Free-Space Coupling Type Fan-in/Fan-out Device for 4-Core Fiber with Low Insertion Loss

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Abstract: We present a pair of free-space coupling type fan-in and fan-out devices for 4-core fiber having an insertion loss of 0.42 dB or less within C-band over the range of -10 to 70°C. © 2022 The Author(s)

1. Introduction

Space division multiplexing (SDM) is a promising technology not only for increasing capacity per fiber, but also for reducing cost-per-bit and improving energy efficiency to keep up with the growth of exponential optical transmission capacity [1]. In general, characteristics of fan-in/fan-out (FI/FO) device that couples multicore fiber (MCF) to ordinary single-core fiber (so-called SMF), and vice versa, are said to have a significant impact on the viability and performance of SDM concepts [2]. Various types of FI/FO device configurations have been reported, including the fiber bundle type, fused taper type, 3D waveguide coupling type, and free-space coupling type, so far. In recent years, characteristics of FI/FO device using a 4-core or 7-core fiber have been improved. For example, it was reported that the average insertion loss (IL) was 0.3 dB for the bundle type, 0.7 dB for the fused taper type, and 2.8 dB for the free-space coupling type, and that the crosstalk (XT) was -52 dB, -62 dB, and -40 dB or less, respectively [3-5].

In this paper, we report the FI and FO devices for the 4-core fiber with even lower average insertion loss achieved by using specially designed free-space coupling configurations with multiple lenses with different focal lengths. We fabricated a pair of FI and FO to measure XTs between cores. ILs were measured with both FI only and the pair of FI and FO. As a result, low average ILs of 0.14 dB for FI and 0.29 dB for the pair of FI and FO were obtained at a wavelength of 1.55 μm at room temperature. Furthermore, in order to verify the practicality of this device, optical characteristics were evaluated within C-band over the range of -10 to 70°C, and ILs ≤ 0.4 dB and XTs ≤ -57 dB were obtained for all four cores.

2. Design of fan-in/fan-out

Figure 1(a) illustrates the configuration diagram of the FI and FO devices we fabricated. Light beams entering in the ports #1-#4 of SMFs pass through the FI and couple to each core of the 4-core fiber. Then, they pass through the FO and couple to the ports #5-#8 of SMFs. Figure 1(b) is an internal view of the FI, representing the layout of parts for optical space-coupling of the SMF and the 4-core fiber. We used a commercially available uncoupled 4-core fiber with a clad diameter of 125 μm. The core pitch is 50 μm and cores are arranged in a square. The four SMFs are also arranged in a square at pitch P, similar to the core arrangement of the 4-core fiber. In addition to these optical fibers, multiple aspherical convex lenses with different focal lengths are placed near the end of each fiber. The four lenses with focal length of f_1 convert light beams emitted from the SMF ends into collimated beams and refract them. These refracted beams are then coupled to the four cores of the 4-core fiber through a single lens with focal length of f_2 located near the end of the 4-core fiber. The f_1 and f_2 lenses are placed with a distance Z. The FO has symmetrical configuration as the FI although it is not shown in the figure.

In the design of our FI and FO, the pitch P between the four SMFs is an important parameter that determines external dimensions of the FI and FO, and ease of fabrication. As mentioned above, the SMF and lens must be placed each other with an approximate distance of the focal length, so they are pre-assembled with a holding part before assembling the FI/FO. This pre-assembly is commonly referred to as an optical collimator, and its outer diameter depends on the size of the part holding the lens and SMF or 4-core fiber and influences the determination of the pitch P. With our design, the pitch was set at 4mm or more in order to avoid physical interference between optical collimators and to provide an alignment margin to reduce the coupling losses which may be increased by tolerances of constituent parts and the core pitch deviation.

We investigated the focal length of the lens to achieve the target pitch, 4mm or more. Figure 1(c) shows a fiber coupling model of SMF and 4-core fiber. The mode field diameters are 10.4 μm for SMF and 8 μm for 4-core fiber, and they are coupled with two lenses. By changing the distances d_1 and d_2 between each fiber and lens, the

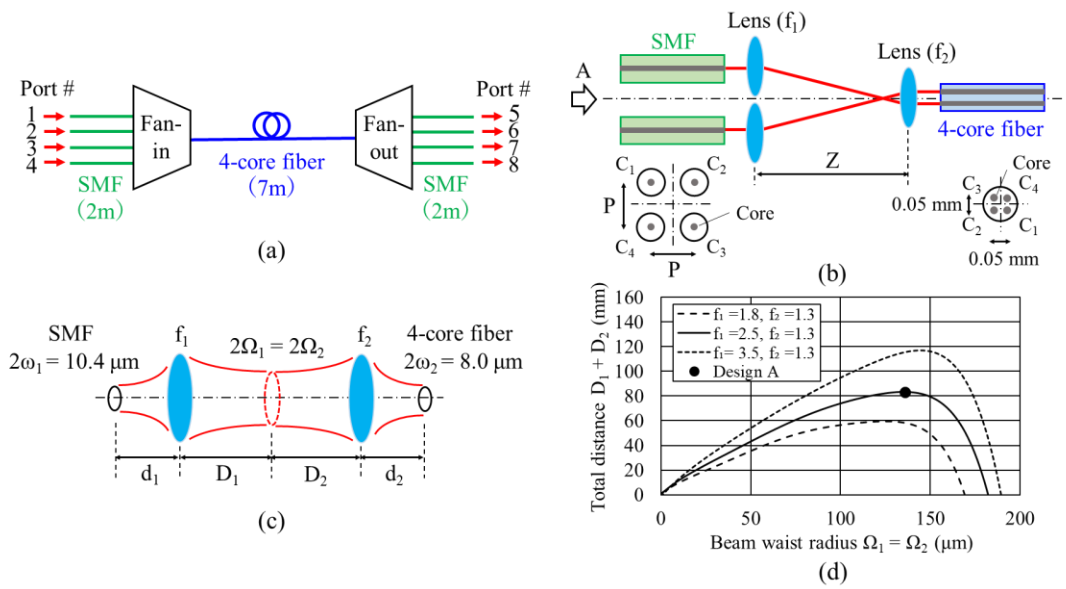

Fig.1 (a) Configuration diagram of a pair of fan-in and fan-out devices. (b) Internal view of the fan-in that represents the layout of parts and the cross-sectional view of fibers from the point A. C_n SMF is coupled to C_n core in 4-core fiber (n=1-4). (c) Fiber coupling model of SMF and 4-core fiber. (d) Relationship between beam waist radius and the sum of distances to the beam waist position.

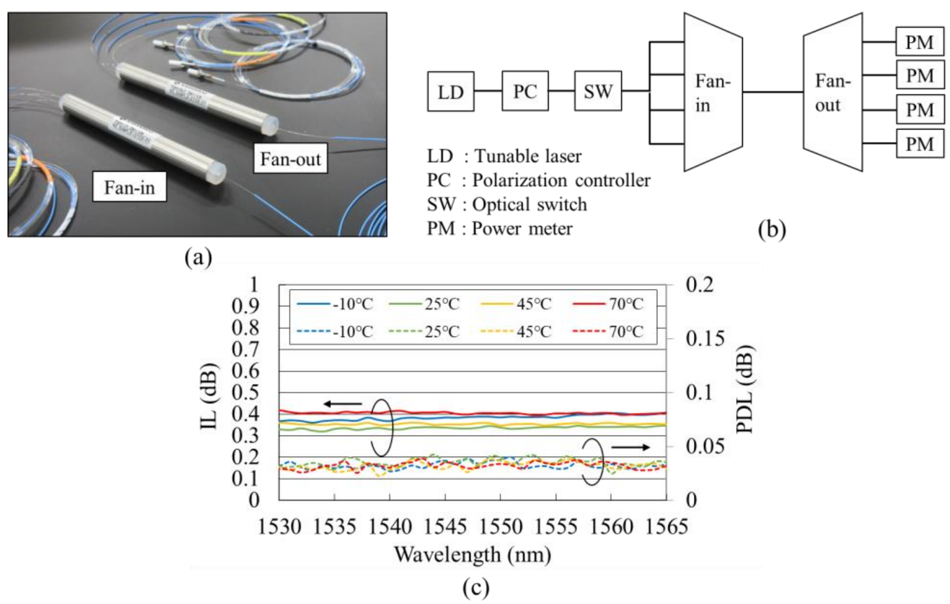

Fig. 2 (a) External photograph of fabricated fan-in and fan-out devices. (b) Measurement setup for optical characterization. (c) Wavelength dependence of IL and PDL in the optical path from port #1 to port #5 of fan-in and fan-out devices within C-band over the range of -10 to 70°C.

corresponding beam waist diameters $2\Omega_1$ and $2\Omega_2$ and the distances D_1 and D_2 to the beam waist position from the lenses can be changed arbitrarily, but their maximum values are limited by the focal lengths f_1 and f_2. Figure 1(d) shows calculated results of the sum of the distances to the beam waist position, $D_1 + D_2$, based on fiber coupling theory. The beam waist radii of collimators of the SMF and the 4-core fiber have the same value, $\Omega_1 = \Omega_2$, and were changed. The results are shown for f_1 of 1.8, 2.5, and 3.5 mm with f_2 of 1.3 mm, and it can be seen that the maximum value of $D_1 + D_2$ increases as f_1 increases. Each curve is of an ideal condition without any coupling losses due to beam diameter deviation and beam waist position deviation between collimators of the SMF and 4-core fiber. We fabricated the device with conditions of point of Design A in Figure 1(d), that is, $f_1 = 2.5$ mm, $f_2 = 1.3$ mm, $\Omega_1 = \Omega_2 = 135$ µm, and $Z = D_1 + D_2 = 83$ mm. The SMF pitch P, 4.3 mm is obtained with this $D_1 + D_2$ and the refraction angle of the beam determined by the curvature of the lens of f_2, which satisfies the target pitch $P \geq 4$ mm.

Table 1 (a) Insertion losses of fan-in at room temperature at a wavelength of 1550 nm. (b) Insertion losses and crosstalks of fan-in and fan-out devices at room temperature at a wavelength of 1550nm. (c) Maximum values of optical characteristics of fan-in and fan-out devices within C-band over the range of -10 to 70°C

(a)

Port #		IL (dB)
Fan -in	Port 1	0.16
	Port 2	0.11
	Port 3	0.16
	Port 4	0.13
Avg.		0.14

(b)

Port #		Fan-out				Avg.
		Port 5	Port 6	Port 7	Port 8	
Fan -in	Port 1	0.34	-59.5	-61.5	-71.8	-
	Port 2	-61.6	0.24	-62.2	-62.2	-
	Port 3	-65.5	-59.4	0.29	-60.5	-
	Port 4	-69.3	-58.3	-59.0	0.27	-
Avg.		-	-	-	-	0.29

(c)

Unit. dB	Fan-in and Fan-out			
	Port 1	Port 2	Port 3	Port 4
IL max.	0.42	0.42	0.37	0.39
XT max.	-58.6	-60.4	-58.7	-57.0
PDL max.	0.04	0.03	0.03	0.03
WDL max.	0.05	0.04	0.04	0.03
TDL max.	0.09	0.16	0.06	0.12

Insertion loss (dB) Crosstalk (dB)

3. Fabrication and Evaluation

A photograph of the pair of FI and FO devices we fabricated is shown in Figure 2(a). The fabrication method is as follows. First, SMFs and 4-core fiber inserted in φ1.4 mm zirconia ferrules were integrated with corresponding lenses to make optical collimators. Both sides of the lenses and the fiber ends were pre-coated with antireflection film. Then, these optical collimators were set in a metal housing and optically aligned individually. Finally, they were fixed by welding and assembled to an FI or FO device with an outer case. The size of device was φ10 × 100 mm. The measurement setup is shown in Figure 2(b). A wavelength variable CW light was used as light source connected to each FI port via a polarization controller (PC) and optical switch (SW), and an optical power meter was connected to each FO port. The optical characteristics were measured with cutback method to eliminate excess loss from optical instruments other than FI/FO device. Figure 2(c) shows the results of measuring IL and polarization-dependent loss (PDL) in the optical path from ports #1 to #5 within C-band over the range of -10 to 70℃. The maximum values of IL and PDL were 0.42 dB and 0.04 dB, respectively.

Table 1 summarizes the measurement results for all ports. Table 1(a) shows the ILs of FI measured at room temperature at the wavelength of 1550 nm. The data was obtained by measuring the optical power radiated from the 4-core fiber end on the FO side before fabricating the FO. The IL of each port was 0.11 to 0.16 dB, and the average value was 0.14 dB, which was lower than previously reported devices [3-5]. The ILs and XTs for the FI and FO pair measured under the same conditions are shown in Table 1(b). The IL of each port was 0.24 to 0.34 dB, and the average value was 0.29 dB, which was about twice as high as that of FI only. This is because the FI and FO have the same configuration. We also confirmed that XTs were less than -58 dB for all port combinations. Table 2(c) shows the maximum values of optical characteristics obtained from the measurement results of each port within C-band over the range of -10 to 70℃. All ports achieved IL of 0.42 dB or less and XT of -57 dB or less. The maximum values of PDL, wavelength-dependent loss (WDL), and temperature-dependent loss (TDL) were 0.04 dB, 0.05 dB, and 0.16 dB, respectively.

4. Conclusion

We have developed a pair of free-space coupling type fan-in and fan-out devices for 4-core fiber by using multiple lenses with different focal lengths and obtained characteristics of IL ≤ 0.42 dB and XT ≤ -57 dB within C-band over the range of -10 to 70℃. In particular, the lower IL was achieved as a result of eliminating the factors of increased losses in design and manufacturing. These results suggest that the free-space coupling type FI/FO device can be used at practical SDM systems in the future.

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