Cabling loss characteristics of few-mode fiber under curvature control in high-density cable

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***Abstract*—We investigated the cause of cabling loss in few-mode fiber under curvature control in high-density cable and found dominantly stems from micro bending due to install-fiber-density and tension of the bundle tape.**

Keywords—Few-mode fiber, high-density cable

I. Introduction

Space division multiplexing (SDM) fiber is one of promising technology for overcoming the transmission capacity limit of single mode/core optical fiber [1]. Few-mode fiber (FMF) has the same ease of splicing as conventional single-mode fiber (SMF) and can recover signals suffering from inter-modal crosstalk with numerical calculation using the multi input multi output (MIMO) technique. The efficiency of MIMO depends strongly on the differential modal delay (DMD) of FMF [2]. In our previous study, we proposed a method for reducing DMD by controlling the curvature of optical fiber in high-density cable [3]. This method can increase the tolerance of the FMF index profile design because DMD is controlled after FMF fabrication of FMF, but exhibits a rather large cabling loss. For implementation in practical transmission system, we need to identify the cause of cabling loss and suppress it.

In this paper, we investigate the cause of cabling loss of graded index two-LP mode fiber (GI-2MF) under curvature control in high-density cable and show that stems predominantly from micro bending. After that, we investigate the cable parameter for suppressing induced optical loss. We also measured the effect on cabling loss of cable parameter that controls curvature of GI-2MF.

II. Design and Fabrication

A. Few-mode fiber

Figure 1 shows the index profile of the designed GI-2MF. The relative refractive index profile design is $\Delta n(r)$ is expressed as

$$\Delta n(r) = \begin{cases} -\Delta_{\mathrm{c}}\left[1-\left(\dfrac{r}{a_{\mathrm{c}}}\right)^{\alpha}\right] & (0 \le r < a_{\mathrm{c}}) \\ -\Delta_{\mathrm{tr}} & (a_{\mathrm{sh}} \le r < a_{\mathrm{sh}} + w_{\mathrm{tr}}) \\ 0 & (\text{otherwise}). \end{cases}$$

Here, the measured values of Δ_{c}, a_{c}, a_{sh}, w_{tr}, and Δ_{tr} are 0.34 %, 10.2 µm, 12.5 µm, 5.0 µm, and 0.8 %, respectively. The profile exponent, denoted by α is designed so as to be lower DMD. Table 1 shows the properties of the fabricated optical fiber. The fabricated GI-2MF has a cladding diameter which is same as conventional single mode optical fiber and exhibits two-LP-mode behavior over the C-L band and a sufficiently low intrinsic optical loss. The differential modal delay of fabricated GI-2MF is -48 ps/km although they are same design. It is larger than that we used in [3]. The difference is because of manufacturing variances.

Figure 2 shows bending loss characteristics of the fabricated GI-2MF. Measured wavelength is 1625 nm. Macro bending loss characteristics is shown in (a). The macro bending loss is measured by bending GI-2MF with mandrel. Opened circles, filled circles and triangles represent the result of LP_{01} and LP_{11} mode of GI-2MF and SMF, respectively. Although LP_{11} mode shows rather larger optical loss, both are sufficiently suppressed, where the macro bending characteristics are in accordance with ITU-T G.657.A1 and smaller than conventional SMF. Thus, the fabricated GI-2MF will exhibits no cabling loss due to macro bending. Micro bending loss characteristics of fabricated GI-2MF is shown in (b). The measurement method is same as in [4]. Opened and filled circles represent the result of LP_{01} and LP_{11}, respectively. LP_{01} shows no optical loss increase regardless of lateral pressure. LP_{11} shows macro bending loss when lateral pressure is larger than 0.04 MPa. Both modes shows sufficiently low optical loss even when the lateral pressure is less than 0.06 MPa. As demonstrated in our previous study, lateral pressure is dependent on install-fiber-density [5]. The lateral pressure of 0.06 MPa is equivalent to 9 fiber/mm^2 of install-fiber density [4], which is almost same as that of a cable described in [6].

TABLE I. Properties of Fabricated Optical Fiber

Item		Value
Cladding diameter		125 µm
Effective area (LP_{01})		* 114 µm^2
Optical loss (1625 nm)	LP_{01}	0.22 dB/km
	LP_{11}	0.22 dB/km
Differential modal delay (C-band)		-48 ps/km
Cut-off wavelength (LP_{21})		1.48 µm

* calculated value

B. High-density cable

Figure 3 shows schematic images of the curvature controlled high-density optical fiber cable we fabricated. Its basic structure is the same as a conventional high-density cable [3]. A cross-sectional image is depicted in (a). The cable is composed of units, rip cord, sheath, and strength member. The units are composed of bundled partially bonded optical fiber ribbons. A side view of the bundled fiber unit is depicted in (b). The bundle tape has an intentional tension with the ability of giving partially bonded optical fiber ribbon curvature. The larger tension induces larger fiber curvature. As demonstrated in our previous study, we can control the DMD by the curvature of GI-2MF via the tension of the

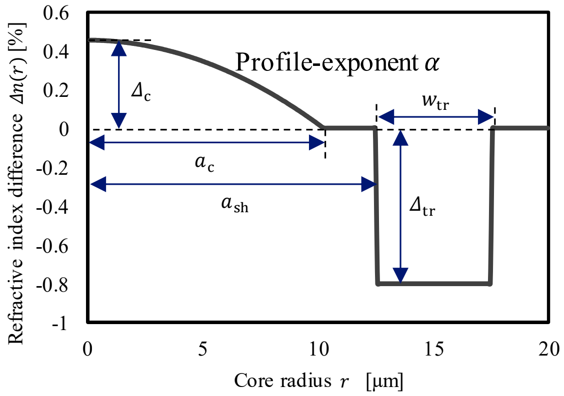


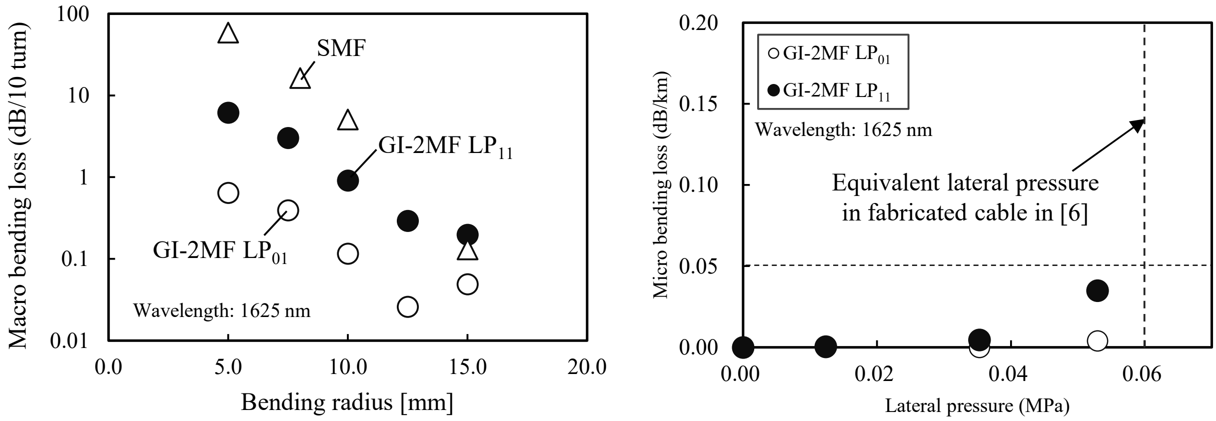
Fig. 1 Index profile of designed graded-index 2LP-mode optical fiber.

bundled tape. We fabricated three cables with relative tensions of 0.25, 0.55, and 0.75, respectively. The relative tension of 0.25 is the same as that of a conventional high-density cable, and that of 0.75 is the maximum value in this cable structure. It is rather smaller than our previous study [3]. We assumed it is caused by the decrement of friction between the bundled unit and sheath due to smaller install-fiber-density.

Table 2 shows the common properties of fabricated high-density cable. We accommodated three GI-2MFs in each 200-fiber cables. Each GI-2MFs are accommodated in another partially-bonded optical fiber tape. The outer and inner diameter is 15.3 mm and 7.8 mm, respectively. Install-fiber-density, is 4.2 fiber/mm^2. Here, install-fiber-density is the number of fiber per inner area. The fabricated cables have sufficiently small install-fiber-density comparing the requirement that we clarified in II.A. Bundle tape that we used for adding intentional tension has pitch and width of 30 mm and 1.3 mm.

TABLE II. PROPERTIES OF FABRICATED HIGH-DENSITY CABLE

Item		Value		
		Cable A	Cable B	Cable C
No. of fibers (That of GI-2MF)		200 (3)		
No. of units		10		
Sheath	Outer diameter	15.3 mm		
	Inner diameter	7.8 mm		
Install-fiber-density (Equivalent lateral pressure)		4.2 fiber/mm^2 (0.02 MPa)		
Bundle tape	Pitch	30 mm		
	Width	1.3 mm		
	Relative Tension	0.25	0.55	0.75



(a) Macro bending loss

(b) Micro bending loss

Fig. 2 Bending loss characteristics of GI-2MF.

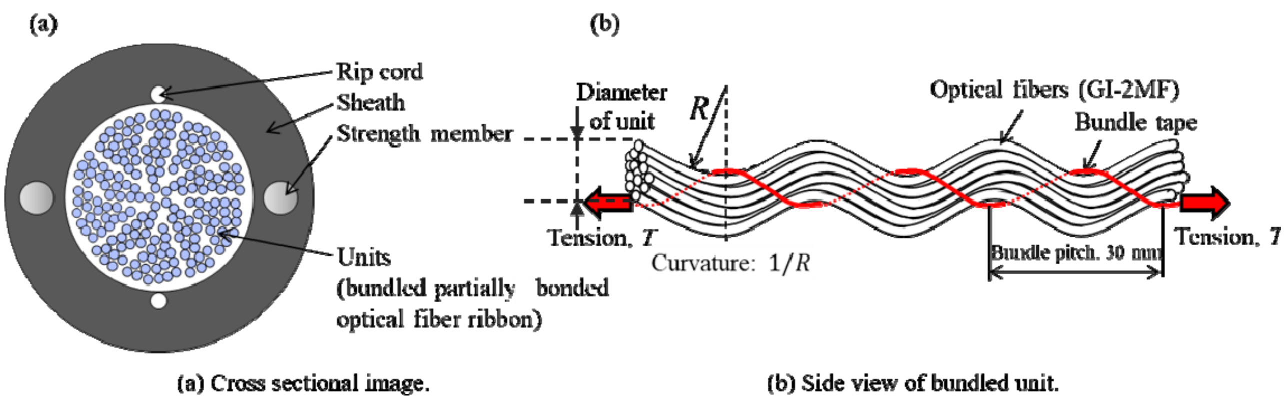


Fig. 3 Schematic image of curvature controlled high-density cable.

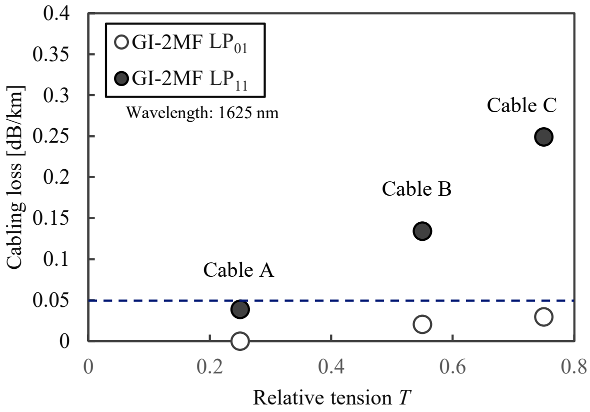


Fig. 4 Cabling loss characteristics of GI-2MF as a function of relative tension *T*.

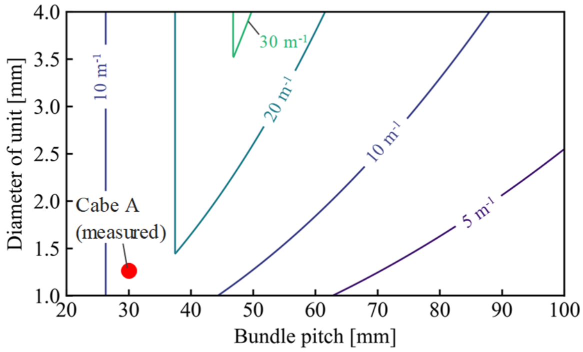


Fig. 5 Induced curvature as a function of bundle pitch and diameter of unit.

III. Results and Discussion

Figure 4 shows the cabling loss characteristics of GI-2MF as a function of relative tension *T*. The opened and filled circles show the results of LP_{01} and LP_{11}, respectively. The measured wavelength is 1625 nm. Both modes show sufficiently small cabling loss smaller than 0.05 dB/km when relative tension is 0.25, which is caused by reduced lateral force via controlled install-fiber-density. LP_{11} shows cabling loss larger than 0.05 dB/km when relative tension is 0.55 or larger. The cabling loss is induced by the tension of bundle tape.

To reduce the tension of bundle tape, we investigated induced curvature as a function of bundle pitch and diameter of unit by geometrical calculation as shown in Fig. 5. The basic model is same as our previous study [6]. A red circle shows the cable A. The contour lines show the gained curvature with bundle pitch and diameter of units, where the lateral pressure induced by bundle tape is fixed as to be same as the cable A. The lateral pressure is calculated by the model described in [6]. We found that we can maximize curvature by optimizing diameter of unit and bundle pitch.

IV. Conclusion

We investigated the cause of cabling loss in few-mode fiber under curvature control in high-density cable and found that predominantly stems from micro bending. The few-mode fiber that we used in this experiment shows sufficiently low cabling loss when the lateral pressure is less than 0.06 MPa, which is equivalent to 9 fiber/mm^2. We also evaluated the effect of tension of bundle tape in high-density cable for cabling loss and found that the excess cabling loss is caused by tension of bundle tape, and shows cable design for maximizing curvature.

Acknowledgment

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