

Crosstalk behavior of cores in multi-core fiber under bent condition

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Abstract: Measurement results of bending diameter dependence of the crosstalk of each core in a multi-core fiber are presented. The crosstalk of cores shows different diameter dependence although the difference in core parameters is very small. The behavior is explained by taking into account the change of propagation constant caused by the fluctuation in the diameter and the refractive index of cores. The diameter dependence simulated with coupled-power theory shows the same tendency with the measured crosstalk.

Keywords: multi-core fiber, crosstalk, coupled-power theory

Classification: Optical fiber

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1 Introduction

Communication traffic on an optical transmission system has been growing and the continuous expansion of transmission capacity has been required. Disruptive technologies have been expected to break the limit of incremental technology of the optical transmission system. In Japan, discussions regarding the issue have been initiated. Space division multiplexing employing a multi-core fiber (MCF) has been proposed as one of the key solutions to this issue [1].

The most important characteristic on the MCF as a transmission medium is crosstalk. Clarifying the crosstalk behavior of the MCF is indispensable to apply the MCF as transmission lines. We have presented the length dependence of the crosstalk on a quasi-homogeneous MCF, which shows low crosstalk values thanks to the very small deviation in core parameters, and have proposed an analysis method using the coupled-power theory [2, 3]. Another issue on the crosstalk characteristics is the effect of bending [4]. The analysis method based on the coupled-mode theory regarding bending and twisting effect on a MCF has been proposed to explain the bending diameter dependence of crosstalk. The comparison between simulation result and measured crosstalk on a core of 2-m heterogeneous MCFs, which have quite different characteristics between a center core and outer cores, has been presented [5].

In this paper, we show the measured bending diameter dependence of crosstalk of a 7-core quasi-homogeneous MCF. The crosstalk characteristics on each outer core are presented for the first time. The outer cores show the different behavior even for the small difference in core parameters. The explanation model for the behavior is proposed. Finally, simulation results with the coupled-power theory are presented.

2 Crosstalk measurement on cores of a bent MCF

2.1 A sample and measurement setup

Figure 1 (a) shows sectional view of the MCF prepared for this experiment. The stack and draw method was employed for the fabrication of the MCF. A special diameter arrangement was prepared for the cores to clarify the crosstalk behavior of a MCF with small deviation in core parameters. The diameter of outer cores was designed to be about a few percent smaller than the diameter of a center core. The outer cores whose diameters were categorized into two groups were arranged alternately circumference direction. Figure 1 (b) shows the measured core diameter difference of the fabricated MCF. A halogen light source and a digital microscope were employed. Diameters of the cores were estimated through binary coded processing on digitally recorded images. The diameter difference against the averaged diameter of outer cores is plotted in arbitrary unit because absolute values of the measured diameter include some uncertainty for the setting of threshold level. The measured results indicate that the alternate diameter arrangement of outer cores is realized. The pitches between each core were about $39.2\ \mu\text{m}$.

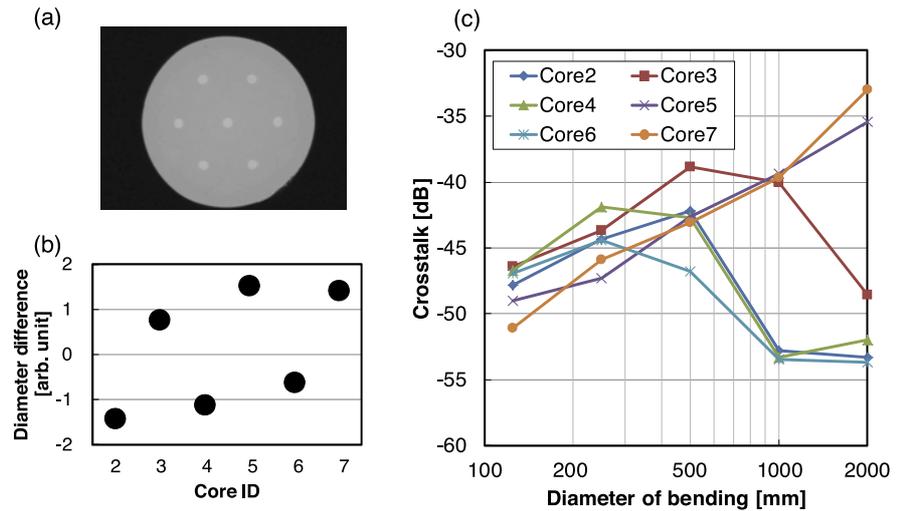


Fig. 1. (a) A cross sectional view of a fabricated MCF. (b) Measured core diameter difference of outer cores of a fabricated MCF: A halogen light source and a digital microscope were used for the measurement. (c) Measured bending diameter dependence of crosstalk of a 100-m MCF. Outer-core (core ID = 2 - 7) crosstalk for a center core (core ID = 1) excitation was measured at wavelength of 1550 nm.

A relative refractive index difference of the cores was about 0.4%. Mode field diameters at 1550 nm ranged from $9.52 \mu\text{m}$ to $9.77 \mu\text{m}$ for all cores. The fabricated MCF shows quasi-homogeneous optical characteristics.

The same measurement setup with our previous reports [2, 3] was used for crosstalk measurement. Crosstalk values were calculated from a ratio of the maximum power from the outer cores to the power of the center core. Free-coil samples with length of 100 m were prepared. Prepared coil diameters were 2000 mm, 1000 mm, 500 mm, 250 mm and 125 mm. We have loosely stored the free-coil samples into a c-groove slot, which is designed for an optical fiber cable [6], for stabilizing bending condition during the crosstalk measurement.

2.2 Measurement results

Figure 1 (c) shows bending diameter dependence of measured crosstalk of outer cores. The crosstalk values linearly deteriorate as a function of bending diameter in logarithmic scale. However, the crosstalk values of outer cores suddenly drop at the respective bending diameter larger than 500 mm. The behavior of outer cores is roughly categorized into two groups. The classification with the core ID originates from the alternate core diameter arrangement. Even-ID cores have the maximum crosstalk at the diameter (hereafter D_m) from 250 mm to 500 mm. The D_m of odd-ID cores are larger than those of the even-ID cores. The D_m of core 3 was about 1000 mm. Core 5 and core 7 did not show the maximum crosstalk within the measured di-

ameter range. The small fluctuation in core parameters resulted in the large difference in the bending diameter dependence of crosstalk.

3 Discussion

3.1 Maximum-crosstalk diameter difference on outer cores

The effective index of outer cores varies according to the bending and twisting on a MCF and can be presented by the following equation [5].

$$n_i = n_{i0} \left[1 + \frac{\Lambda}{(D_b/2)} \cos \theta_i(z) \right] \quad (1)$$

where subscript i denotes core ID ($i = 2-7$), n_{i0} is a refractive index without any fluctuation, n_i is a refractive index under the bending and the twisting, Λ is a pitch of adjacent cores, D_b is a bending diameter and θ_i is a rotation angle by the twisting.

A relative refractive index difference $\delta\Delta_i$ between a center core and an outer core can be expressed as a following equation using Eq. (1) and the assumption that $\Lambda/(D_b/2) \ll 1$. The assumption is appropriate for a MCF in most bending condition.

$$\delta\Delta_i = \frac{n_i^2 - n_1^2}{2n_i^2} \approx \delta\Delta_{i0} + \frac{\Lambda}{(D_b/2)} \cos \theta_i, \quad (2)$$

$$\delta\Delta_{i0} = \frac{n_{i0}^2 - n_1^2}{2n_{i0}^2} \quad (3)$$

where $\delta\Delta_{i0}$ is an initial refractive index difference of i -th core relative to the core 1, which is a center core.

The change of relative refractive index induced by bending causes the change of propagation constant β . The deviation of core diameter also results in the change of β . The variation of D_m shown in Fig. 1 can be explained taking into account both the effects. Figure 2 (a) shows the β behavior that is originated from the change of structural parameters of a core. The horizontal

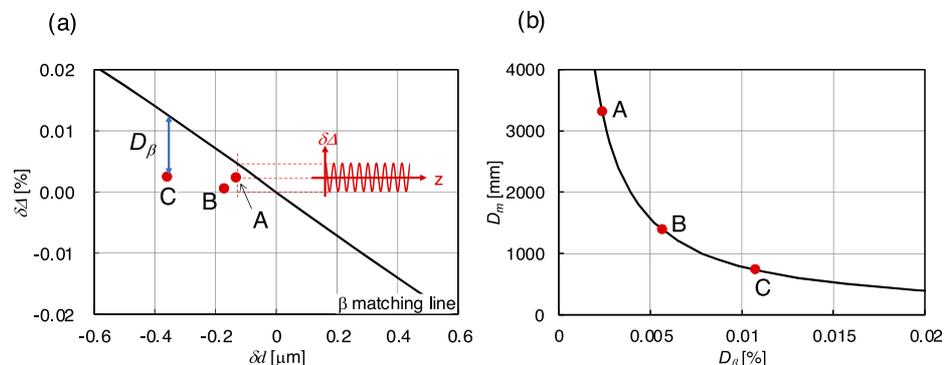


Fig. 2. An explanation model for variation in D_m : (a) the comparison of β matching line and core parameters difference between outer cores and a center core. Sinusoidal lines colored in red is schematic of $\delta\Delta_i$ given by Eq. (2). (b) D_β dependence of D_m .

axis is the diameter deviation δd of outer cores given by $\delta d = d_i - d_1$. The vertical axis is relative refractive index difference $\delta\Delta$ between outer cores and a center core given by Eq. (2). A core diameter of $8.0826\ \mu\text{m}$ and a relative refractive index difference of 0.3989% were employed as parameters of the center core. The black solid line is β matching line, on which the both β of the center core and an outer core are matched and the crosstalk between the cores drastically increase. Red circle symbols are examples of outer cores for explanation. A red line shows a diagram of refractive index oscillation given by Eq. (2) for core A.

The amplitude of an oscillation increases with decreasing a bending diameter D_b . If the trace of oscillation reaches to β matching line, as with the red oscillating line, the β matching causes crosstalk degradation. The D_m is a diameter at which the β of adjacent core matches. The definition is the same with r_{pk} in Ref [5]. The crosstalk of the MCF under the bending and twisting condition will be observed as integral values over the index oscillation. It should be noted that frequency distribution of sinusoidal wave such as Eq. (2) is weighted around maximum amplitude. The weighted distribution causes the sudden change of crosstalk by bending. Core A and core C have the similar $\delta\Delta_{i0}$ and different δd_i . The distances to β matching (hereafter D_β) are different owing to the difference in δd_i . The difference in the distance results in the difference in D_m .

Figure 2 (b) shows a relationship between D_β and D_m . A black line is calculated from Eq. (2) and the β matching line. The figure indicates that D_m of core A, core B and core C are 3319 mm, 1390 mm and 734 mm. The D_β of a fabricated MCF can be estimated from measured D_m . The D_β of the even-ID cores and core 3 is estimated to about 0.015% and about 0.008% , respectively. The D_β would be less than 0.005% for core 5 and core 7.

3.2 Bending diameter dependence simulation with coupled-power theory

We have proposed to use the coupled-power theory for explaining the length dependence of the crosstalk of MCFs in Ref [2, 3]. The coupled-power theory can explain the bending diameter dependence of crosstalk by introducing the index change caused by bending and twisting.

We have defined a power coupling coefficient between i -th core and j -th core h_{ij} as

$$h_{ij}(z) = \eta_{ij}(z)/L_{cij}(z) \quad (4)$$

where η_{ij} and L_{cij} are a power conversion efficiency and a coupling length between i -th core and j -th core. The power conversion efficiency and the coupling length are obtained by the coupled-mode theory. The effect of bending and twisting is incorporated through η_{ij} and L_{cij} estimation.

Figure 3 shows the comparison of measured crosstalk and simulated crosstalk. Black solid symbols show measured results. Red lines show simulation results. Twisting pitch of 5 turns per 100 m and the relative refractive indexes of all cores of 0.4% were employed for the simulation. The diameters of each

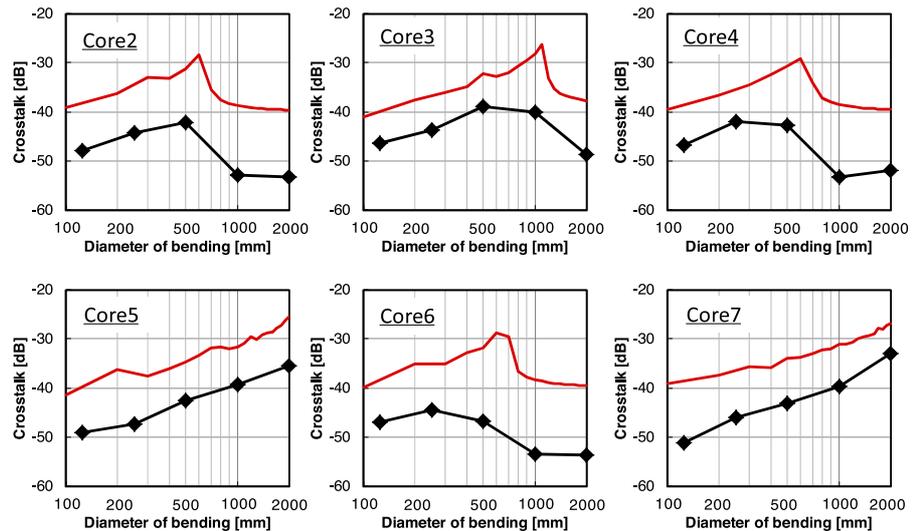


Fig. 3. Bending diameter dependence of crosstalk at 1550 nm: Black solid symbols are measured data of a fabricated MCF with 100-m free coil. Red lines are simulation results.

core were set to $8.05 \mu\text{m}$ (core 1), $7.63 \mu\text{m}$ (core 2), $7.83 \mu\text{m}$ (core 3), $7.69 \mu\text{m}$ (core 4), $7.93 \mu\text{m}$ (core 5), $7.70 \mu\text{m}$ (core 6) and $7.94 \mu\text{m}$ (core 7), respectively. The diameter configuration for the simulation agrees with the core diameter design of the fabricated fiber.

Simulation results show the same tendency with measurement results. Both the results showed the similar slope over small bending diameter region. The amount of crosstalk change around D_m was also the same level between the simulation results and the measurement results. However, simulated crosstalk values are about 10-dB larger than the measured crosstalk values. The discrepancy is probably caused by the overestimation of parameter h .

4 Conclusion

We have experimentally demonstrated a bending diameter dependence of the crosstalk on each outer core of a 7-core MCF for the first time. The cores showed the different diameter dependence in spite of the small fluctuation of structural parameters. The behavior can be understood by taking into account the change of propagation constant that is caused by the change of structural parameters of cores. The bending diameter dependence of crosstalk simulated by the coupled-power theory shows the same trend with the measured crosstalk.

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