Optical interconnection for a polymeric PLC device using simple positional alignment

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Abstract: This study proposes a simple cost-effective method of optical interconnection between a planar lightwave circuit (PLC) device chip and an optical fiber. It was conducted to minimize and overcome the coupling loss caused by lateral offset which is due to the process tolerance and the dimensional limitation existing between PLC device chips and fiber array blocks with groove structures. A PLC device chip and a fiber array block were simultaneously fabricated in a series of polymer replication processes using the original master. The dimensions (i.e., width and thickness) of the under-clad of the PLC device chip were identical to those of the fiber array block. The PLC device chip and optical fiber were aligned by simple positional control for the vertical direction of the PLC device chip under a particular condition. The insertion loss of the proposed 1 x 2 multimode optical splitter device interconnection was 4.0 dB at 850 nm and the coupling loss was below 0.1 dB compared with single-fiber based active alignment.

OCIS codes: (130.3990) Micro-optical devices; (200.4650) Optical interconnects; (250.5460) Polymer waveguides; (230.4000) Microstructure fabrication.

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1. Introduction

Optical interconnection between fiber and optical device chips is the essential factor in fabricating a low cost, high performance PLC device. To this end, studies on various optical

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coupling technologies are being conducted. Optical interconnection requires a complex process involving the fabrication of an optical device chip and alignment. Among these processes, researches on the fabrication of optical device chips are generally concentrated on polymer pattern replication due to its simplicity, speed, and low cost [1–6], while researches on optical alignment technology are concentrated on the improvement of positional accuracy. The fiber array block with groove structures, which can be coupled precisely with a PLC device chip and fiber due to its ability to maintain the same pitches for the chip and fiber, is essential for the positional alignment of an optical fiber. Studies on the fabrication processes of fiber array blocks are being conducted using various technologies such as ultraviolet (UV) exposure/etching and a mechanical machining process, and they are being conducted separately from the optical device chip process. Therefore, their dimensional accuracy has limitations because of these different fabrication processes. In previous studies, optical interconnection through passive alignment by simple mounting of the fiber using a dimensionally designed groove was reported. However, additional complex processes such as laser processing and the fabrication of a 3-dimentional structure were required [7,8]. Therefore, a more efficient optical coupling technology implemented by a simple process is required.

The aim of this study is to develop a new process to simultaneously conduct PLC device chip fabrication and optical interconnection via a polymer replication process. This study relates to the simultaneous fabrication of PLC device chips and fiber array blocks using sequential polymer molding processes, and the coupling of the two optically through simple position control.

2. Concepts of optical interconnection

We developed a process to minimize the coupling loss caused by the process tolerance between an optical device chip and a fiber array block. Misalignment between optical fibers can be classified into the following: axial gap, alignment angle, and lateral offset. Among these factors, lateral offset primarily affects optical loss, and is expressed by Eq. (1) below [9],

$$Loss_{Lateral\ misalignment}\left(dB\right) = -10\log\left(1-\frac{2x}{\pi R}\right). \tag{1}$$

where x and R represent lateral offset and core radius, respectively.

Since the optical uniformity of the multi-channel can be expressed with the difference between the maximum and minimum output power of each channel, assuming the input powers are the same across all channels, uniformity was determined by the loss between the maximum and minimum output. As regards the separate fabricating processes for the optical device chip and the groove structures, lateral offset (x_n) and pitch (p_{n-1}) between each channel have limitations due to process tolerance, as shown in Fig. 1(a). The optical uniformity of the PLC device chip and the fiber array block were determined according to alignment accuracy. To solve these problems, an optical PLC device comprising three pieces was fabricated with the same replicated polymer structure, two fiber array blocks and one PLC device chip. That replicated polymer structure was used for the sub-mold of a PLC device chip and then the parts of that replicated polymer structure became fiber array blocks. Therefore, the polymer molding process can control lateral offset (x_n) and pitch (p_{n-1}) because it directly replicates the same micro patterns of a sub-mold, which was used for the fiber array block, in PLC device chip. Figure 1(b) schematically depicts the concept of an optical interconnected PLC device by a polymer molding process.

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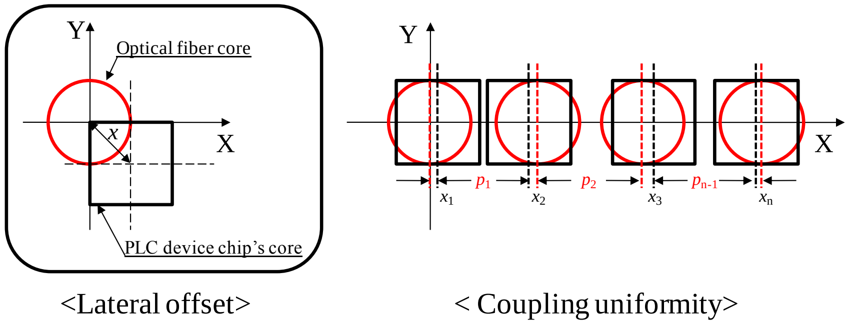
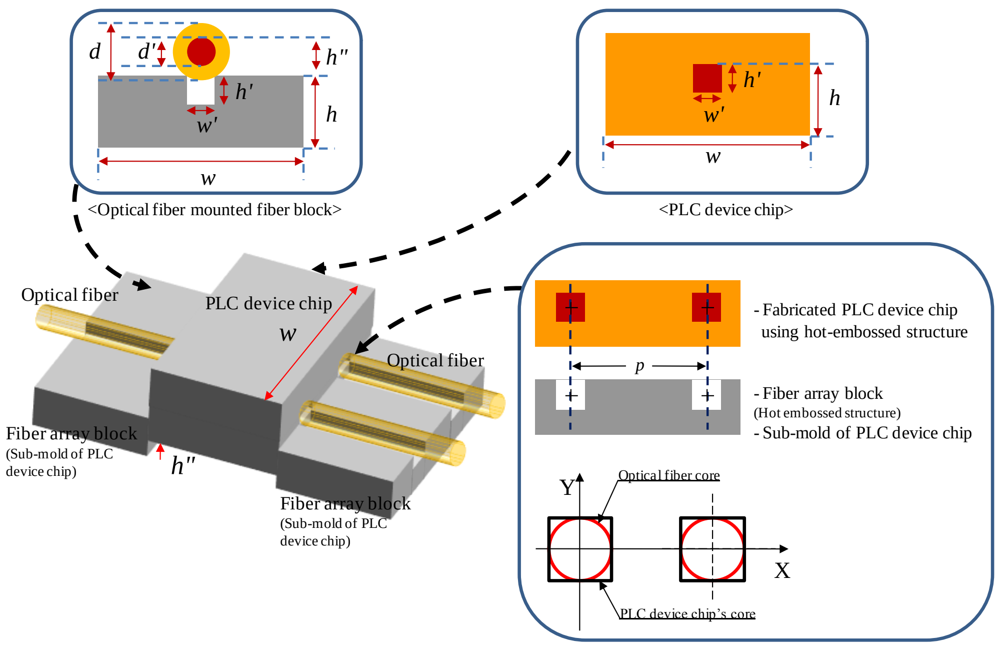


(a)



(b)

Fig. 1. (a) Dimensional accuracy between the PLC device chip and the optical fiber; (b) schematic configuration of the optical interconnected PLC device.

Figure 1(b) shows the coupling structure of a 1 x 2 optical splitter device chip and fiber. The fiber array block was fabricated using the hot-embossing process [10], and a sub-mold was used to fabricate the PLC device chip. Therefore, all the dimensions (w, h, w', h', p) of the fiber array block and the PLC device chip's under-clad were the same.

The optical interconnection process was carried out only by single-axis control. Specifically, optical alignment was achieved such that the PLC device chip and the fiber array block were fixed at the same height and width, and then the PLC device chip rose by the distance h'', which is caused by mounting the optical fiber in the groove. The optical fiber's dimensions are as follows: core diameter of d' and fiber diameter of d.

3. Fabrication of the integrated interconnection structure

Figure 2 shows the process procedure for the optical interconnection between the fiber and the optical splitter device chip.

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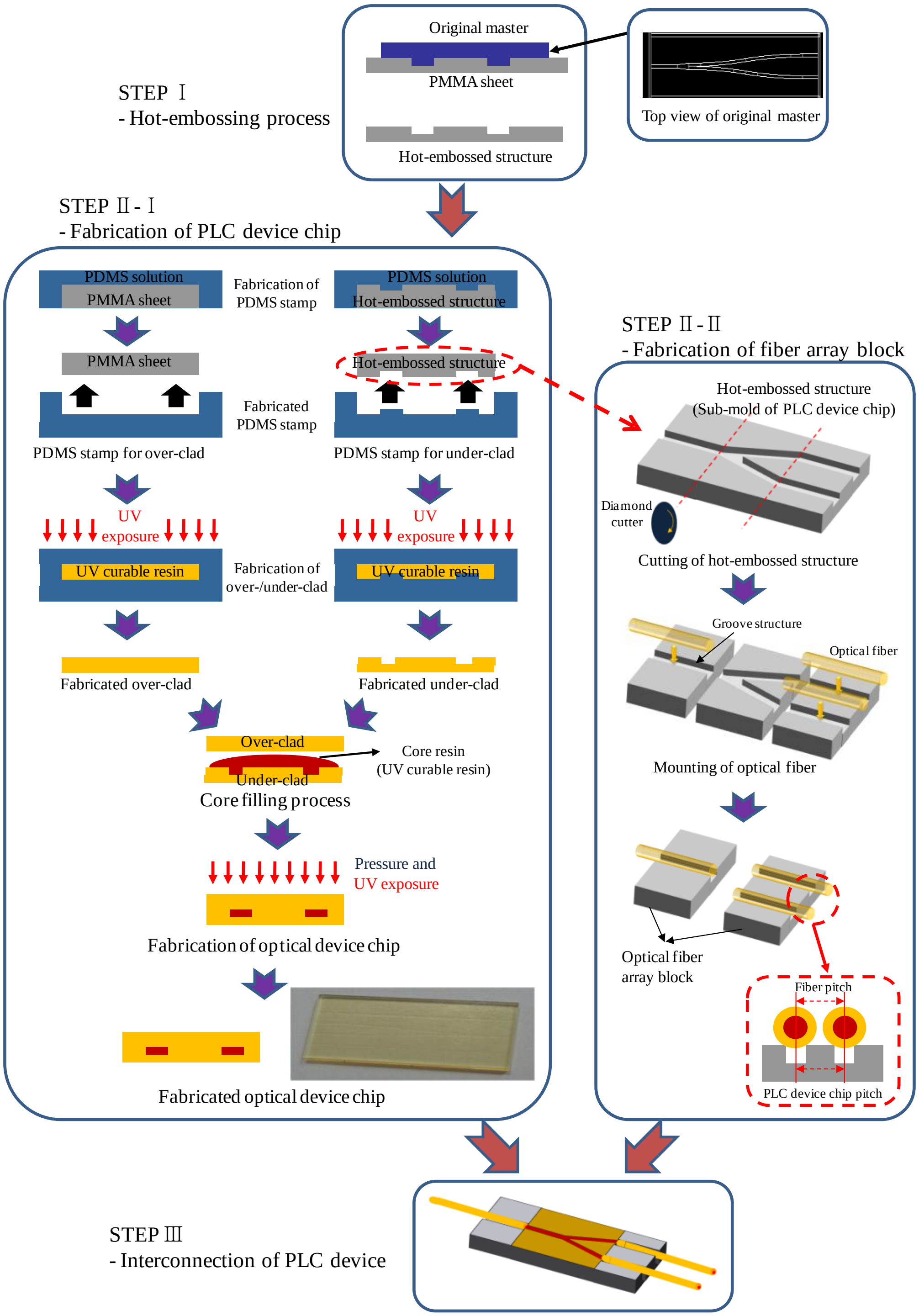

Fig. 2. Schematic diagram of the optical interconnection between the PLC device chip and the optical fiber.

To fabricate the polymer channel structure, the first step (Step-I in Fig. 2) in the optical interconnection of the splitter device, NIL (Obducat Co., NIL6) equipment was used. Photolithography was applied to the fabrication of the silicon original master. Using an α-step

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(KLA Tencor Co., US/Alpah-step IQ) and an optical microscope (Mitutoyo Co., MF), a width of 198 μm, a height of 202 μm and an output port pitch of 1,395 μm were measured in the fabricated silicon original master. To reduce surface energy, the surface of a Si master was coated with a fluorosilane monolayer using the vapor deposition method, while the hot-embossing process was carried out on a polymethylmethacrylate (PMMA) sheet with a thickness of 400 μm. The pressure was applied step by step to improve the accuracy of the replication. The process temperature and de-molding temperature were fixed at 150 °C and 70 °C, respectively, while pressure was applied at 16 bar, 25 bar and 30 bar (for 30 s, 30 s and 5 min) so that the pattern could be reproduced with the dimensional change maintained below 1 μm.

The second step (Step II) can be classified into two sub-steps: the first sub-step (Step II-I) involves the fabrication of the optical splitter device chip, the second (Step II-II) the fabrication of the fiber array block. The under-clad was fabricated via sequential polymer molding processes using a hot-embossed structure. It was fabricated using a UV curable resin and a polydimethylsiloxane (PDMS) mold. The over-clad was fabricated in the same way using a PMMA sheet without a pattern. The under- and over-clad were fabricated for 10 min at 3 bar pressure in an N_2 atmosphere by the UV exposure process. A UV curable resin (Chem Optics Co., WIR30-480) with a refractive index of 1.4856(@830 nm) was used as the clad. The thickness (h) and width (w) of the hot-embossed pattern, PDMS mold, and under-clad were reproduced with identical dimensions, i.e., h = 400 μm, w = 8,300 μm. As the core material, a UV curable resin (Chem Optics Co., WIR30-500) with a refractive index of 1.4968(@830 nm) was used. To minimize the slab's thickness and improve the core's degree of cure, liquid core resin was dropped into the under-clad, and the over-clad was brought into contact with the under-clad and then pressure was applied for full contact with each other. The UV exposure process was performed for 10 min at 10 bar pressure in an N_2 atmosphere all over the surface. The hot-embossed pattern fabricated in the first step (Step I) consisted of the input port of a straight channel, a splitting part, and the output ports of two straight channels. In the fabrication of the fiber array block (Step II-II), that hot-embossed pattern was split into an input port, splitting part, and output ports using a diamond cutter. Of these parts, the straight channels of the input port and output port were used as the only groove. A PCSF (core: 200 μm, clad: 230 μm, jacket: 500 μm, NA: 0.48) with a core the same size as that of the optical splitter device chip (NA: 0.183) was used as the optical fiber. The optical fiber was mounted on the groove using UV curable epoxy. The fiber array block and optical splitter device chip were fabricated using the hot-embossed pattern. Therefore, it can be optically interconnected with positional tolerances of less than ± 1 μm. Figure 3 shows the SEM image according to the replication process, as shown in Fig. 2.

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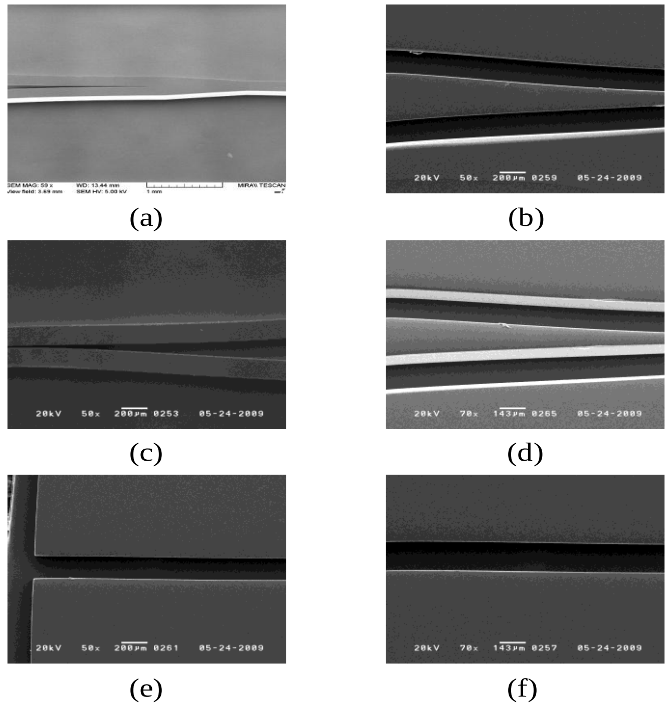

Fig. 3. SEM images of structures according to the replication procedure: (a) the original Si master in step I; (b) the hot-embossed structure in step I; (c) the PDMS mold in step II-I; (d) the under-clad structure in step II-I; (e) the hot-embossed straight channel used as the groove structure in step II-II; and (f) the under-clad straight channel used in step II-I.

In the third step (Step III), optical interconnection of the optical splitter device chip and the fiber array block fabricated in the second step (Step II-I and Step II-II) was conducted. For the optical interconnection, the optical splitter device chip rose by a distance of *h”* using a z-axis stage having accuracy of below 1 μm, while the input port fiber block, optical splitter device chip and output port fiber array block were aligned at the same height and width. Here, theoretically, *h”* becomes 330 μm in terms of structural size. The fiber array block and optical splitter device chip were bonded using UV curable epoxy. The interconnection of the optical splitter device was completed by UV exposure for 30 s.

To evaluate the effectiveness of the proposed method, the optical interconnection of a 12-channel straight multimode waveguide was performed. The optical interconnection of the straight multimode waveguide was performed using the same method. The dimensions of the straight waveguide (NA: 0.183) were 50 μm x 50 μm in the cross-sectional area, with pitch of 250 μm; and a multimode fiber (NA: 0.275) with dimensions of 50 μm for the core and 125 μm for the clad was used. Here, theoretically, *h”* becomes 82 μm in terms of structural size.

4. Results and discussion of the optical interconnected PLC device

Figure 4 shows the fabricated optical device chip and the optical fiber mounted fiber array block. Figures 4(a) and 4(b) show the cross-sectional image of the fabricated optical splitter device chip and the optical fiber mounted fiber block. Figure 4(b) shows that the distance between the optical fiber’s core and the fiber block’s top plane was measured as 331 μm using an optical microscope (Mitutoyo Co., MF). Figures 4(c) and 4(d) show cross-sectional images of the fabricated 12-channel straight waveguide and the optical fiber mounted fiber array block. The distance between the optical fiber’s core and the fiber array block’s top plane was measured at 84 μm using an optical microscope (Mitutoyo Co., MF), with positional uniformity of below 1 μm.

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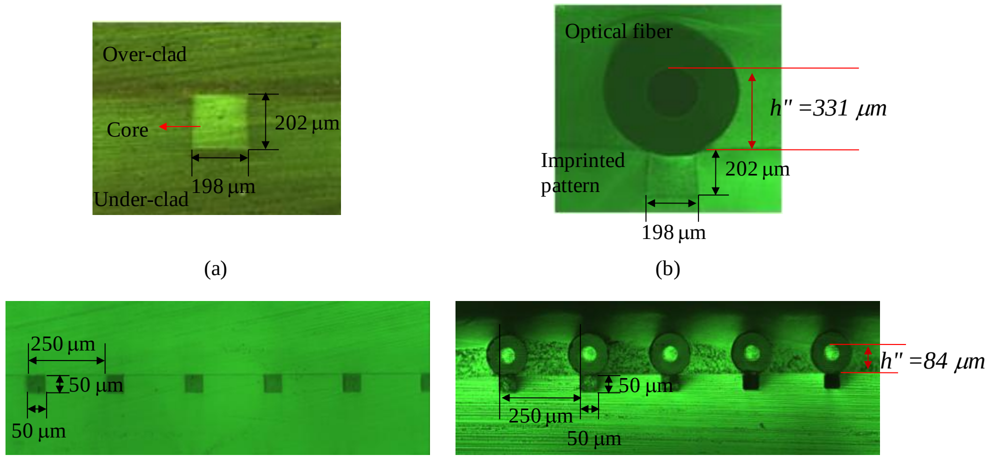

(a) (b) (c) (d)

Fig. 4. Cross-sectional images of the optical device chip and the fiber mounted fiber array block: (a) the 1 x 2 optical splitter chip; (b) the fiber mounted fiber block for the optical splitter; (c) the 12-channel straight waveguide chip; and (d) the fiber mounted fiber array block for the straight channel waveguide.

Finally, the optical characteristics of the optically interconnected device were measured. The light source used for the measurement was an 850 nm VCSEL (Vertical Cavity Surface Emitting Laser). Figure 5 shows the results obtained for the optically interconnected optical device.

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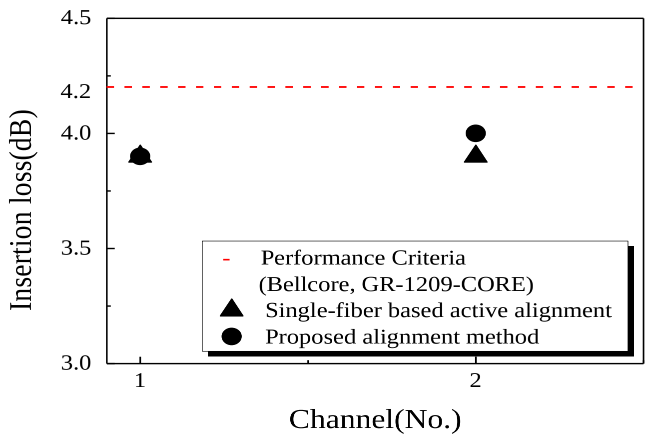
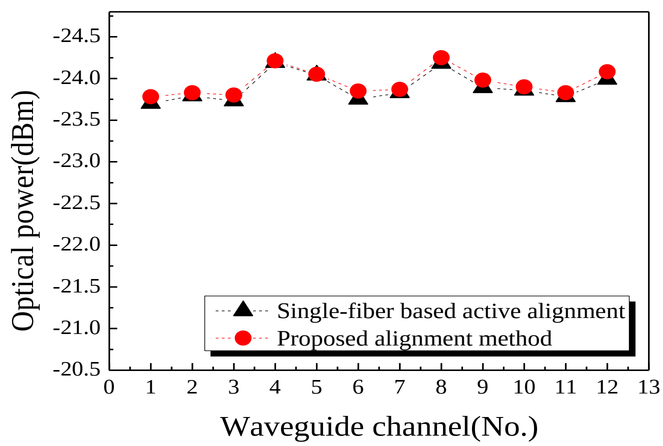


(a)



(b)

Fig. 5. Optical characteristics of the optical device according to optical interconnection: (a) 1 x 2 optical splitter; (b) 12-channel straight waveguide.

Figure 5(a) shows the insertion losses of the splitter device according to the optical coupling. The triangular symbol value shown in Fig. 5(a), which means the insertion loss of the optical splitter device by single-fiber based active alignment, was 3.9 dB; and the optical intensity uniformity of Ch 1 and Ch 2 was measured below 0.1 dB. The circular symbol value shown in Fig. 5(a), which is the insertion loss of the optical splitter device by the proposed alignment method, was 4.0 dB; and the optical intensity uniformity of Ch 1 and Ch 2 was also measured below 0.1 dB. The dashed line represents the criteria of the 1 x 2 single-mode optical splitter device. For a 1 x N single-mode optical splitter device, insertion loss and optical uniformity are specified according to the Bellcore criterion (GR-1209-CORE). Based on that criterion, the insertion loss and optical uniformity of a 1 x 2 optical splitter device must satisfy 4.2 dB and 0.6 dB, respectively. Therefore, we confirmed that the proposed simple positional alignment can be used as the optical coupling method. Figure 5(b) shows the optical intensities of the 12-channel straight waveguide according to optical coupling. The measurement of the straight waveguide was conducted for a length of 110 mm. The power of the laser beam was –22.3 dBm. The optical intensities of the single-fiber based active

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alignment, as shown in Fig. 5(b), ranged from −23.7 dBm to −24.2 dBm, and the optical intensities uniformity was measured below 0.5 dB. The circular symbol values, which are the optical intensities using the proposed alignment method, also show that coupling loss of below 0.1 dB compared with single-fiber based active alignment was measured; and the optical intensities uniformity was also measured below 0.5 dB. Therefore, we confirmed the effectiveness of the proposed method through optical coupling of the multi-channel waveguide.

5. Conclusion

To minimize and overcome the coupling loss caused by the process tolerance difference between PLC device chips and fiber array blocks with groove structures, this study was performed in an attempt to develop a new process for simultaneously conducting PLC device chip fabrication and optical interconnection using a polymer replication process.

Simultaneous fabrication of a PLC device chip and a fiber array block with a groove structure was conducted using a sequential polymer molding process using an original master, and then optical coupling was conducted using simple positional alignment.

For the optical interconnection, a hot-embossed pattern having the same dimensions as those of the under-clad pattern was used as a fiber array block. Therefore, the core of the PLC device chip and that of the fiber could be aligned by raising the PLC device chip by a height of *h"*, at the same heights and widths. The insertion loss of the 1 x 2 multimode optical splitter device interconnected for this study was confirmed as 4.0 dB at 850 nm, while optical coupling loss was confirmed within 0.1 dB compared with single-fiber based active alignment. Finally, the effectiveness of this study was confirmed through optical coupling of the 12-channel straight multimode waveguide. The proposed optical interconnection method was conducted through multimode waveguide and fiber. It could be also applied to the optical interconnection of single-mode waveguide, if used as original master that was designed by considering the diameter of the optical fiber's clad at the straight channel for the groove.

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