Differential Modal Delay Controlling of 4-LP Mode Optical Fiber by High-Density Cable with Low Cabling Loss

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Abstract: We first clarified the design of low-loss-increment cable with 4-LP-mode fiber. We numerically and experimentally confirmed the feasibility of differential modal delay control and a 25 ps/km controllability potential with low cabling loss. © 2024 The Author(s)

1. Introduction

Space division multiplexing (SDM) fiber, including few-mode fiber (FMF), is a promising candidate for overcoming the transmission capacity limit per optical fiber [1]. Moreover, it has been reported that mode division multiplexing (MDM) systems utilizing FMF need to use multiple input multiple output (MIMO) digital signal processing (DSP), which can recover signals suffering from crosstalk during transmission. Recently, several research groups reported 3.56 Peta-bit/s transmission by 55-mode optical fiber [2] and field deployment of 15-mode optical fiber cable [3]. DSP's circuit complexity and power consumption strongly depend on differential modal delay (DMD) [4]. Thus, we previously proposed a novel method that reduced a DMD of two-LP mode graded-index fiber (2LP-GIF) by controlling the curvature of optical fiber in high-density cable. However, the cable caused a rather large optical loss increment because of micro bending loss due to cable parameters [5]. On the other hand, FMF with a further number of propagation modes is necessary to achieve a larger transmission capacity. To construct a practical transmission system, we must consider excess optical loss increase on higher-order modes [6]. Furthermore, we must consider DMD between each LP mode group because maximum absolute DMD finally determines DSP complexity. However, there are no studies to reveal DMD characteristics of FMF with more than 2-LP mode and to control DMD, nor to keep optical loss increase low.

In this paper, we first clarify cable design for low loss increment of 4-LP mode fiber (4LP-GIF). Then we show the achievable curvature within the low loss increment design. After that, we numerically and experimentally examine the curvature dependent DMD change of each LP mode group. We inferred a potential to control DMD of 4LP-GIF of 25 ps/km for without optical loss increase by simulating micro bending caused by cable parameters of bundle tape and optical fiber unit. We also examine fabricated curvature-controlled high-density cables to confirm the validity of fiber and cable design.

2. Fiber and cable design

To investigate optical loss increase, we designed a refractive index profile of 4LP-GIF and parameters of curvature-controlled high-density cable. The design parameters of the index profile of the designed 4LP-GIF are the same as in our previous work [5]. The relative refractive index profile $\Delta n(r)$ is expressed as

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

Here, the measured values of α, Δ_{c}, a_{c}, a_{sh}, w_{tr}, and Δ_{tr} were 2.0, 0.82 %, 10.5 µm, 12.1 µm, 6.6 µm, and 0.68 %, respectively. Note that Δ_{c} is higher than what we previously reported [7]. Table 1 lists the properties of the fabricated optical fiber. It supports LP_{01}, LP_{11}, and LP_{21}+LP_{02} modes over the C+L band. Moreover, the macro bending losses of all propagation modes were less than 1 dB/10turn at bending radius R and wavelength of 15 mm and 1625 nm, respectively. We measured 4LP-GIF optical loss increase due to lateral pressure to examine the micro bending loss sensitivity. The measurement method is the same as in [8]. We measured optical loss by optical time domain reflectometry (OTDR). The length of fiber under test (FUT) is 1 km. Figure 1 shows the result of micro bending loss sensitivity of 4LP-GIF. Circles, triangles, and squares indicate the results of LP_{01}, LP_{11}, and LP_{21}+LP_{02} modes, respectively. Although LP_{11} and LP_{21}+LP_{02} modes exhibit slight optical loss increases at lateral pressure larger than 0.1 MPa, all propagation modes of 4LP-GIF show optical loss increases less than 0.05 dB/km under lateral pressure of 0.2 MPa. This lateral pressure is twice large as that in conventional high-density cable [9].

We then design cable parameters for low optical loss increase. The basic structure of curvature-controlled high-density cable is the same as [10]. Figure 2 shows a schematic configuration of curvature-controlled high-density cable. The cable comprises a rip cord, sheath, strength member, and units. The units comprise bundled partially bonded optical fiber ribbon and wound by bundle tape with periodical bundle pitch p. To induce curvature to optical fiber, we intentionally control the tension of bundle tape T. For reduction of optical loss increase in high-density cable, we must consider micro bending loss induced by lateral pressure P. Here, P is expressed as $P = P_{\mathrm{install}} + P_{\mathrm{bundle}}$, where P_{install} is lateral pressure due to install-fiber-density ρ. P_{install} as a function of ρ that we have already reported in [9]. P_{bundle} is lateral pressure due to T. Assuming the unit receives uniform P_{bundle}, it is expressed as $P_{\mathrm{bundle}} = 2T/\pi D_{\mathrm{u}} p$, where D_{u} is the diameter of unit. We should design cable parameters to keep P less than 0.2 MPa, considering micro bending loss characteristics of the 4LP-GIF. Figure 3 shows P as a function of T, where we set D_{u} and p as 1.2 mm and 30 mm, typical values for conventional high-density cable. Upper and bottom lines indicate the ρ results of 8.6 fiber/mm^2 and 4.2 fiber/mm^2, respectively. To keep P less than 0.2 MPa, we should make T less than 18 N if ρ is 4.2 fiber/mm^2 and T less than 20 N if ρ is 8.6 fiber/mm^2.

Table 1. Properties of fabricated optical fiber

Item		Value
Cladding diameter		125 μm
Effective Area (LP_{01}, LP_{11}, LP_{21}, LP_{02})		82 μm^2 *, 111 μm^2 *, 150 μm^2 *, 169 μm^2 *
Optical loss	LP_{01}	0.28 dB/km
	LP_{11}	0.28 dB/km
	LP_{21}+LP_{02}	0.28 dB/km
Macro bending loss at R = 15 mm (at 1625 nm, LP_{21}+LP_{02})		< 1 dB/10turn
Cut-off wavelength (LP_{31})		1.48 μm

* calculated value from finite difference method from measured refractive index profile

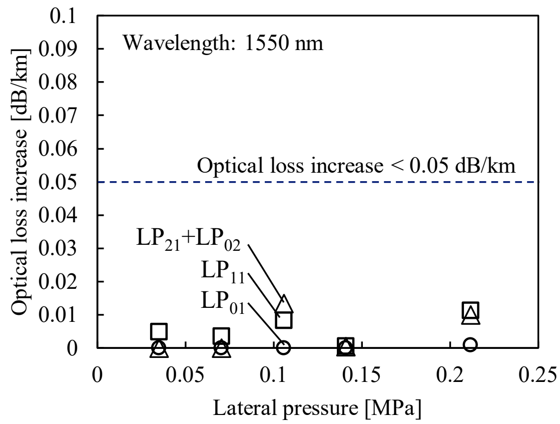
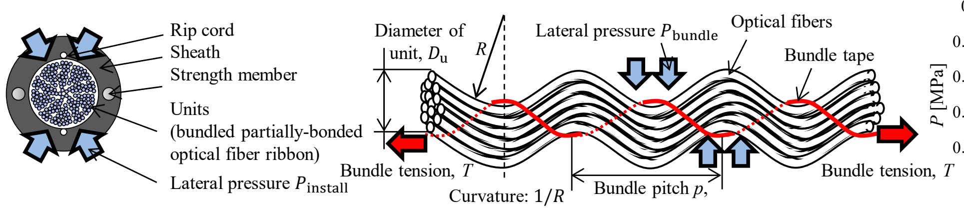


Fig. 1. Micro bending loss characteristics as a function of lateral pressure.



(a) Cross-sectional image.

(b) Side-view of a unit.

Fig. 2. Schematic image of curvature-controlled high-density cable.

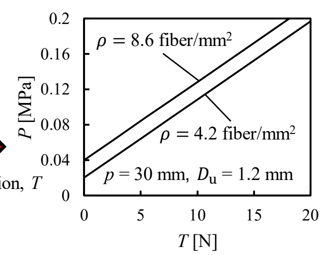


Fig. 3. P as a function of T.

Next, we examine the feasibility of DMD control by curvature for 4LP-GIF. Figure 4 compares measured and calculated curvature-dependent DMD change at 1550 nm. Here, the DMD change is the difference between before and after adding curvature. Circles, triangles, and squares indicate the measured DMD change for LP_{01}-LP_{11}, LP_{01}-LP_{21+02} and LP_{11}-LP_{21+02}, respectively. The length of FUT is 1 km. We measured the DMD change of the 4LP-GIF wound on four bobbins with different diameters. The measurement method is the same as described in [11]. Blue, gray, and orange lines indicate the calculated result for LP_{01}-LP_{11}, LP_{01}-LP_{21+02}, and LP_{11}-LP_{21+02}. We calculated the DMD change by a finite element method. The measured DMD change of LP_{01}-LP_{11} is insensitive to curvature. On the other hand, the DMDs related to LP_{21}+LP_{02} change more significantly. They are in good agreement with the calculated results. Therefore, we confirmed the validity of the calculation. Then, we calculated achievable curvature and DMD change as a function of D_{u} and p. Figure 5 (a) and (b) indicate the contour map of controllability of curvature and DMD, respectively. Here, we assume P = 0.2 MPa, found not to exhibit excess micro bending loss. Considering the manufacturability of optical fiber cable, we set the range of p and D_{u} as 20–40 mm and 1–4 mm, respectively. When p and D_{u} are 28 mm and 4 mm, we achieve DMD controllability of 25 ps/km with low excess micro bending loss.

3. Optical loss characteristics of fabricated cable

Then, we examined optical loss characteristics of fabricated three curvature-controlled high-density cables to confirm the validity of designed 4LP-GIF and T. We fabricated the cables with ρ of 4.2 fiber/mm^2 to minimize P_{install}. The T of fabricated cables are 2.5, 5.5, and 7.5 N, and p and D_{u} are 30 mm and 1.2 mm, respectively. Figure 6 shows the measured cabling loss at 1550 nm as a function of P. Cabling loss is the optical loss difference between before and after cabling. Filled circles, triangles, and squares indicate the result for 4LP-GIF of LP_{01}, LP_{11}, and LP_{21}+LP_{02} mode. Opened circles and triangles show the result for 2LP-GIF of LP_{01} and LP_{11} described in [10]. The length of fiber under test is 1 km. We measured optical losses by OTDR. The result for 4LP-GIF shows sufficiently small cabling loss regardless of P less than 0.05 dB/km. In contrast, the result of 2LP-GIF of LP_{11} modes exceeds 0.05 dB/km when P is larger than 0.06 MPa. Thus, we confirmed the validity of the curvature-controlled high-density cable design.

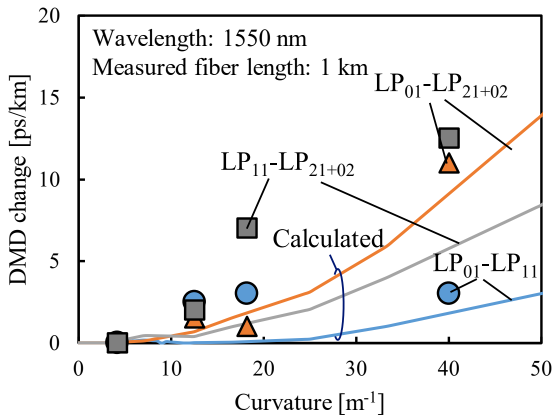


Fig. 4. DMD change characteristics as a function of curvature.

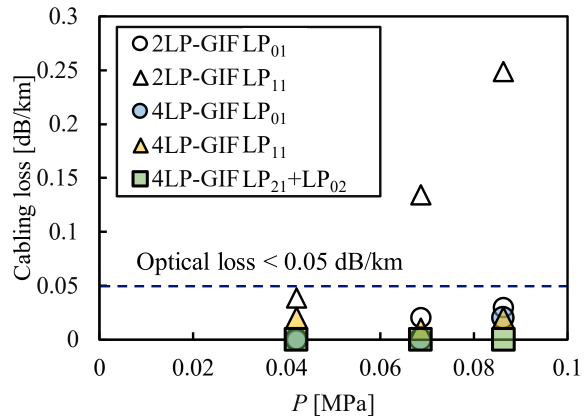


Fig. 6. Cabling loss characteristics of 4LP-GIF in curvature-controlled high-density cable as a function of P.

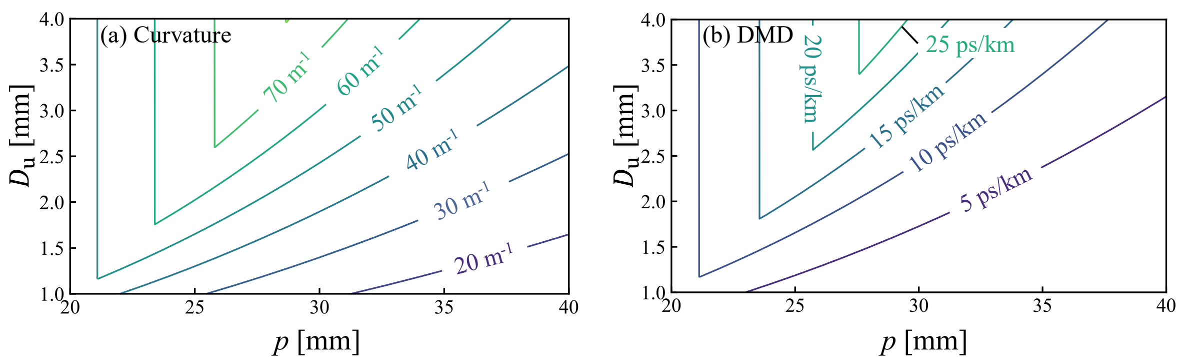


Fig. 5. Controllability for 4LP-GIF as a function of p and D_u. (a) Curvature, (b) DMD.

4. Conclusion

We have first clarified the cable design for DMD control with a low loss increment of 4LP-GIF. After that, we confirmed the feasibility of each LP mode group's curvature-dependent DMD change. Then, we inferred a potential to 25 ps/km controllability of DMD for 4LP-GIF without optical loss increase with D_u and p for 28 mm and 4 mm, respectively. We also fabricated the curvature-controlled cables with different P_{bundle} and confirmed the small cabling loss characteristics of less than 0.05 dB/km with a P of 0.08 MPa.

5. Acknowledgement

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