fixed analyzer method [11] for measuring the SMD of the FUTs. We measured the optical power transmitted by the FUT over the wavelength range from 1546 to 1586 nm by using a tunable laser, a photo-detector, and an analogue-to-digital converter. We obtained the SMD by calculating the second moment of the Fourier transform spectrum of the optical power depending on the optical frequency.

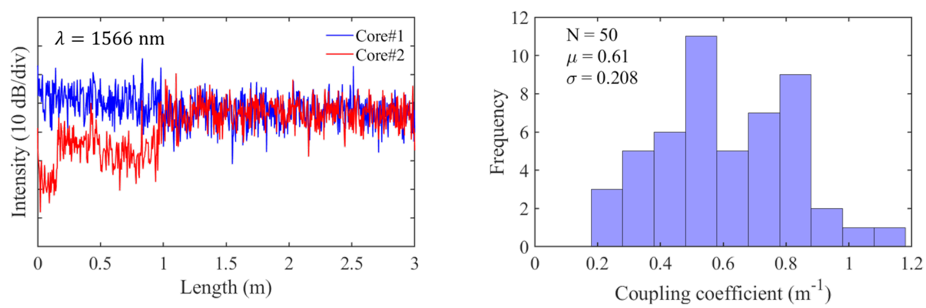


(a) (b)

Fig. 1. Experimental setup for measuring (a) the PCC and (b) the SMD.

3.2 Experimental Results

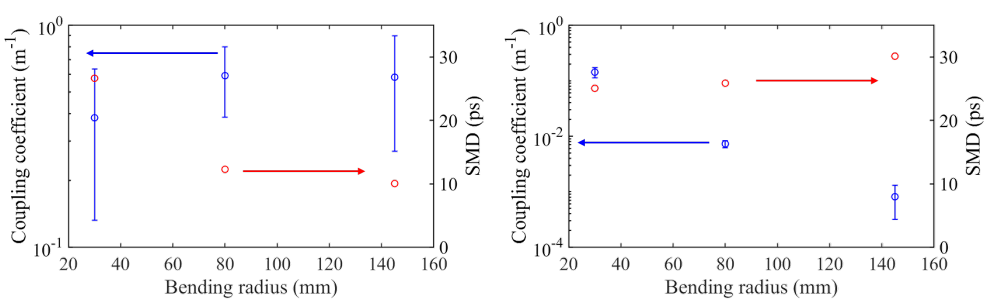
Figure 2(a) shows an example of the waveform for the homogeneous 2CF measured with the OFDR when the bending radius of the FUT was 80 mm. The blue and red lines represent the backscattered power from cores #1 and #2, respectively, with respect to the distance. We confirmed from Fig. 2(a) that the backscattered power from core #2 sharply increased at several points and fully coupled to that from core #1 at around 1.2 m. Figure 2(b) shows an example of the histogram of the PCC when the bending radius of the homogeneous 2CF was 80 mm. The average value of the PCC was 0.61 m^{-1}, and the standard deviation was 0.21 m^{-1}.



(a) (b)

Fig. 2. Examples of the experimental results: (a) the waveform measured with the OFDR and (b) the histogram of the PCC.

Figure 3 shows the PCC and SMD depending on the bending radius, where (a) and (b) represent the results for the homogeneous and heterogeneous 2CFs, respectively. The horizontal, left, and right axes correspond to the bending radius of the FUT, the PCC, and the SMD, respectively. The blue symbols represent the average value of the PCC values measured 50 times, and the error bars indicate standard deviations. The red symbols show the SMD values. We first focus on the results for the homogeneous 2CF described in Fig. 3(a). The PCC for the homogeneous 2CF did not show apparent dependence on the bending radius. On the other hand, the SMD clearly decreased with the bending radius. We next focus on the results for the heterogeneous 2CF described in Fig. 3(b). Unlike the results for the homogeneous 2CF, the PCC for the heterogeneous 2CF obviously decreased with the bending radius, and the SMD increased. We also confirmed from Fig. 3(a) and 3(b) that the SMD decreases with the PCC increases.



(a) (b)

Fig. 3. PCC and SMD depending on the bending radius for the (a) homogeneous and (b) heterogeneous 2CFs.

3.3 Discussion

We first discuss the bending radius dependence of the PCC. The PCC strongly depends on the difference in the propagation constants between the cores. It is known that the propagation constant difference Δβ can vary with the bending and twisting states of the FUT [6,7]. Figure 4(a) shows a schematic diagram of a bent fiber. When a fiber is bent, the propagation constant of the core located outside the fiber axis of the fiber equivalently increases and that located inside decreases. If the two cores are positioned in a linear manner with respect to the bending direction, Δβ varies greatly from the original Δβ in a straight state. The amount of the variation of Δβ increases with the smaller bending radius. If the two cores are placed perpendicular to the bending direction, Δβ does not change from the original Δβ. It is known that the power coupling between cores occurs mainly when Δβ becomes zero [6,7].

For the homogeneous 2CF, the two cores have originally the same propagation constants. Therefore, independent of the bending radius, Δβ always become zero when the cores are placed perpendicular to the bending radius as shown in Fig. 4(b). We considered that that is why the PCC for the homogeneous 2CF did not show the apparent dependence on the bending radius.

For the heterogeneous 2CF, the two cores have originally different propagation constants. Thus, the smaller bending radius, the smaller the propagation constant difference. We considered that this is the reason why the PCC for the heterogeneous 2CF decreases with the bending radius due to this.

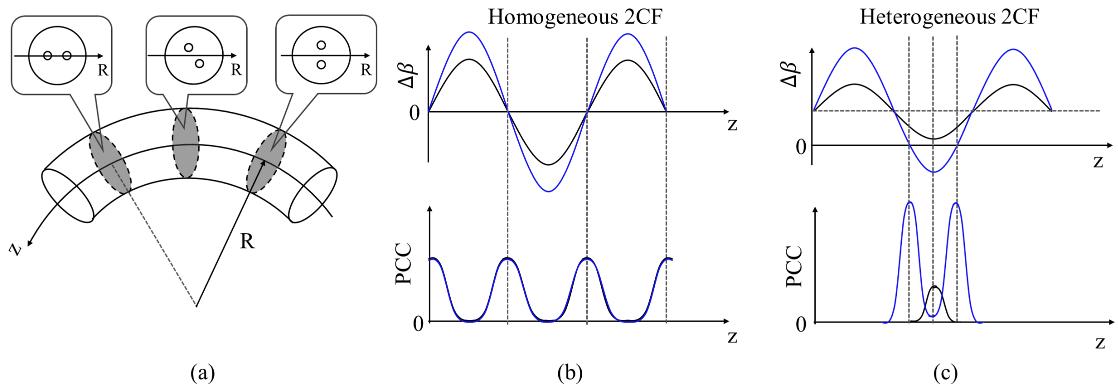


Fig. 4. Schematic diagram for explaining how the PCC changes with the bending and twisting states of the FUT.

4. Conclusions

We experimentally investigated the PCC depending on the bending radius for the first time using homogeneous and heterogeneous 2CFs. The PCC for the homogeneous 2CF did not depend much on the bending radius, whereas that for the heterogeneous 2CF clearly decreased with the bending radius. We also discussed the relationship between the PCC and SMD. We believe these findings would be useful when designing the fibers or transmission systems.

5. References

[1] T. Hayashi et al., "Record-low spatial mode dispersion and ultra-low loss coupled multi-core fiber for ultra-long-haul transmission," J. Lightwave Technol. **35**, 450-457 (2017).
[2] G. Rademacher et al., "High capacity transmission in a coupled-core three-core multi-core fiber," J. Lightwave Technol. **39**, 757-762 (2021).
[3] K. -P. Ho et al., "Statistics of group delays in multimode fiber with strong mode coupling," J. Lightwave Technol. **29**, 3119-3128 (2011).
[4] K. -P. Ho et al., "Mode-dependent loss and gain: statistics and effect on mode-division multiplexing," Opt. Express **19**, 16612-16635 (2011).
[5] S. Mumtaz et al., "Reduction of nonlinear penalties due to linear coupling in multicore optical fibers," IEEE Photon. Technol. Lett. **24**, 1574-1576 (2012).
[6] T. Sakamoto et al., "Fiber twisting- and bending-induced adiabatic/nonadiabatic super-mode transition in coupled multicore fiber," J. Lightwave Technol. **34**, 1228-1237 (2016).
[7] T. Hayashi, "Multi-core fibers for space division multiplexing," in *Handbook of Optical Fibers*, G. -D. Peng, ed. (Springer, 2019).
[8] M. Nakazawa et al., "Nondestructive measurement of mode couplings along a multi-core fiber using a synchronous multi-channel OTDR," Opt. Express **20**, 12530-12540 (2012).
[9] A. Nakamura et al., "Optical time domain reflectometry for simultaneously characterizing forward and backward crosstalk along multi-core fibers," J. Lightwave Technol. **40**, 6257-6263 (2022).
[10] M. Uyama et al., "Wideband impulse response measurement of coupled 2-core fibers of various lengths employing dual-comb coherent sampling," in Proceedings of OFC 2022, M1E.5.
[11] T. Hayashi et al., "Randomly-coupled multi-core fiber technology," Proc. IEEE, doi: 10.1109/JPROC.2022.3182049