Fan-in/out polymer optical waveguide for a multicore fiber fabricated using the Mosquito method

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Abstract: A fan-in/out polymer optical waveguide with 25-μm cores and 40-μm interchannel pitch is fabricated for a multimode multicore fiber using a microdispenser. We design a fan-in/out structure to which the Mosquito method is applicable since the Mosquito method is capable of drawing a circular graded-index core three-dimensionally. Then, we experimentally fabricate a 10-cm long fan-in/out polymer waveguide with seven cores, which is expected to connect a multicore fiber and a fiber ribbon. A minimum insertion loss of 5.26 dB at 850-nm wavelength for a 10-cm long fan-in/out waveguide is experimentally observed. Causes of variation in the insertion loss and interchannel pitch are discussed.

OCIS codes: (250.5460) Polymer waveguides; (060.2340) Fiber optics components; (060.1810) Buffers, couplers, routers, switches, and multiplexers.

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1. Introduction

Over the last couple of years, the traffic of telecom and datacom networks has increased explosively by employing wavelength division multiplexing (WDM) systems. However, the maximum optical power that can be coupled to an optical fiber is limited because "fiber fuse" is a concern [1]. So, a solution named 3M—multi-level modulation, multimode control, and multicore fiber—has been proposed for sustaining much higher data traffic [2]. Actually, 7-core and 19-core single-mode multicore fibers have been already developed, and over 100 Tbit/s transmission through single-mode multicore fibers has been demonstrated [3, 4]. For realizing multicore fiber based optical links, several technical issues should be addressed: one of them is how to launch each core in multicore fibers and guide the output light from them to other optical components.

Several methods have already been proposed for multicore fibers. Lens devices are capable of coupling the light from and to each core with high efficiency, but their large size is problematic [5]. A tapered fiber bundle is also a candidate for fan-in/fan-out devices, and it exhibited high coupling efficiency, while its mechanical strength and mass productivity would be concerns [6]. A fan-in/out laminated polymer waveguide was reported. Polymer waveguides allow a compact coupling system and could address the mechanical strength issue. However, the fan-in/out polymer waveguide currently reported is structured for a pitch conversion only in the horizontal direction. Since the fan-in/out polymer waveguide consists of multiple planer waveguides (fabricated using conventional photo lithography) that are stacked layer by layer, it should be difficult to realize the pitch conversion in the vertical direction [7]. On the other hand, a glass fan-in/out waveguide is reported. The waveguide is fabricated utilizing multi-photon absorption with an ultrafast laser, which allows three dimensional core alignment [8].

In this paper, we propose a fan-in/out polymer optical waveguide capable not only horizontally converting the pitch of parallel cores but also rearranging the vertical core alignment. First, we design a fan-in/out waveguide in which 7 cores are hexagonally stacked at one end in order to connect it to a multicore fiber, while the 7 cores are horizontally aligned at the other end for the connection with a fiber ribbon or parallel laser/detector modules.

Next, we employ the Mosquito method for fabricating the designed fan-in/out polymer waveguides. We developed the Mosquito method as a photomask-free fabrication technique for circular graded-index (GI) core polymer optical waveguides applicable to on-board optical interconnects [9]. Here, we focus on one of the unique characteristics of the Mosquito method: the ability to draw cores three-dimensionally. Although most of the fan-in/out devices already reported are for single-mode multicore fibers, in this paper, we feature a multimode multicore fiber with 25-μm core diameter and 40-μm pitch because of the ease of fabrication [10].

2. The Mosquito method

The Mosquito method is a fabrication method we developed for circular-GI core polymer waveguides using a microdispenser. In the Mosquito method, a viscous core monomer is dispensed into another viscous cladding monomer from a thin needle attached to a syringe, as shown in Fig. 1. The needle can scan freely, as programmed in the desk-top robot. Finally, both core and cladding monomers are cured under UV exposure, followed by postbaking.

It has already been confirmed that the core diameter could be reduced by decreasing the dispensing pressure, by increasing the scan velocity of the needle, or by using a thinner needle. We controlled the core diameter to a desired value by optimizing those parameters and actually realized single-mode waveguides with less than 10-μm core [11, 12].

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As the waveguide materials, UV curable silicone resins (FX-W712 for core: the monomer viscosity is 12,000 cps; FX-W713 for cladding: the monomer viscosity is 10,000 cps supplied by ADEKA Co.) are used. We already confirmed that an almost ideal (parabolic) GI profile was formed in a 50-µm circular core when using these silicone resins, and the numerical aperture of the fabricated waveguide was 0.2 [13]. We also confirmed that the propagation loss of the fabricated waveguide was 0.033 dB/cm at 850-nm wavelength, which is the lowest level of propagation loss for polymer waveguides composed of silicone resins ever reported.

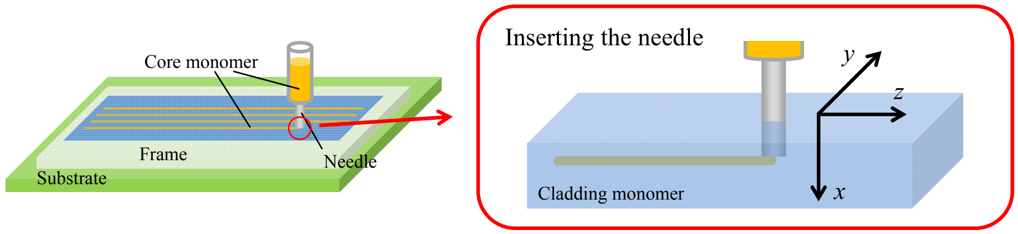

Fig. 1. The Mosquito method.

3. Fan-in/out waveguide design

Figure 2(a) shows a cross-sectional view of a 7-core multicore fiber with 26-µm core diameter and 39-µm interchannel pitch fabricated by OFS [10]. In this research, we focus on this model.

At first, in order to fabricate the fan-in/out polymer waveguide for this multicore fiber, the interchannel pitch of the polymer waveguides needs to be reduced to that of the multicore fiber. Figure 3 shows a cross-section of a preliminary fabricated waveguide with 25-µm cores, the same core diameter as that of the multimode multicore fiber. The cores are formed by dispensing the core monomer with 250-kPa pressure and by scanning a needle with 100/230-µm inner/outer diameters at 24 mm/s. The interchannel pitch for the needle scan is set to be 40 µm.

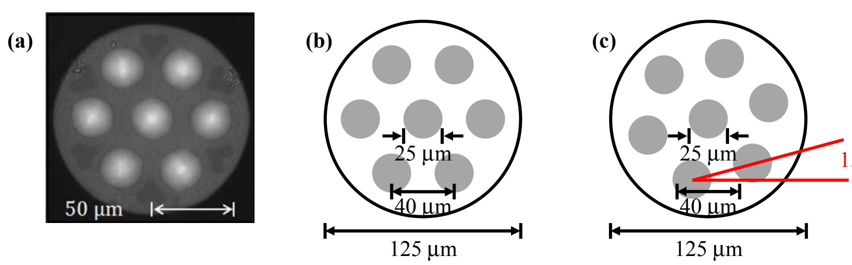

Fig. 2. Cross-sections: (a) multimode multicore fiber © [2012] IEEE. Reprinted, with permission, from [10], (b) fan-in/out polymer waveguide designed to connect with (a), and (c) 15° tilted structure of (b).

From Fig. 3, the observed pitch is close to the pre-set value of 40 µm, but it is not constant for all the cores probably because of the cladding monomer flow caused by the needle scan. For accurately aligning all the cores with a 40-µm pitch, adopting a thinner needle would be a solution, by which the monomer-flow effect could be reduced. However, as another solution, we design the core alignment of the fan-in/out waveguides as shown in Fig. 2(c): the 7 cores aligned on three layers, as shown in Fig. 2(b), are rotated 15° counterclockwise to obtain the designed core alignment shown in Fig. 2(c). In this structure, the neighbor cores are not located on the same layer (same height), so the needle scans at different heights in the cladding monomer to form neighboring cores. Hence, the monomer flow effect from the neighbor core scan could be reduced.

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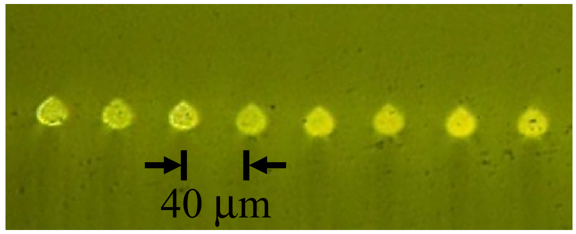

Fig. 3. Cross-section of a fabricated waveguide with 25-µm core diameter and 40-µm interchannel pitch.

Next, we design the axial core alignment in a 10-cm long fan-in/out polymer optical waveguide, as shown in Fig. 4. The waveguide consists of a 2-cm long straight part, and a 6-cm long fan-in/out structure followed by another 2-cm long straight part. In detail, we divide the three-dimensional fan-in/out structure into two: a 5-cm long section and a 1-cm long section: the former one is for horizontally curved cores with an S-shaped curvature for horizontally expanding the pitch, and the latter is for vertically curved (S-shaped) cores for aligning the cores in line in order to fit to the core alignment for a conventional fiber ribbon. Here, the cores do not cross, because the needle scan for crossed cores can disturb the core alignment dispensed in advance. The cores in the waveguides are numbered in order as they are dispensed. The bending radius and bending angle of each horizontal and vertical bending part are shown in Table 1. The core alignment has a centrosymmetry around core 4, so cores 1 and 7, cores 2 and 6, and cores 3 and 5 each should have the same bending radius and angle.

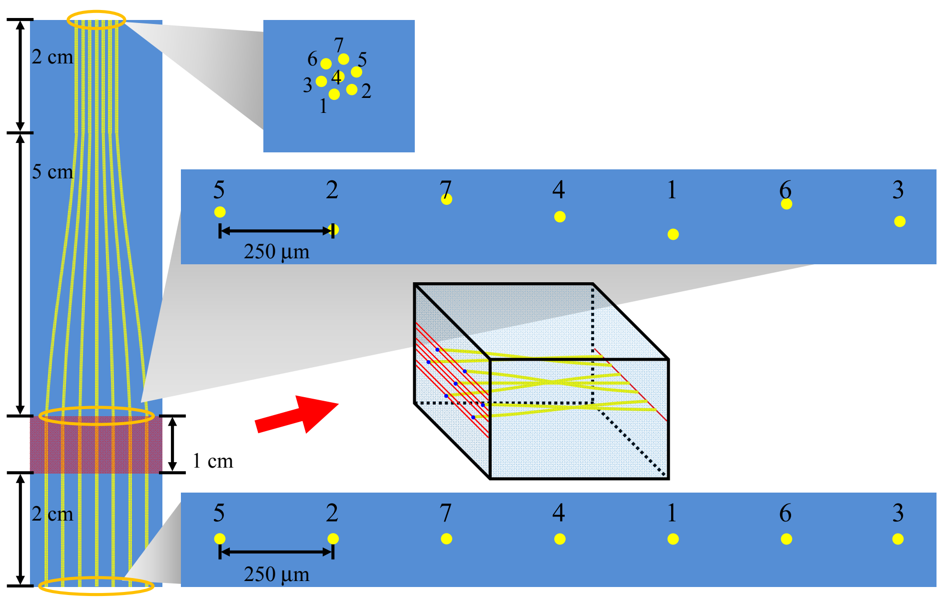

Fig. 4. Fan-in/out waveguide design.

Table 1. Bending radius and bending angle in the designed fan-in/out polymer waveguide shown in Fig. 4

Core number		1, 7	2, 6	3, 5
Horizontal bending	R	2604 mm	1330 mm	880 mm
	θ	0.55°	1.08°	1.63°
Vertical bending	R	635 mm	833 mm	2500 mm
	θ	0.46°	0.34°	0.11°

As shown in Table 1, the bending radius R for the fan-in/out structure is designed to be larger than 600 mm, and the bending angle is quite small. In our previous report [13], we confirmed when the bending radius is larger than 20 mm, no bending loss was observed in the perpendicularly-bent waveguide fabricated with the same material compositions as that for the fan-in/out waveguides shown in this paper. From this result, the bending loss due to the fan-in/out structure should be negligible under the design shown in Table 1.

As a preliminary experiment, we fabricate a 3-core fan-in/out waveguide, which correspond to cores 3, 4, and 5 as shown in Fig. 5. Here, the waveguide design is the same as the 7-core fan-in/out waveguide shown in Fig. 4: both ends have 2-cm straight-core regions and 6-cm fan-in/out region is in the middle. From Fig. 6, the core alignment is slightly degraded compared to the original design, particularly in the vertical alignment. We suppose this degradation could be attributed to core 3 not being sufficiently bent vertically. In order to address the alignment degradation issue, we investigate the core alignment accuracy in a waveguide in which one core is bent only in the vertical direction. In detail, we fabricate a 3-core waveguide: two cores are not bent but straight while only the third is bent vertically, as shown in Fig. 7. The waveguide length is set to be 5 cm. One of the two straight cores (core 3) is dispensed on the upper layer that is located 100-μm higher than the lower layer on which core 1 is located. Core 2 is bent vertically such that one end is on the lower layer while the other end is located on the upper layer: the height difference between cores 1 and 3 should be 100 μm. The horizontal interchannel pitch is 250 μm, which is wide enough to exclude the effect of needle scan for the neighboring cores. Cross-sections of the both ends (a) and (b) in the fabricated waveguide are shown in Fig. 8.

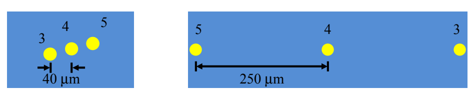

Fig. 5. Cross-sections of designed 3-core fan-in/out waveguide.

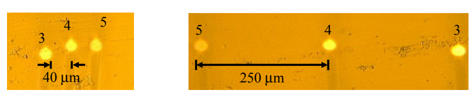

Fig. 6. Cross-sections of a fabricated 3-core fan-in/out waveguide.

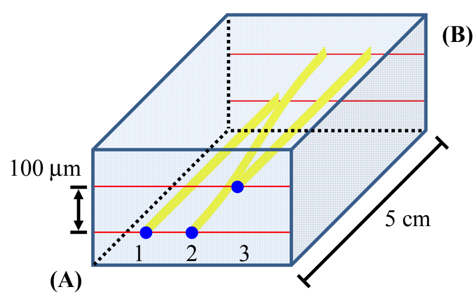

Fig. 7. Waveguide design with vertically bent structure.

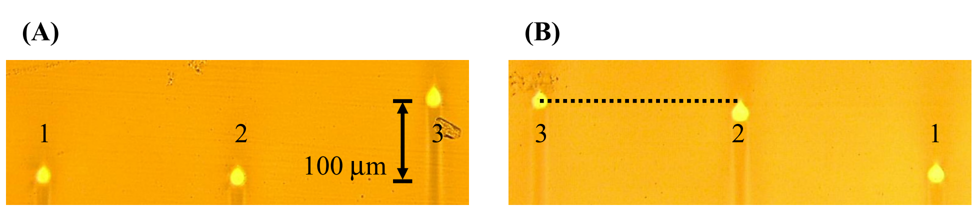

Fig. 8. Cross-sections of a fabricated vertical bending waveguide.

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Although core 2 has to be located at the same height as core 3 at end (b), core 2 is not fully bent to reach the same height as core 3, as shown in Fig. 8.

Hence, the 3-core fan-in/out waveguide is fabricated again by adjusting the needle-scan program in which the results for the core alignment degradation observed in Fig. 6 are reflected. The cross-sections of the fabricated waveguide are shown in Fig. 9. We confirm that the core alignment at both ends is very close to the original design.

Figures 10 and 11 show cross-sections of a 5-core fan-in/out waveguides fabricated before and after the needle-scan program correction, respectively. In the same way, Fig. 12 and 13 show cross-sections of the 7-core fan-in/out waveguides fabricated before and after corrections on the needle-scan height, respectively. Here, we successfully realized the designed 7-core fan-in/out waveguide as shown in Fig. 13 using the Mosquito method. The overview of the fabricated 7-core fan-in/out waveguide is shown in Fig. 14. A fan-in/out structure is visually confirmed.

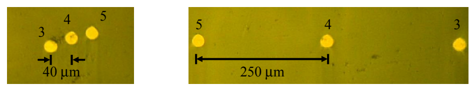

Fig. 9. Cross-section of a 3-core fan-in/out waveguide fabricated after needle-scan program correction.

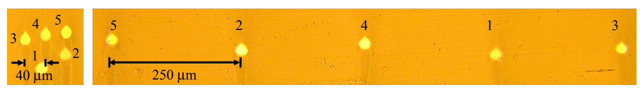

Fig. 10. Cross-section of a 5-core fan-in/out waveguide fabricated before needle-scan program correction.

Fig. 11. Cross-section of a 5-core fan-in/out waveguide fabricated after needle-scan program correction.

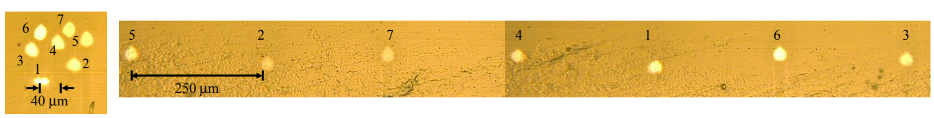

Fig. 12. Cross-section of a 7-core fan-in/out waveguide fabricated before needle-scan program correction.

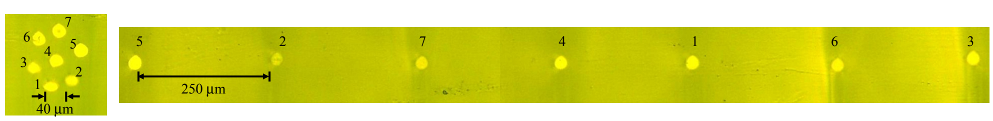

Fig. 13. Cross-section of a 7-core fan-in/out waveguide fabricated after needle-scan program correction.

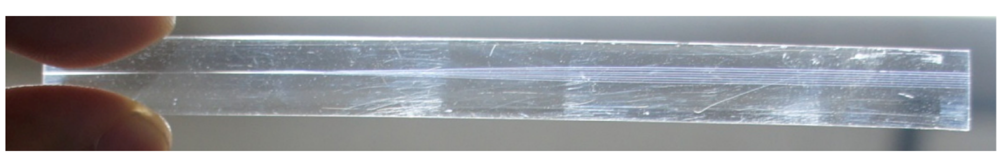

Fig. 14. Over-view of a fabricated 7-core fan-in/out waveguide.

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4. Characterization

4.1 Pitch accuracy

One of the most important characteristics for a fan-in/out device is the pitch accuracy. Therefore, we measure the pitch accuracy of the fabricated fan-in/out polymer waveguides. First, at the end for connecting with a multicore fiber, the pitch between each core and core 4 in the 3-core, 5-core, and 7-core fan-in/out waveguides is measured. For obtaining the pitch data, the boundary of core and cladding is detected from the digital image of the cross-sections shown in Fig. 9, 11, and 13; then each core center is determined by approximating a perfect circular core shape. The results are summarized in Table 2. Although the pitch is designed to be 40 μm, the measured pitch values have some deviations, and the pitch deviation tends to increase with increasing the number of stacked cores. The dispensed core could be moved in the cladding monomer due to the monomer flow caused by each needle scan. With increasing the number of the cores, a small core migration per each needle scan could be accumulated, resulting in larger pitch error.

Table 2. Pitch from core 4 at the hexagonal stacked core end

Core number	1	2	3	5	6	7
3-core waveguide			42.5 μm	39.7 μm		
5-core waveguide	47.2 μm	42.0 μm	40.9 μm	39.4 μm		
7-core waveguide	50.0 μm	47.8 μm	44.4 μm	50.4 μm	52.7 μm	56.8 μm

Meanwhile, at the other end of the 3-, 5- and 7-core fan-in/out waveguides, the pitch is optically measured as follows: The light emitted from an 850-nm LED is coupled to a 1-m long 200-μm core step-index (SI) MMF. The output end of the SI MMF is butt-coupled to the end of a fan-in/out polymer waveguide (hexagonally stacked side). Here, the core diameter of the SI MMF is large enough to launch all the cores in the fan-in/out waveguide. On the other hand, a 1-m long 50-μm core GI MMF is butt-coupled to the other end of the fan-in/out waveguide to collect the output light from each core and to guide it to an optical power meter. At the connection between the waveguide and GI MMF, the GI MMF horizontally scans along the edge of the waveguide, and then the output power is plotted with respect to the scanned distance. Since a peak is observed in the plot when the GI MMF is accurately aligned to each core in the fan-in/out waveguide, the pitch is defined as the peak distance of corresponding two cores. The measured power profiles over the scan distance of GI MMF are shown in Fig. 15 for a 3-core, 5-core, and 7-core fan-in/out waveguides. Here, the horizontal axis shows the distance from core 4, and the numbers on the peaks in Fig. 15 denote the core number corresponding to those shown in Fig. 9, 11, and 13. In Table 3, the pitches between each core and core 4 are summarized.

We already investigated the pitch accuracy in the polymer waveguides fabricated using the Mosquito method, and confirmed that the pitch was controlled to be 126.7 ± 2.6 μm when 12 channels were just aligned parallel with a pre-set pitch of 125 μm [14]. The pitch accuracy in the fan-in/out waveguide is lower than our previous result.

From the cross-sectional photo shown in Fig. 13, the pitch accuracy in the vertical direction is evaluated in the seven-core fan-in/out waveguide, and a deviation of ± 12 μm in the pitch is observed. Compared to the vertical pitch deviation shown in Fig. 12, a remarkable improvement is achieved by correcting the needle-scan program.

That means further improvement of the pitch accuracy in the fan-in/out waveguide is possible by adjusting the viscosity of the cladding monomer in order to reduce the monomer flow effect and by implementing a real-time feedback using a CCD-camera to the needle-scan program for correcting the position accuracy of the desk-top robot.

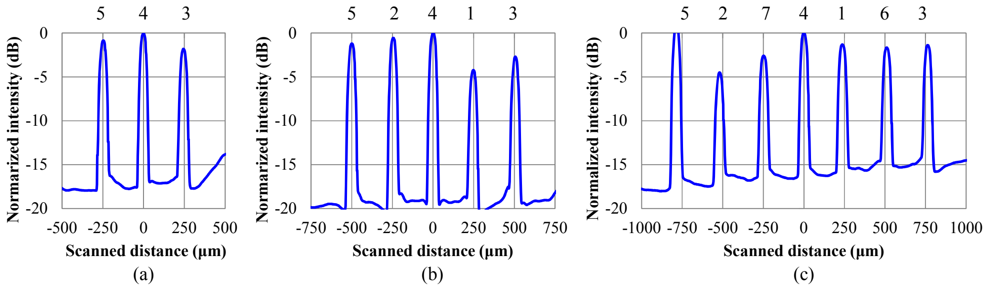

Fig. 15. Output power profile at one-dimensionally aligned core end of (A) 3-core fan-in/out waveguide, (B) 5-core waveguide, and (C) 7-core waveguide.

Table 3. Measured pitch from core 4 at the one-dimensional aligned core end

Core number	5	2	7	1	6	3
3-core waveguide	248 µm					244 µm
5-core waveguide	500 µm	244 µm		248 µm		506 µm
7-core waveguide	776 µm	510 µm	248 µm	238 µm	510 µm	764 µm

4.2 Insertion loss

The insertion losses of the fabricated 3-, 5-, and 7-core fan-in/out waveguides are measured. The light emitted from an 850-nm VCSEL is coupled to a 25-µm GI-MMF for launching a core in the fan-in/out waveguides (at the hexagonally stacked core side). Another 25-µm GI-MMF is used for a detection probe to guide the output light from the waveguide to an optical power meter. When the waveguides are butt-coupled to the MMFs, matching oil is not used. The results are shown in Fig. 16.

It is obvious that core 5 shows the lowest loss in the 3-core and 5-core fan-in/out waveguides. In these two fan-in/out waveguides, higher insertion loss tends to be observed in the cores formed in advance, so that the insertion loss of core 5 (dispensed at the end of all the cores) is the minimum.

It is interesting that core 4 was programmed to be straight (neither bent horizontally nor vertically). Nevertheless, core 4 does not show the lowest insertion loss. Contrastingly, the lowest insertion loss is 3.14 dB at core 5 in the 5-core an-in/out waveguide, which is comparable to the average insertion loss (2.36 dB) of the waveguide with straight core alignment (10-cm long). This could be because the needle scan for the latter cores results in the cores formed in advance to have microbending.

Meanwhile cores 6 and 7 in the 7-core fan-in/out waveguide show higher insertion loss than core 5, although cores 6 and 7 are dispensed after core 5. Note that cores 6 and 7 need to be bent vertically with bending radiuses smaller than core 5 in the horizontal bending. Although core 5 is bent horizontally with a bending radius as small as 880 mm (comparable to the vertical bending radius of core 6 and 7) and bent angle (1.6°) is larger than cores 6 and 7, core 5 shows the minimum insertion loss. As mentioned in section 3, originally the bending loss in the fan-in/out waveguide is expected to be negligible. However, from the results in Fig. 16, we confirm the vertical bending could contribute to the insertion loss more than horizontal bending. So, the design should be modified to have shallow vertical bending. The results for the redesigned fan-in/out waveguides will be presented elsewhere [15].

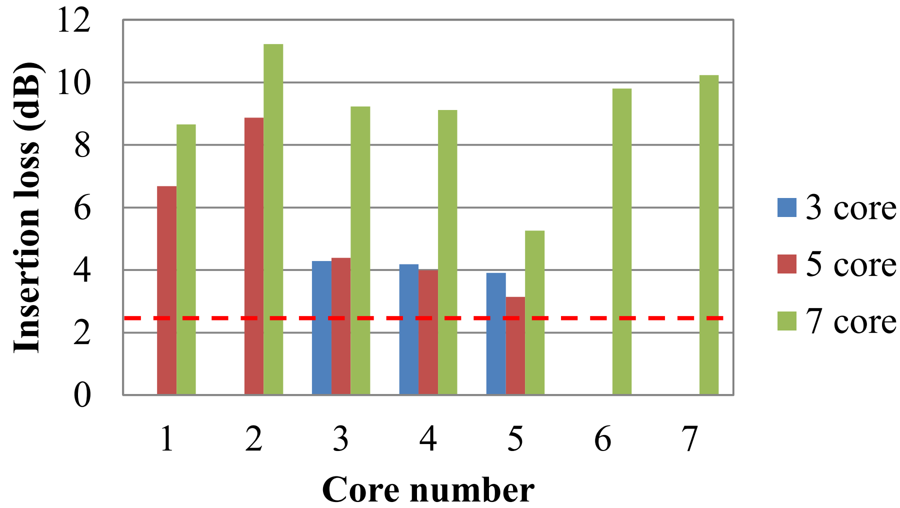

Fig. 16. Insertion loss of the fabricated 3-core, 5-core, and 7- core fan-in/out waveguides at 850-nm wavelength (10-cm long). Red broken line: Averaged insertion loss of 10-cm long straight waveguide.

4.3 Interchannel crosstalk

In the reports on multicore fibers, interchannel crosstalk has been a topic of much focus, and several methods are already reported to maintain low crosstalk. Therefore, the crosstalk should be small enough in fan-in/out devices as well. The crosstalk in the fabricated 7-core fan-in/out polymer waveguide shown in Fig. 13 was evaluated. For the crosstalk measurement, core 4 is launched via a 25-µm GI MMF probe, and the crosstalk at the end where the cores are aligned in line is measured as −25.5 dB on average for 6 cores. Since the insertion loss would significantly influence on the crosstalk, the crosstalk will be discussed more deeply elsewhere [15] after re-designing the fan-in/out structure to reduce the insertion loss.

5. Summary

We succeeded in fabricating a fan-in/out polymer optical waveguide for a multimode multicore fiber by applying the Mosquito method. The pitch accuracy needs to be improved particularly at the end where the cores are hexagonally stacked. Optimization of cladding-monomer viscosity should be a key solution as well as real-time feedback method to the needle scan program. An insertion loss as low as 3.14 dB in a 10-cm long 5-core fan-in/out waveguide was observed, which is comparable to a straight waveguide. We believe the Mosquito method is a promising technique to fabricate polymer waveguides with wide variety of wiring patterns.