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Design and Fabrication of Three-dimensional Polymer Optical Waveguide-based Fan-in/out Device for Multicore Fibers

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Abstract: In this paper, a compact (10-mm long) and low-loss fan-in/-out polymer waveguide is successfully fabricated using the Mosquito method, in which four cores three-dimensionally vary their arrangemnent from one end to the other and they are precisely aligned to couple to a multicore fiber.

Introduction

In recent years, the data traffic of intra and inter datacenter networks has grown rapidly and is forecasted to continuously keep surging in the future as well. To sustain the growth of data traffic, there are high expectations for upgrading the optical fiber links in those networks. Over the last couple of years, single-mode optical fiber (SMF) links with high bandwidth distance product are being deployed in those networks particularly in large-scale datacenters. Currently, even for intra datacenter netowrks, wavelength division multiplexing (WDM) links start being installed to achieve 400 Gbps transmission and beyond.

However, with increasing the number of wavelengths to be multiplexed, the optical power density in a fiber core increases, which would be a concern to cause fiber fuse. Therefore, space division multiplexing (SDM) technology using multicore fibers (MCFs) has been intensively studied over the last couple of years. In MCFs, multiple cores are bundled in one fiber. However, due to the difference of core arrangement in the cross-section, SMFs and MCFs cannot be directly connected. Hence, the connection technique of MCFs and SMF arrays has been a critical issue. There have been several reports of fan-in/fan-out (FIFO) devices such as bundled fibers [1], multiple lens modules [2], and glass/ polymer waveguides [3,4]. Since the polymer waveguide FIFO device previously reported is fabricated using photolithography, it includes just a horizontal pitch conversion structure, while vertical core spacing remains unchanged. In contrast, in the glass waveguide FIFO devices, cores are fanned in/out three dimensionally, which is enabled by a three-dimensional small beam scan of a high-power laser to form the cores in a glass cladding. In this case, since the waveguide is essentially composed of one material, the core index contrast could not be freely adjusted for low bending loss.

To address these issues, we propose a polymer waveguide FIFO device with three-dimensional fan-in/out cores for MCFs. This new FIFO polymer waveguide is fabricated applying the Mosquito method we developed [5]. Although we already confirmed that the Mosquito method allowed to form multiple single-mode cores that were arranged at one end to be coupled to an MCF while one dimensionally aligned in the other end [6], the core alignment accuracy and the insertion loss were issues to be addressed.

In this paper, we present a compact and low loss FIFO waveguide in which four cores are three dimensionally rearranged from one end to the other. Such a device is realized by re-designing the core arrangement structure. Then, the core position accuracy is improved to decrease the coupling loss, while the bending loss is also remarkably reduced by adjusting the index contrast and bending structure.

Waveguide Fabrication Method

The Mosquito method is applied to fabricate the FIFO waveguides. The fabrication process is shown in Fig. 1. 1) A liquid cladding monomer is coated on a glass substrate to have a thickness of 500 μm. 2) Another liquid monomer for the core is dispensed from a thin needle of a syringe into the cladding monomer using a micro-dispenser, while the needle scans on a three-dimensional core patterns for FIFO 3) Finally, the core and cladding monomers are entirely cured by UV light exposure to obtain a FIFO waveguide. We preveiousely reported in [7] that a FIFO waveguide for multimode MCF was successfully fabricated using the Mosquito method, while fabrication condition for single-mode FIFO waveguide has been investigated, where laminated structures in which cores are stacked in vertical rows is introduced [6].

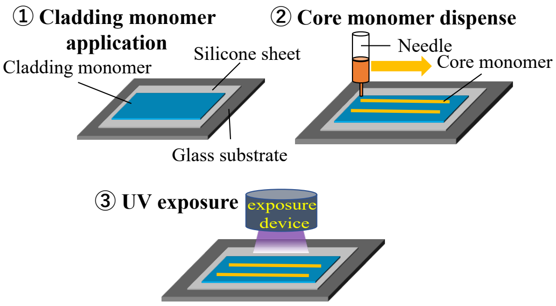

Fig. 1 Waveguide fabrication process

FIFO waveguide design and fabrication

In this paper, FIFO waveguides are designed for a four-core MCF, as shown in Fig. 2.

A. Cross-Sectional Structure optimization

In the Mosquito method, as a syringe needle scans in the liquid cladding monomer repeatedly to dispense all the multiple cores, the characteristics and cross-sectional shape of the cores dispensed earlier can be largely affected by the needle scan for the adjacent cores dispensed later. In fact, when the second core is dispensed right above the first core already dispensed in the cladding, we observe that the properties of the first core (dispensed on a lower height) tend to deteriorate due to the cladding monomer flow caused by the needle scan, as shown in Fig. 3. In this experiment, the core spacing in the *y* direction is fixed to be 50 µm, while the *x*-directional spacing is deliberately varied when dispensing multiple cores. In these waveguides, the cores are not bent for FIFO but dispensed on just a straight path. It is found in Fig. 3 that the insertion loss of the core placed on a lower height tends to deteriorate with decreasing the horizontal spacing, and when the *x* directional spacing is narrower than 15 µm, a 1-dB loss difference between higher and lower cores could be observed at 1550 nm. Therefore, we re-design the core arranging structure at the MCF side cross section, as shown in Fig. 4, Here, a "laminated structure" in which Ch. 3 and Ch. 1 are dispensed right above Ch. 1 and Ch. 2,

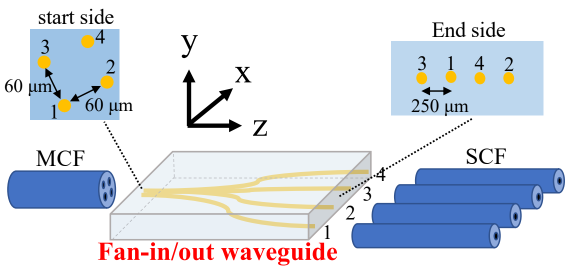

Fig. 2 Schematic of FIFO waveguide

respectively is rotated counterclockwise with a 30° to avoid aligning two cores in a vertical row. In these waveguides, the cores are not bent for FIFO but dispensed on just a straight path, as well. Then, 25 mm-long FIFO waveguides are fabricated by the Mosquito method. In the fabricated waveguides, loss reductions of 0.2 ~ 0.8 dB due to the new structure are confirmed, as shown in Fig. 4(b). In this FIFO waveguide, the core bending structure is not optimized, and thus the insertion loss is still as high as 2 to 3 dB.

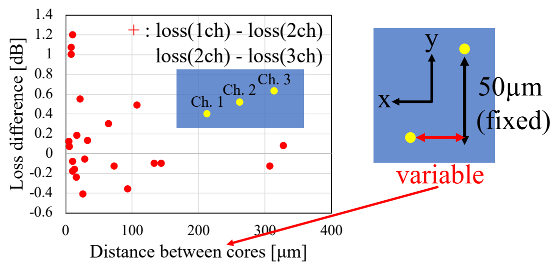

Fig. 3 Relationship between the core arrangement and the insertion loss

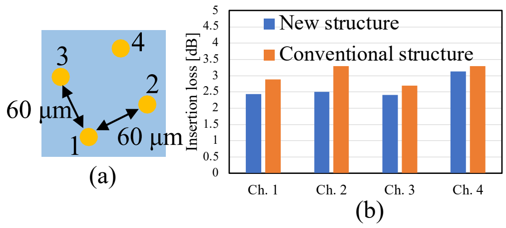

Fig. 4 (a)Cross-sectional structure of FIFO waveguide, and
(b) Insertion loss dependence on the cross-sectional structure

B. Core Dispensing Position Accuracy

Other issue in the Mosquito method is that the cores dispensed earlier are dragged to the needle scan direction (the *z*-axis direction in Fig. 2) when the next cores are dispensed in the vicinity of the prior cores. Thus, the FIFO structure of the four cores shown in Fig.2 is deteriorated due to the core position shift in the axial direction, which causes unwanted core arrangement distortion at the waveguide ends. This core arrangement distortion is feedbacked to the needle-scan path program: the starting point of the needle scan is deliberately displaced in the *z* direction one by one with an 1100-µm length to compensate the core position shift. Then, a symmetrical FIFO structure as designed in Fig. 2 is successfully formed as shown in Fig. 5, by which we expect that the FIFO waveguides could be shortened because the core positions are stabilized within a short waveguide length.

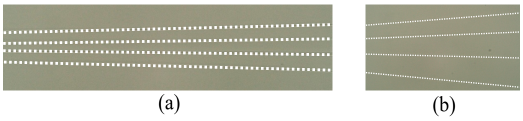

Fig. 5 Top-view of the FIFO structure after needle-scan correction (a) Top view of MCF side (b)Top view of fiber array side

C. Fabrication for Low-loss and Subminature FIFO Waveguide

In order to realize the FIFO structure shown in Fig. 2 in a waveguide length as short as 5 to 10 mm to fit it in an MT connector, the core bending particularly for Ch. 1 and 4 needs to be steep, which could increase the bending loss. So, a cosine function is introduced to the core S-shaped bending structure, which is expected to allow the bending loss lower than the bending losses of the previous S-shaped bending structure that simply combines two arcs of quadrant [7]. Furthermore, the needle-scan program is not defined by a single cosine function from the start to the end of the scan path but is developed to interpolate multiple target positions over which the needle should pass. The target positions are selected from the designed cosine curve with an equal interval. This revision of the needle-scan program allows to dispense the core on the designed paths more accurately. The core arrangement in a fabricated waveguide at both ends are shown in Fig. 6. All the cores are confirmed to have circular cross-sectional shapes and are successfully placed on the designed positions within a ±3 μm accuracy.

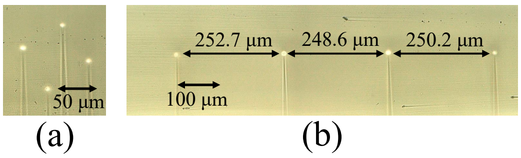

Fig. 6 (a) Cross-sectional view of fabricated FIFO waveguide for MCF side, and (b) for a fiber array side

The insertion loss of a fabricated 10-mm long FIFO waveguide is measured using the setup shown in Fig. 7, where a 4-ch. MMF ribbon with a 250-μm pitch is coupled to the end (b) in Fig. 6 of the FIFO waveguide. The results are shown in Fig. 8. As shown in Fig. 8(a), the insertion loss is as low as 1 dB, and is almost the same as that of a straight waveguide with the same length. Hence, the bending loss is sufficiently lowered in such a short waveguide. Meanwhile, from the NFP result in Fig. 8(b), a FIFO waveguide with almost the same core arrangement as that for the fiber array could be fabricated, where signal light can be simultaneously coupled to all the four cores in the FIFO waveguide from an MMF ribbon.

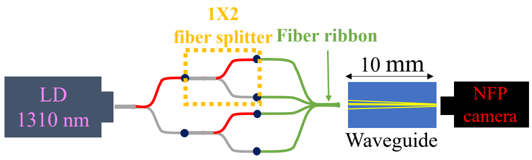

Fig. 7 Measurement setup

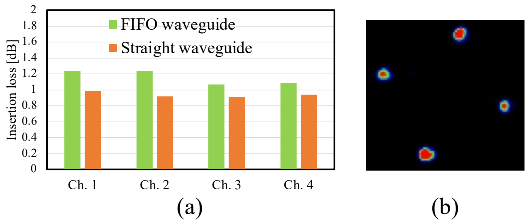

Fig. 8 (a) Comparison of insertion loss between a straight and a FIFO waveguides (b) NFP at the output end of the FIFO waveguide

Conclusion

In this paper, a three-dimentional polymer waveguide FIFO device, which could work as a connection element under the practical usage of MCFs is proposed by fabricating it with the Mosquito method. By re-designing the core arrangement and bending structures, as well as the needle-scan program, the cores could be dispensed on a designed path more accurately to achieve low insertion loss. The fabricated FIFO waveguide with a length as short as 10 mm exhibited the lowest insertion loss of 1.09 dB at 1310 nm. Because of the high core position accuracy, four cores in the FIFO waveguide exhibited high coupling efficiency at the connection with a 1-D arrayed fiber ribbon. This three-dimensional FIFO waveguide with low loss and compact size is expected to be integrated in a connector in the actual applications.

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