Low-Loss and Low-Mode-Dependent-Loss Fan-In/Fan-Out Device for 6-Mode 19-Core Fiber

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(Top-Scored Paper)

***Abstract*—This paper describes a low-loss fiber-bundle-type fan-in/fan-out (FI/FO) device for 6-mode 19-core fiber, which exhibits a low mode-dependent loss (MDL) with a physical-contact connection for all the cores. We reveal that reducing the offset at the connection of few-mode fibers (FMFs) at butt coupling does not necessarily result in a minimum MDL, and the FMFs should be aligned so as to minimize the MDL, by experimentally investigating the MDL as a function of the lateral offset at butt coupling. We develop a precise rotational alignment mechanism to accurately adjust the core position without any complex alignment equipment, and we introduce a hexagonal microhole into a ferrule to accurately arrange the fibers. With these technologies, we successfully suppress the mode-dependent loss of the FI/FO device. The device provides a low MDL variation of less than 2 dB for all the cores with good optical properties such as a low excess loss, low core-to-core crosstalk, and a high return loss. The fabricated FI/FO device also achieved the highest reported spatial multiplicity connection of more than 100 with a small footprint as well as a low connection loss. Other optical properties that we obtained such as the modal crosstalk are also described.**

***Index Terms*—Fan-in and fan-out device, few-mode fiber (FMF), multicore fiber (MCF), optical connector, space division multiplexing (SDM).**

I. Introduction

SPACE division multiplexing (SDM) transmission systems with multicore and/or few-mode (FM) fibers are a promising approach for overcoming the transmission capacity limit of conventional transmission systems [1]. Typical SDM systems utilize core multiplexing with multicore fibers (MCFs) or mode multiplexing with FM fibers (FMFs). To construct such systems, connection devices are needed such as fan-in/fan-out (FI/FO) devices for MCFs that couple each core with individual single-core fibers or a mode multiplexer (MUX)/demultiplexer (DEMUX) that couples each FMF mode with individual single-mode (SM) fibers. Recently, there have been several reports that combine core multiplexing and mode multiplexing with few-mode multicore fibers (FM-MCFs) with a view to achieving an ultra-large transmission capacity [2]–[4]. To realize these systems requires either the combination of a FI/FO device for FM-MCF and an array of mode MUX/DEMUXs for each FMF or their integration such as a FI/FO-integrated photonic lantern fabricated by ultrafast laser inscription [5]. Although, the latter approach has advantages in terms of integration, there has been no report describing a FI/FO-integrated mode MUX/DEMUX with a spatial multiplicity exceeding 100. On the other hand, the former approach can deal with the adjustment of each core unit and also use any device for a single-core FMF such as an FM amplifier or a mode MUX/DEMUX, which makes easy to construct the FM-MCF system.

Over the past few years, several types of FI/FO devices have been devised mainly for single-mode MCFs including a fiber bundle type [6]–[11], a fuse fiber type [12], a free space optics type [3], [13] and a three-dimensional waveguide type [14], [15]. Of these types, the fiber bundle type has advantages in terms of a low connection loss, low crosstalk (XT) properties, and a small footprint. It also has the potential to achieve pluggable connection and high power durability with physical-contact connection while utilizing conventional optical connector components [6], [8], [10]. There have been several studies on fiber bundle type FI/FO devices with a spatial multiplicity of less than 30 such as for SM 7-core [6]–[8], 12-core [9], [10], and 19-core [11] fiber. Furthermore, we demonstrated the first fiber bundle type FI/FO device for 6-mode 19-core fibers with a spatial multiplicity of more than 100 [16]. We reduced the mode-dependent loss (MDL) at the connection point between our FI/FO device and the FM-MCF, which is one of the most important characteristics for FMF transmission [17]–[19].

In this paper, expanding on our report in [16], we provide improved alignment results designed to achieve a lower loss and lower MDL variation for all the cores of less than 2 dB at a connection point between our FI/FO device and the 6-mode 19-core fiber. This paper also describes in detail results regarding the design and fabrication of a fiber bundle type FI/FO device for FM-MCFs. The rest of this paper is organized as follows. Section II describes the influence of offset misalignment at a connection point on MDL by investigating the relationship between them. The design guideline for achieving a low-loss

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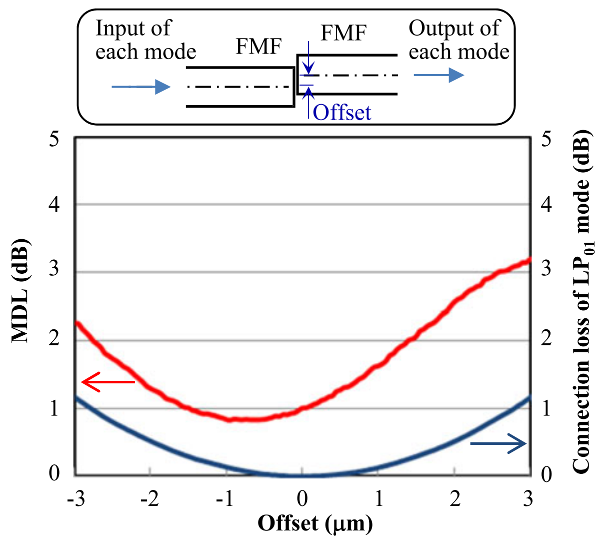

Fig. 1. Example result of relationship between offset and MDL of 6-mode FMF including mode MUX/DEMUX.

FI/FO device is also provided in this section. Section III describes both the introduction of a hexagonal micro-hole into a ferrule and the development of a rotational alignment mechanism, which are the keys to realizing a low-loss FI/FO device. Section IV shows our alignment method based on the MDL variation and also shows our experimental results for the fabricated FI/FO device. The relationship between rotational angle and MDL variation is estimated. This section also describes such optical properties as the MDL, its wavelength dependence, core-to-core XT, modal XT, and the return loss of the fabricated device after alignment. We offer our conclusions in Section V.

II. Influence on MDL at Butt Coupling

First, we investigated the MDL that occurs at butt coupling in FMF. The butt coupling MDL is mainly caused by the difference between the connection losses of each mode under misalignment, and it can be calculated from the power of the overlap integral of each modal field. Based on our calculation, the connection loss where there was misalignment of higher-order modes such as the LP_{02} mode was about four times that of the LP_{01} mode for typical 6-mode FMF [4]. This result indicates that we should align the FMFs at butt coupling as precisely as possible to reduce the MDL of the connection device.

Moreover, in practical use, we should consider the influence of the modal interference on the MDL, which is caused by the modal-XT of the mode MUX/DEMUX, the stress on the fiber [20], and other splicing points. Fig. 1 shows an example measured result for the relationship between the offset of the FMF at butt coupling and the MDL. Each of the 6 modes (4-LP mode) was excited by a multi-plane light conversion type mode MUX [21] and each output power demultiplexed with a mode DEMUX of the same type was measured. The offset is scaled based on the optimum alignment for the LP_{01} mode whose measured connection loss is also plotted in Fig. 1. As a light source, we used filtered amplified spontaneous emission (ASE) input at a wavelength of 1.55 μm (bandwidth: 0.5 nm) to suppress the fluctuations during the measurement. The losses were measured using almost the same method described in [21] except for the presence of the connection point. Here, we consider its output power to be the sum of all the outputs of the same mode group for one input of a mode group to remove the effect of intra-mode group mixing inside the fiber. For example, the output power for an LP_{11a} input, $P\,(LP_{11a})$, is defined as

$$P\,(LP_{11a}) = P_{LP_{11a},\,LP_{11a}} + P_{LP_{11a},LP_{11b}} \quad (1)$$

where the subscripts mean the input port and the output port in order. We also consider that the average coupling efficiency, Γ, of the same mode group is calculated from the average of output power for each input, for example, $\Gamma\,(LP_{11})$ is defined as

$$\begin{aligned}\Gamma\,(LP_{11}) &= P\,(LP_{11})\,/P_{\text{in}} \\ &= \{P\,(LP_{11a}) + P\,(LP_{11b})\}\,/\,(2P_{\text{in}}) \quad (2)\end{aligned}$$

where P_{in} is the input power. Furthermore, we define the MDL as the difference between the maximum and minimum values of $\Gamma\,(LP_{01})$, $\Gamma\,(LP_{11})$, and $\Gamma\,(LP_{21/02})$.

As shown in Fig. 1, the MDL did not always reach its minimum value when the offset was zero. This is probably due to the difference between the centroids of each mode field caused by the modal-XT or core asymmetry. This result suggests that reducing the offset at the connection of FMFs at butt coupling is not necessarily results in a minimum MDL, and the FMFs should be aligned so as to minimize the MDL.

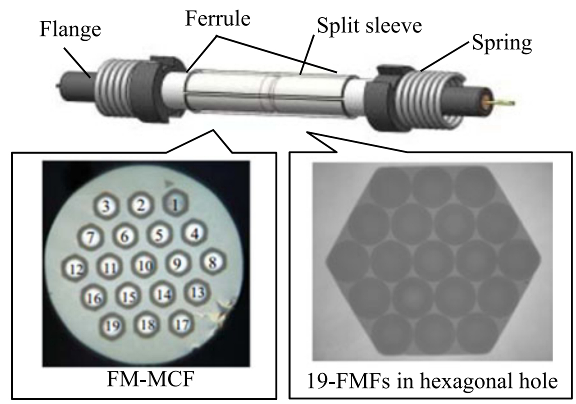

Fig. 2. Basic configuration of fabricated fiber-bundle type pluggable FI/FO device.

III. Fabrication of FI/FO Device

On the basis of the results in section II, we fabricated a fiber bundle type FI/FO device. To minimize the MDL, we introduced a hexagonal micro-hole for a bundle of small diameter FMFs and developed a rotational alignment mechanism.

A. Hexagonal Micro-Hole Ferrule

Fig. 2 shows the basic configuration of our FI/FO device, which consists of two ferrules and a split sleeve. The FM-MCF we used had a cladding diameter of 246 μm and a core pitch of 43.4 $\pm$ 0.7 μm [4]. As shown in Fig. 2, the FM-MCF was

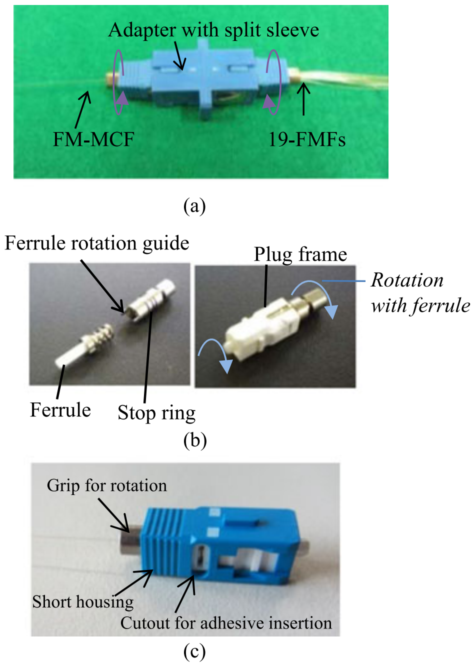

Fig. 3. Photograph of fabricated device. (a) Pluggable FI/FO device, (b) Rotational mechanism, (c) Plug structure.

inserted into a circular micro-hole in one of the ferrules. The small diameter single-core FMFs were inserted into a hexagonal micro-hole in the other ferrule, which has almost the same structure as that used for an SM 12-core fiber [10]. Here, the cladding diameter of the FMFs was reduced to almost the same value as the core pitch of the FM-MCF and they were closely packed in the hexagonal micro-hole whose relative position corresponded to each core of the FM-MCF. The FMFs can be closely packed easily by introducing a hexagonal hole instead of a circular hole, and thus the offset at each core could be reduced. Then, the fibers were fixed in place with adhesive. The ends of the ferrules and fibers were properly spherically polished to achieve physical-contact (PC) connection for all the cores [22], [23]. In our previous work on an SM 12-core FI/FO device, we then connected the ferrules with a simple clip. In this work, by applying this structure to conventional simplex connector components, we were able to realize a pluggable connection with a push-pull operation in the same way as with a conventional optical connector. This has advantages in terms of ease of handling and alignment.

B. Rotational Alignment Mechanism

We developed a rotational alignment mechanism for the FI/FO device to adjust the absolute core positions of the FMFs with pluggable connection. The mechanism was originally designed for a polarization maintaining (PM) fiber connector, and we have applied it to an MCF optical connector [23]. Fig. 3 shows photographs of the fabricated device. As shown in Fig. 3(a), the device size was sufficiently small and almost the same as a conventional SC-type optical connector. As shown in Fig. 3(b), a stop ring in the device has guides that fit the key guide, which enables the ferrule to rotate even when it is integrated in the plug frame. Here, with the conventional PM fiber connector, the rotational alignment is completed by performing imaging alignment. They are then fixed in place with adhesive and integrated in the connector housing. On the other hand, we need rotational alignment for the FM-MCF connection to minimize the MDL compared with the result in Section II. To meet this requirement, we changed the mechanical design of the connector housing as shown in Fig. 3(c). We shortened the housing to make it possible to both hold and rotate a stop ring even when it is integrated in the housing. In addition, we introduced a cutout structure in the housing that can be filled with adhesive to fix them in place once the rotational alignment has been completed. In this structure, we can align the rotational angle precisely by measuring the MDL for all the cores, and thus we can easily minimize the MDL.

Here, the lateral offset change caused by the rotation at the outermost cores for the FM-MCF, Δ, is expressed as

$$\Delta = 2\Lambda \cdot \sin^{-1}\theta \tag{3}$$

where Λ and θ are the core pitch of the FM-MCF and the rotational angle, respectively, assuming that θ is small and that the eccentricity of the ferrule can be ignored. We can see that we must rotate it with sub-degree precision to align the core position with sub-micrometer precision. As regards the alignment accuracy of the conventional PM fiber connector, there is clearance between the plug and key guide that is formed in the flange, which allows the ferrule to rotate a maximum of about ± 2.6 degrees when connected. This would result in a maximum offset of 3.8 μm at the outermost cores. In this study, to achieve low-loss and low-MDL connection, we changed the clearance to suppress the rotational angle misalignment to less than ± 0.9 degrees, which in the worst case corresponds to a 1.3 μm offset. Therefore, using this improved structure, we could reduce any increase in the MDL variation caused by rotational angle misalignment with pluggable connection to less than about 1 dB as estimated from Fig. 1.

IV. Experiments and Optical Performance

Fig. 4 shows the experimental back-to-back setup we used to evaluate the influence that connecting the fabricated FI/FO device had on the MDL. As shown in Fig. 4, each of the 6 modes was excited by a multi-plane light conversion type mode MUX. Fig. 4 also shows the launched near field patterns for light transmitted through the mode MUX. To measure the MDL at each core, a single-core FMF was coupled to each measured core with an active alignment method at the facet of the FM-MCF. Then, the output power from the FMF was demultiplexed with a mode DEMUX and measured at each mode with a power meter. We measured the transmittance of all the output power for one input for all the cores. The transmittance of the same mode group was estimated in the same manner as described in section II. Fig. 5 shows an example transmittance result for each input mode and the MDL at a center core when we changed the offset between the FM-MCF and the FI device without the adapter. We confirmed that the MDL did not reach its minimum value when the offset was zero as with the case in Fig. 1, which also

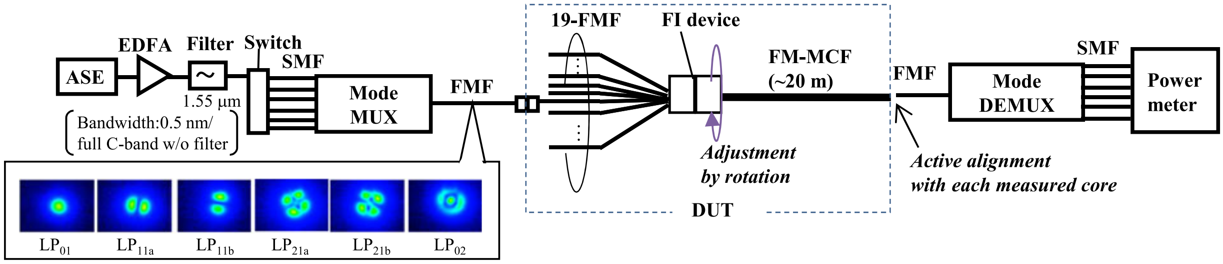

Fig. 4. Experimental setup.

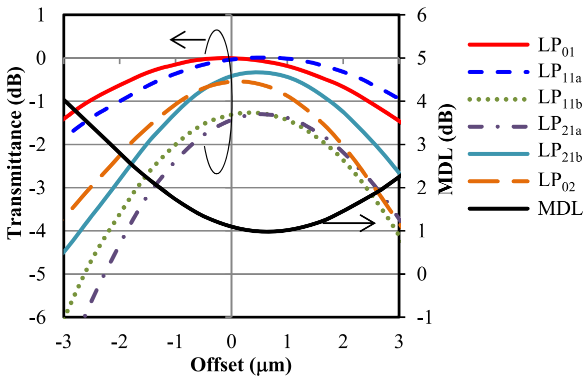

Fig. 5. Transmittance for each input and MDL including mode MUX and DEMUX as a function of offset between FM-MCF and FMF.

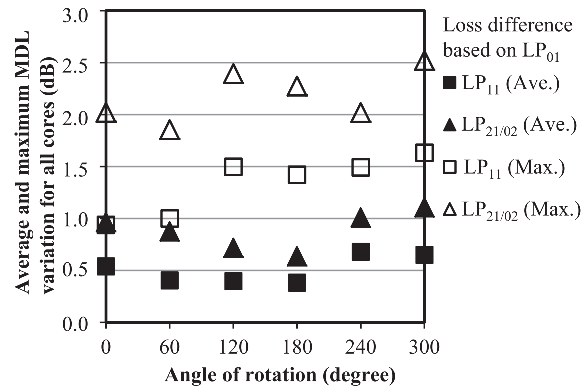

Fig. 6. Measured average and maximum MDL variation with different rotational angles. Squares are average and maximum values of loss difference between LP_{01} and LP_{11}, respectively. Triangles are average and maximum values of loss difference between LP_{01} and $LP_{21/02}$, respectively.

indicates the need for offset adjustment by using the rotational alignment mechanism we developed.

A. MDL Variation After Connection

We first determined the rotation angle by measuring the MDL dependence on the rotation angle. To measure the MDL, we connected the ferrules of the FI device and the FM-MCF by plugging them into the adapter and we then adjusted the rotation angle. In this measurement, we eliminated the use of a wavelength filter as a light source to average the wavelength dependence of the MDL variation. We also measured the MDL of the setup by eliminating the device under test (DUT) and subtracted the MDL of the setup from the measured MDL of each core. Since the relative position of each core is hexagonal, they could be aligned at each 60° angle of rotation. We then measured the average and worst values of the MDL variation for all 19 cores by changing the rotational angle of the FI device. Fig. 6 shows the measured average and maximum MDL variation with different rotational angles. The rotational angle was scaled based on a key mark formed in the guide of the FI device. As shown in Fig. 6, the average and maximum values of the MDL variation changed with each rotational angle. When we take the use of the FI/FO device in the transmission system into consideration, a smaller worst MDL value for all the cores is preferable to a smaller average value in terms of gain equalization. Thus, we set the rotational angle of the FI device at about 60°, and we completed the alignment at this angle thus minimizing the worst MDL variation for all the cores. Fig. 7 shows the measured MDL variation at each core on insertion of an FI device and the FM-MCF after rotational adjustment.

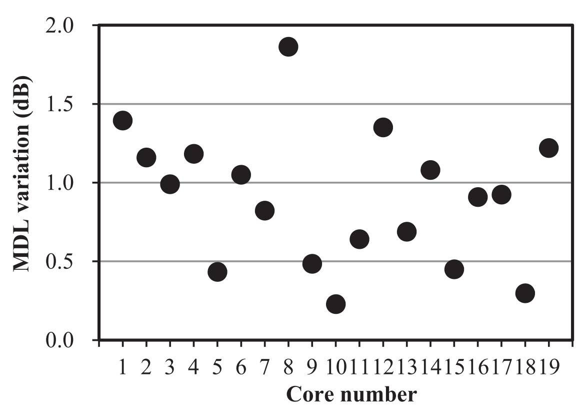

Fig. 7. Measured MDL variation at each core on insertion of FI device and FM-MCF.

In this figure, the core number corresponds to that depicted in Fig. 2. Almost all the MDL variation values were successfully reduced to less than 2 dB for all the cores compared with those of our previous report [16]. Fig. 8 shows the loss breakdown for each input mode based on each LP_{01} output power. We can see that the MDLs for the higher mode inputs such as the LP_{21} and LP_{02} inputs were larger than those for the LP_{01} mode. In addition, the MDL at the outermost cores of the FM-MCF tended to be higher than that at the inner cores, which indicate that the lateral offsets of the outermost cores were higher. In the measurement, the coupling loss of the LP_{01} mode was also small at less than 0.6 dB for all the cores.

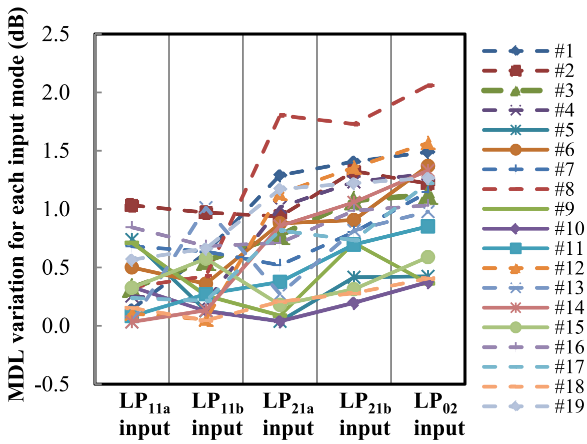

Fig. 8. Breakdown of measured MDL variation at each core for each input mode based on LP_{01} output power. Dashed line indicates twelve outermost cores of FM-MCF.

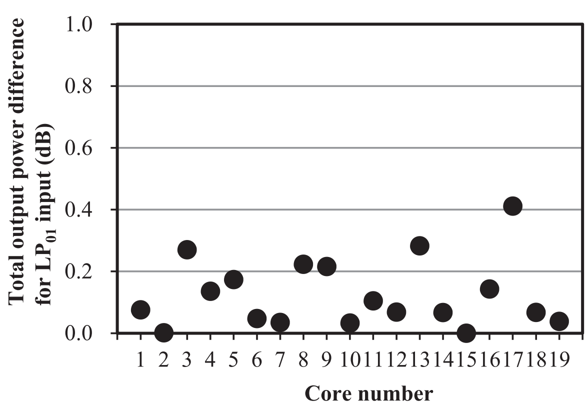

Fig. 9. Total output power difference between all cores for LP_{01} input mode.

We also measured the total output power loss without the mode DEMUX when each mode was excited in a measured core through the FI device and the mode MUX, which is almost the same as the measurement previously reported for a free space type FI/FO device [3] except for the presence of the FO device. By measuring the excess loss of the total output power on insertion of the FI device and the FM-MCF, we can estimate how much power leaks to the cladding mode at butt coupling. Fig. 9 shows the difference in the total output power between all the cores for an input mode of LP_{01}. The difference was sufficiently small and less than 0.5 dB for all the cores. In addition, the mode dependent loss of the total output power was less than 1.7 dB for all the cores.

B. Wavelength Dependence

Fig. 10 shows the wavelength dependence of the output power for each mode group with 10 and 8 cores, respectively, including mode MUX and DEMUX. These core numbers were selected as an example because each of the MDL variations was the minimum and maximum value. Although those output powers fluctuated, which appears to be as a result of the modal mixing caused by the connection point between the FI/FO device and the FM-MCF, we confirmed that they exhibited no significant degradation over the C-band.

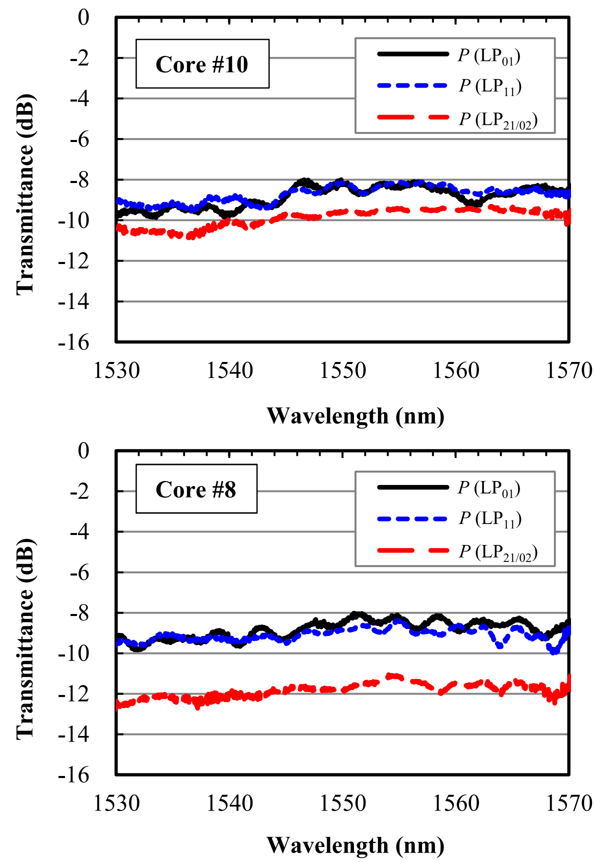

Fig. 10. Wavelength dependence of output power for each mode group including mode MUX and DEMUX.

TABLE I
MEASURED MODAL-CROSSTALK WITHOUT DUT

Unit: dB	Output LP_{01}	Output LP_{11a}	Output LP_{11b}	Output LP_{21a}	Output LP_{21b}	Output LP_{02}
Input LP_{01}	N.A	−12	−11	−19	−21	−17
Input LP_{11a}	−13	N.A	N.A	−13	−13	−15
Input LP_{11b}	−11	N.A	N.A	−14	−14	−13
Input LP_{21a}	−16	−13	−12	N.A	N.A	N.A
Input LP_{21b}	−18	−13	−13	N.A	N.A	N.A
Input LP_{02}	−17	−15	−12	N.A	N.A	N.A

C. Crosstalk Properties

We confirmed that the core-to-core XT at each core and mode was less than −60 dB when an optical signal was launched from the port corresponding to the adjacent core of an FMF. This is thanks to the short span of the FM-MCF in our experiment and the trench-assisted structure of the core profile, as well as the low-loss connection of our fabricated FI device.

We also measured the modal-XT including the mode MUX and DEMUX for all the cores with the same setup as shown in Fig. 4 without the optical filter. The measured modal-XT for a back-to-back system without a DUT is summarized in Table I.

TABLE II
MEASURED MODAL-CROSSTALK AT CORE NUMBER 10 WITH DUT

Unit: dB	Output LP_{01}	Output LP_{11a}	Output LP_{11b}	Output LP_{21a}	Output LP_{21b}	Output LP_{02}
Input LP_{01}	N.A	−9	−9	−18	−20	−17
Input LP_{11a}	−9	N.A	N.A	−12	−10	−11
Input LP_{11b}	−10	N.A	N.A	−12	−12	−11
Input LP_{21a}	−15	−10	−11	N.A	N.A	N.A
Input LP_{21b}	−15	−11	−11	N.A	N.A	N.A
Input LP_{02}	−15	−11	−10	N.A	N.A	N.A

TABLE III
MEASURED MODAL-CROSSTALK AT CORE NUMBER 8 WITH DUT

Unit: dB	Output LP_{01}	Output LP_{11a}	Output LP_{11b}	Output LP_{21a}	Output LP_{21b}	Output LP_{02}
Input LP_{01}	N.A	−9	−10	−18	−20	−16
Input LP_{11a}	−9	N.A	N.A	−10	−12	−14
Input LP_{11b}	−10	N.A	N.A	−13	−11	−10
Input LP_{21a}	−12	−8	−9	N.A	N.A	N.A
Input LP_{21b}	−15	−8	−9	N.A	N.A	N.A
Input LP_{02}	−14	−8	−9	N.A	N.A	N.A

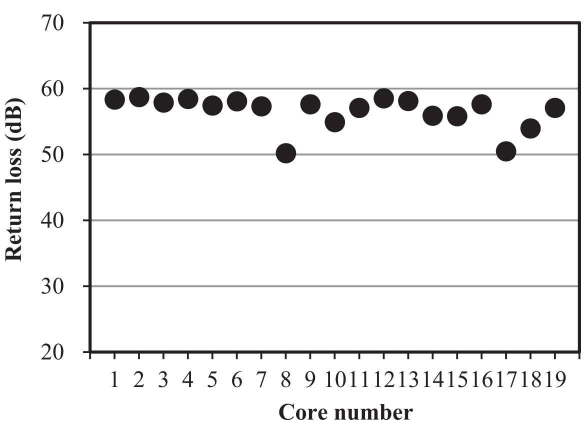

Fig. 11. Return loss of fabricated FI device at 1.55 μm.

Those at core numbers of 10 and 8 are summarized in Tables II and III, respectively. As shown in these tables, the modal-XT becomes large on insertion of the FI device and the FM-MCF. We also confirmed that the impact on the modal-XT becomes larger as the MDL variation increases by comparing Tables II and III. A smaller modal-XT is preferable for an FMF transmission system, however, this XT can be compensated for by utilizing multiple-input and multiple-output (MIMO) technology.

D. Return Loss

Fig. 11 shows the return loss at the connection point between the FI device and the FM-MCF, which was measured with an optical low-coherence reflectometry at a wavelength of 1.55 μm. All the cores provided a sufficiently high return loss of more than 45 dB, which is a criterion for judging advanced PC connection. This enabled us to achieve high power tolerance for realizing a long-haul and ultra-large capacity transmission system with optical amplifiers.

V. CONCLUSION

We developed the first fiber bundle type FI/FO device for 6-mode 19-core FM-MCF with a low loss and a low MDL by utilizing an accurate closely packed fiber arrangement. Based on the result of our MDL investigation at butt coupling, we successfully fabricated FI/FO device with a low-MDL variation by introducing a hexagonal micro-hole into a ferrule and optimizing the alignment, which we realized by using a precise rotational-alignment mechanism. The FI/FO device achieved the highest reported spatial multiplicity connection with a small footprint as well as a low-MDL variation of less than 2 dB with the C-band for all the modes and all the cores. Our FI/FO device has been successfully applied to dense SDM transmission [4] and could prove useful for constructing a dense SDM transmission system in the future.

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