A method for differential modal delay reduction by using curvature of few-mode optical fiber in high-density cable

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Abstract: We propose a method of controlling the differential modal delay of 2LP-mode graded-index fiber by using the curvature of fiber in high-density cable. The method achieved a 50% reduction in the C-L band.

1. Introduction

Space division multiplexing (SDM) fiber, including few-mode fiber (FMF), is actively studied to overcome the transmission capacity limit per single core [1]. Moreover, it has been reported that mode division multiplexing (MDM) systems using FMF can use multiple input multiple output (MIMO). A MIMO system can recover signals suffering from crosstalk during transmission by using a numerical calculation. The circuit complexity and power consumption for the calculation is strongly dependent on differential modal delay (DMD) [2]. Therefore, several low DMD fibers have been proposed [3, 4]. Alternatively, the use of DMD-managed transmission lines, combining different types of FMF with specific DMD coefficient to ensure low DMD, has been proposed [5, 6]. In both case, we need to fabricate specific DMD coefficient concisely. However, although the ideal design for DMD has been clarified [3, 4], DMD drastically changes because of manufacturing variances, and as yet there is no method to adjust DMD after fabricating the FMF.

In this paper, we propose a high-density cable that can reduce DMD by controlling the state of the optical fiber. Specifically, the curvature of the optical fiber can be controlled by varying a manufacturing parameter of the high-density cable. First, we describe the profile design of graded-index 2LP-mode fiber and give a theoretical analysis of DMD as a function of curvature. We then describe a method for controlling the fiber curvature in high-density cable. After that, we demonstrate the DMD reduction method by testing fabricated high-density cables. We also clarify the profile exponent values with which to achieve low DMD in high-density cable in the C-L band.

2. Design and fabrication

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

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

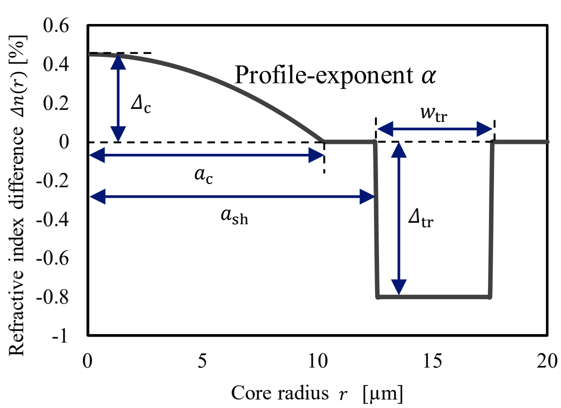


Fig. 1. Index profile of designed graded-index 2LP-mode optical fiber.

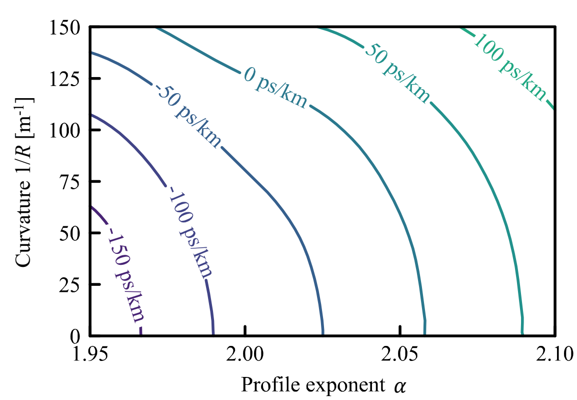


Fig. 2. DMD as a function of profile exponent and curvature.

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, mainly affects DMD [3, 4]. Table 1 shows the properties of the fabricated optical fiber. It shows two LP mode behavior over the C-L band and sufficiently low intrinsic optical loss. Moreover, the bending loss characteristics are sufficiently low at the upper end of the L band.

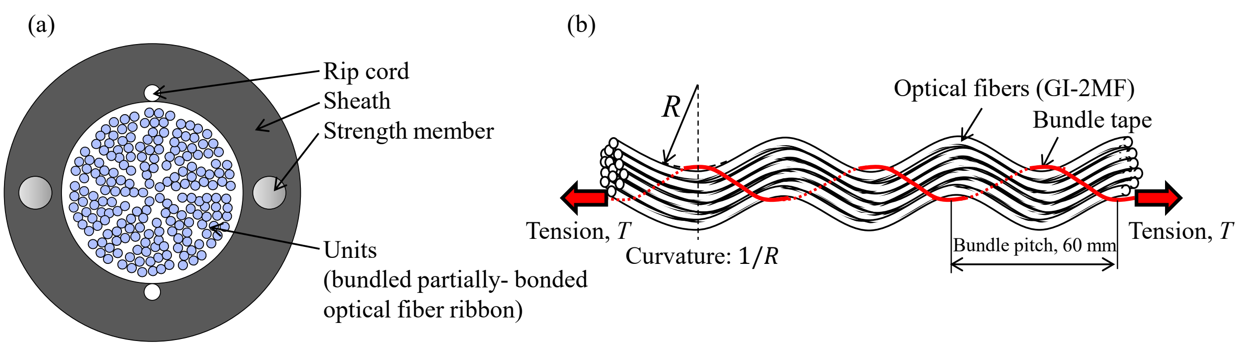
We calculated the DMD of bent GI-2MF by using the finite element method. Here, we define curvature as the inverse of the bending radius. Figure 2 plots the DMD as a function of the profile exponent and curvature at a wavelength of 1550 nm. We can see that a larger curvature modifies the DMD positively and monotonically. This means that we need to consider the curvature in the case of accommodating FMF in cable and during installation in the field because these operations modify the curvature of the FMF. In other words, the DMD is controlled by the fiber curvature.

To confirm the feasibility of DMD control by using high-density cable, we measured the change in DMD of FMF in curvature-controlled high-density cable. Figure 3 shows a schematic image of the fabricated high-density cable. A cross-sectional image is depicted in (a). Its basic structure is the same as conventional high-density cable [7]. The cable is composed of a rip cord, sheath, strength member, and units. The units are composed of bundled partially-bonded optical fiber ribbon. A side view of the bundled fiber unit is depicted in (b). The bundle tape has a large tension with the ability of giving the optical fiber curvature. The curvature model is the same as in our previous study [8]. In this way, we can control the DMD of FMF via the high-density cable design.

Table 1. Properties of fabricated optical fiber.

Item		Value
Cladding diameter		125 µm
Effective Area (LP_{01})		* 114 µm^2
Optical loss	LP_{01}	0.22 dB/km
	LP_{11}	0.22 dB/km
Bending loss at R=15 (at 1625 nm, LP_{11})		0.24 dB/10turn
DMD (at C-band)		-67 ps/km
Cut-off wavelength (LP_{21})		1.48 µm

* calculated value



(a) Cross-sectional image (b) Side view of bundled fiber unit

Fig. 3. Schematic image of controlling curvature in high-density cable.

3. Results and discussion

Figure 4 shows the measured DMD as a function of the relative tension of the bundle tape. The DMD measurement method is the same as described in [9]. The measurement wavelengths cover the C-L band. The length of fiber under test is 1.5 km. The absolute DMD shows a trend to decrease as the relative tension increases. We achieved a 50% reduction in the C-L band. The optical loss characteristic after cabling is approximately 0.50 dB/km for a relative tension of 2. Although this is rather large for a practical transmission system, it can be reduced by optimizing Δ_{c}, w_{tr}, and Δ_{tr}.

We also clarified the profile exponent values that would give a low DMD in high-density cable. We assumed curvature controllability of 0.1 to 100 m^{-1} and C-L band coverage. Figure 5 shows the profile exponent range to reduce DMD as a function of wavelength. The solid, dashed, and dash-dotted lines represent the profile exponent ranges that achieve 0, ±10, and ±50 ps/km, respectively. As shown in Fig. 2, DMD increases as the profile exponent and curvature get larger. This means that we can get the same DMD with a smaller profile exponent when a larger curvature is applied. Thus, the upper/lower edge of strip-like region in Fig. 5 is reached when the FMF has minimum/maximum curvature. In other words, we can enlarge the profile exponent design range through curvature control. For example, if we want to achieve a differential modal delay within ±50 ps/km in high-density cable at an arbitrary wavelength in the C-L band, the profile exponent should be from 1.99 to 2.07. Thus, we can enhance tolerance by designing the FMF and high-density cable simultaneously.

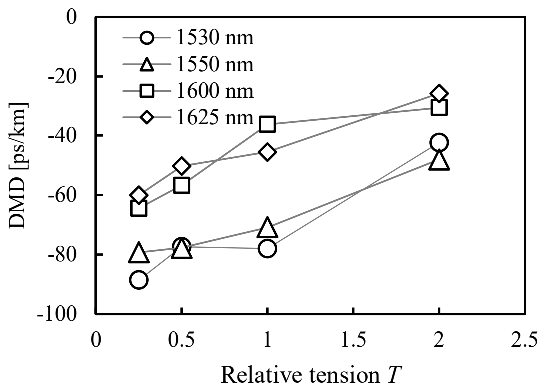


Fig. 4. DMD characteristics as a function of relative tension.

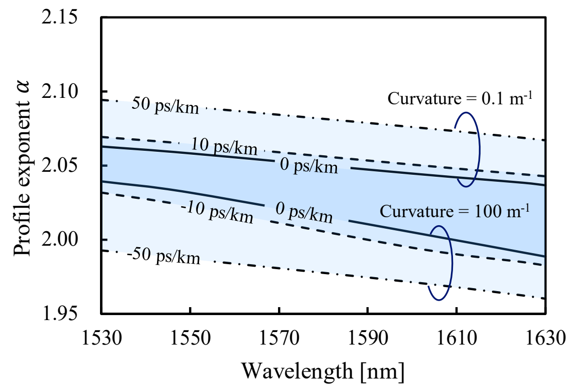


Fig. 5. Profile exponent range to reduce DMD as a function of wavelength.

4. Conclusion

We proposed a method of controlling the differential modal delay of 2LP-mode graded-index fiber through the fiber curvature in high-density cable. The method achieves a 50% reduction in the C-L band. The fiber curvature is controlled by using the tension of the bundle tape. We also clarified the profile exponent design to reduce differential modal delay as a function of wavelength. To achieve a differential modal delay within ±50 ps/km in high-density cable at an arbitrary wavelength in the C-L band, the profile exponent should be 1.99 to 2.07.

5. Acknowledgement

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6. References

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