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Crosstalk behavior of multi-core fiber with structural parameter drift in longitudinal direction

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Abstract: An impact of longitudinal structural parameter drift on crosstalk behavior of multi-core fibers is investigated with a newly proposed semi-analytical method which can easily simulate crosstalk under the various kinds of parameter drifts. The simulation results indicate that the structural parameter drift has an important role in moderating bending diameter dependence of crosstalk of multi-core fibers.

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

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1 Introduction

A multi-core fiber (MCF) has been expected to be a solution to overcome a capacity limit of optical communication systems. The understanding of the crosstalk characteristics of MCFs is very important to put the fiber in practical use. The length dependence [1, 2] and twist and bending effects [3, 4, 5] have been investigated experimentally and analyzed theoretically with the coupled-mode theory and the coupled-power theory in the past. The results indicate that the crosstalk characteristics are strongly affected by bending. The cable that gives fibers a bending radius less than 391 mm was proposed to keep a sufficiently small crosstalk for a certain MCF [6]. The effective bending diameter of fibers in a cable is strongly depending on a cable structure and the effective bending diameter exceeds 1000 mm for certain type of cable [7]. The crosstalk of MCF ought to be stable over wide range of bending diameter to relax the restriction on the cable design.

In this paper, we investigate the effect of longitudinal structure parameter drift on crosstalk characteristics of a MCF. A semi-analytical method is introduced to simulate the drift effects for various conditions. The effect of the parameter drift on the bending diameter dependence of the crosstalk is presented.

2 Simulation method

The crosstalk of MCFs can be simulated by solving the coupled-power equation for a MCF including bending and twisting effects. A power coupling coefficient h of a MCF is given as a following equation [1, 2]:

$$h = \frac{4\kappa^2}{\pi\sqrt{4\kappa^2 + \Delta\beta^2}} \tag{1}$$

where κ is a coupling coefficient, and $\Delta\beta$ is a propagation constant difference between cores. The simulation time with a rigorous numerical method based on the coupled-power theory (hereafter, RNM) is shorter than the simulation time of the coupled-mode theory. However, it takes a lot of doing to simulate crosstalk behavior including longitudinal drift on structural parameters even for the RNM because we need to solve simultaneous coupled-power equations for segments with different structural parameters.

In this paper, we propose a semi-analytical method (SAM) to evaluate the crosstalk for various conditions more easily than the RNM. The SAM simulates crosstalk using averaged h_{avg} that is an integrated value of approximated local h over the length.

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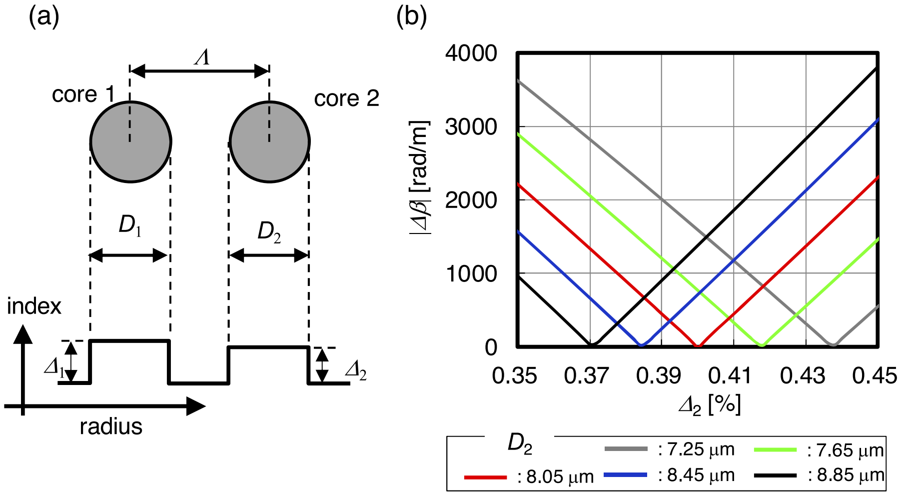

Fig. 1. Simulated absolute value of $\Delta\beta$ as a function of D_2 for different D_2: (a) Schematics of two-core model. (b) Simulation results.

Figure 1 (a) shows a two-core fiber for explanation. Figure 1 (b) shows absolute value of $\Delta\beta$ (hereafter, $|\Delta\beta|$) at 1550 nm as function of Δ_2 for various D_2. The same parameters with Ref. [5] were used: $\Lambda = 39.2\,\mu$m, $\Delta_1 = 0.40\%$ and $D_1 = 8.05\,\mu$m. The Δ_2 where propagation constants of the cores are matched varies with D_2. However, the shape of the Δ_2 dependence of $|\Delta\beta|$ is maintained against D_2 variation. The result indicates that we can estimate $|\Delta\beta|$ for various set of Δ_2 and D_2 by using the Δ_2 dependence of $|\Delta\beta|$ at a certain D_2. The same concept can be applied to the estimation of κ. A local power coupling coefficient h with various core parameters can be calculated by the estimated $|\Delta\beta|$ and κ.

If h is varied with fiber length, averaged power coupling coefficient h_{avg} over length of L is given by

$$h_{avg} = (1/L)\int_0^L h(l)dl, \tag{2}$$

where $h(l)$ is a local power coupling coefficient at l, which is given through the procedure established above. The effects of twisting and bending are introduced to $h(l)$ according to Ref. [5]. The crosstalk of a MCF at length of L, $XT(L)$ is defined by the following equation:

$$\begin{aligned} XT(L) &= (1-\exp(-2h_{avg}L))/(1+\exp(-2h_{avg}L)) \\ &= \tanh(h_{avg}L). \end{aligned} \tag{3}$$

We compared the simulation results of the RNM and the SAM to confirm the validity of the SAM. Figure 2 shows bending diameter dependence of crosstalk with the RNM and the SAM. A blue line and open symbols are simulation results derived by the RNM and a red line and solid symbols are calculation results by the SAM. Following parameters were used for the simulation: wavelength = 1550 nm, $\Delta_1 = \Delta_2 = 0.4\%$, $D_1 = 8.05\,\mu$m, $D_2 = 7.69\,\mu$m, $\Lambda = 39.2\,\mu$m and $L = 100$ m. The twisting effect was considered

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in both the simulation. The result with the SAM is consistent with the simulation results with the RNM. The SAM has sufficient accuracy to analyze the crosstalk behavior of MCFs in addition to high estimation speed.

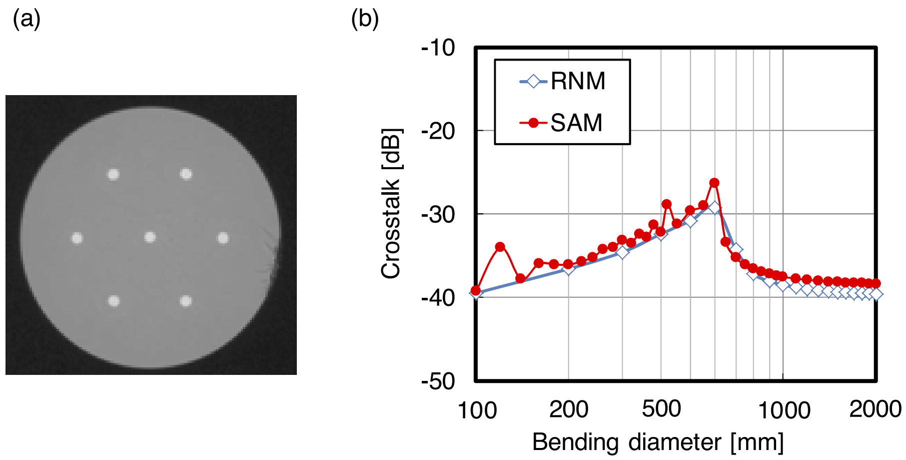

Fig. 2. Bending diameter dependence of crosstalk: (a) A cross sectional view of a fabricated MCF used for the measurement [5]. (b) Comparison of crosstalk between two simulation results.

3 Effect of structural parameter drift

A MCF at the length that is assumed for practical use involves structural parameter drift whose cycle is longer than that of the random imperfection that is already assumed in the coupled-power theory. We employ a concatenation model of a small segment for simulating the effect of structural parameter drift. The SAM can rapidly simulate the crosstalk of the concatenation model because h for each segment with different structural parameters can be estimated without solving simultaneous coupled-power equations for each segment. The drifts are imposed on a fiber by gently changing the structural parameters in longitudinal direction. Here, a sinusoidal drift is used and is given by the following equation.

$$\Delta_2(l) = \Delta_{20} + A_{\Delta} \cos(cl + \varphi), \tag{4}$$

where Δ_{20} is an initial relative refractive index of core 2, A_{Δ} is an amplitude of the drift on core 2, c is a drift pitch, l is a length and φ is an initial phase.

Figure 3 shows length dependence of crosstalk at 1550 nm for different drift conditions. Solid lines are colored by a bending diameter. We use $\Delta_1 = \Delta_{20} = 0.4\%$, $D_1 = 8.05\,\mu\text{m}$, $D_2 = 7.69\,\mu\text{m}$, $c = 2\pi/1000\,\text{rad/m}$ and φ of $\pi/2$ for the simulation. Figure 3 (a) shows simulation results under the condition with no structural drift. The length dependence of crosstalk showed the same slope for all bending diameter. However, 10-dB difference was observed depending on the bending radius. Figures 3 (b) and (c) show the simulation results of a MCF with the parameter drift. Let A_{Δ} be 0.005% and 0.01%

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respectively. The drift caused moderate change in the crosstalk behavior at bending diameter of 250 mm and 500 mm because the crosstalk around the bending diameter of 250 mm and 500 mm was dominated by bending related β matching. In contrast, crosstalk behavior at bending diameter of 1000 mm and 2000 mm was strongly effected by the structural parameter drift. The length dependence of crosstalk at the bending diameter of 1000 mm and 2000 mm was curved at the different length where β matching was caused by the parameter drift. The shape of the curve changes in accordance with the amplitude of the drift. The crosstalk tends to converge within a few dB ranges over the length of longer than 1000 m: the dependence on bending diameter becomes moderate. Structural parameter drift is an important factor on the MCF design.

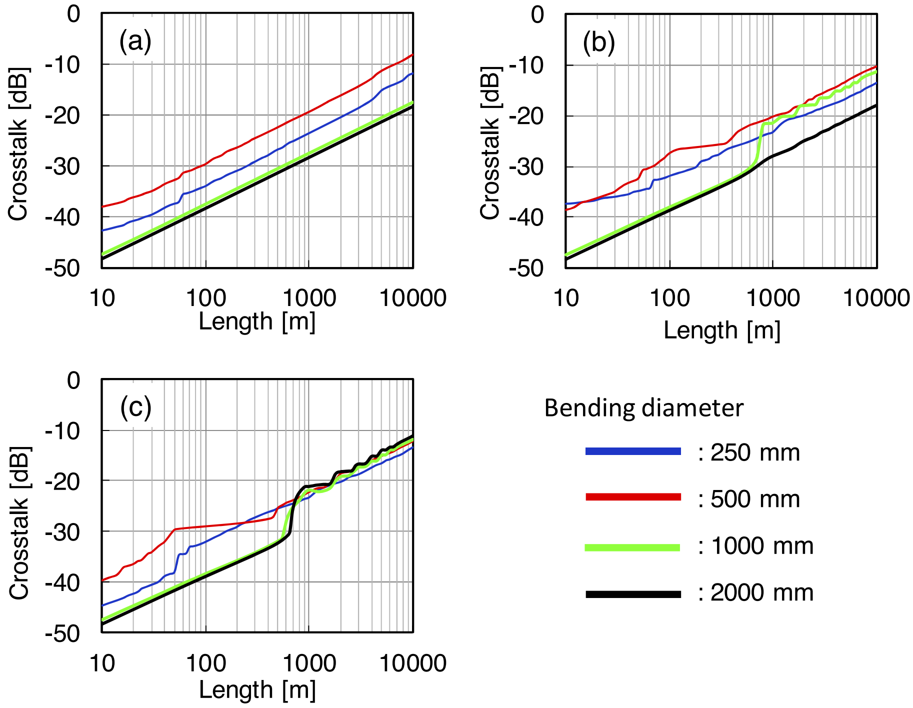

Fig. 3. Length dependence of crosstalk at 1550 nm for various A_Δ: (a) $A_\Delta = 0\%$ (No structural drift). (b) $A_\Delta = 0.005\%$. (c) $A_\Delta = 0.01\%$.

4 Conclusion

We investigated the effect of longitudinal structural parameter drift on the crosstalk characteristics of a MCF. A semi-analytical simulation method is introduced to evaluate the drift effects for various conditions. The impact of the longitudinal drift on MCF-crosstalk characteristics was confirmed by simulation. The simulation results indicate that longitudinal parameter drift reduces the bending effect on crosstalk characteristics over the length that is supposed as a communication line. We should take into account both bending and longitudinal drift for designing MCFs.

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