GI-core Multimode and Single-mode Polymer Waveguides for High-density Co-packaging

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Abstract: We present unique polymer optical waveguide coupler devices fabricated using the Mosquito method to apply for adiabatic coupling with Si photonics chips, three-dimensional fan-in/fan-out devices for multicore fibers, and MUX devices for mode division multiplexing.

1. Introduction

Over the last couple of decades, optical data links have been widely deployed replacing the legacy electrical wiring even in short-reach networks in high-performance computers and datacenters. In current datacenter networks, 50−μm core multimode optical fibers (MMFs) are widely employed, while single-mode fibers (SMFs) are being installed in large-scale datacenters in order to meet the demand for higher bandwidth distance product. Current technology trends are in placing high speed optical transceivers (optical engines) as close to LSI chips as possible, which are called *co-packaged optics* technologies. High-density channel alignment as well as high speed operation is highly anticipated to the co-packaged optical engines. In addition, the necessity of space savings requires the optical engines to be as compact as possible. Hence, silicon (Si) photonics technologies are drawing much attention for co-packaged optical engines with off-chip SMF links. Here, the mode-field diameter (MFD) of the propagating modes in Si cores and conventional SMF cores differ significantly due to their core size and index contrast, which can cause a high coupling loss. To address this high coupling loss issue, *coupler devices* such as grating couplers (GCs)[1] and spot-size converters (SSCs)[2, 3] have been proposed. SSCs are a device for an in-plane edge coupling, and thus, it can save the space in the vicinity of the chips.

Meanwhile, in order to realize much greater transmission capacity, space division multiplexing (SDM) technologies including mode division multiplexing (MDM) have attracted much attention. In the SDM optical links, high-speed signals are multiplexed over different cores in a multicore fiber (MCF) or propagation modes in a few-mode fiber (FMF). For the SDM optical links, specific *coupler devices* called multiplexer/demultiplexer (MUX/DEMUX) are required to be inserted between several different signal light sources and an MCFs/FMFs.

Over the last couple of years, polymer optical waveguides have been expected to be applied for those optical coupler devices, *ex.* adiabatic couplers[2, 3] for SMFs with Si photonics chips, fan-in/fan-out waveguides[4] for MCFs, and Y-branched waveguides for FMFs[5]. In this paper, we introduce a distinctive fabrication method for polymer optical waveguides named *the Mosquito method* we have developed[6]. The unique features of the Mosquito method are in its capabilities to fabricate both multimode and single-mode cores with graded-index (GI) circular cores and to form a wide variety of core patterns even for three dimensional wiring. In the following sections, we present some unique polymer optical waveguide devices created by the Mosquito method.

2. Polymer Waveguide Devices Fabricated Using the Mosquito Method

2.1. The *Mosquito Method*

Fig. 1 shows the procedure of the Mosquito method. In the Mosquito method, first, a liquid state cladding monomer is coated on a substrate. Next, a viscous liquid-state core monomer is dispensed into the cladding monomer from a thin needle of a syringe while the needle scans horizontally and even vertically for drawing 3-D wiring patterns. Finally, the core and cladding monomers are simultaneously cured under UV exposure, followed by post baking to obtain the waveguides.

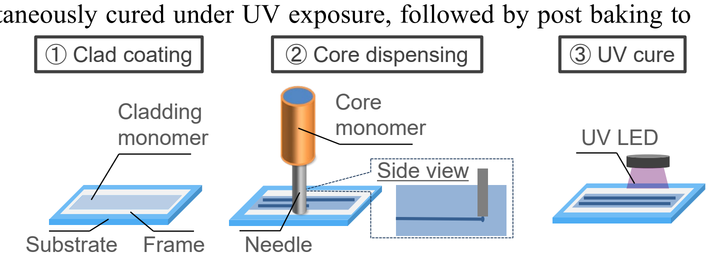

Fig. 1 Fabrication steps of polymer waveguide in the Mosquito method.

2.2. *SSCs for Si Photonics Chips and SMFs*

Fig. 2 shows the design of the SSC composed of a polymer waveguide fabricated using the Mosquito method[7]. Here, an axially tapered polymer core embeds a Si waveguide tapered core as shown in Fig. 2(a), by which the lightwave is adiabatically coupled to the tapered polymer waveguide core.

Then, the MFD increases to the same size as that of SMF to be coupled during the light propagation in the inversely tapered polymer core. The tapered cores are formed with a simple process: just accelerating the needle scan while one core is dispensed in the Mosquito method, as shown in Fig.2(b).

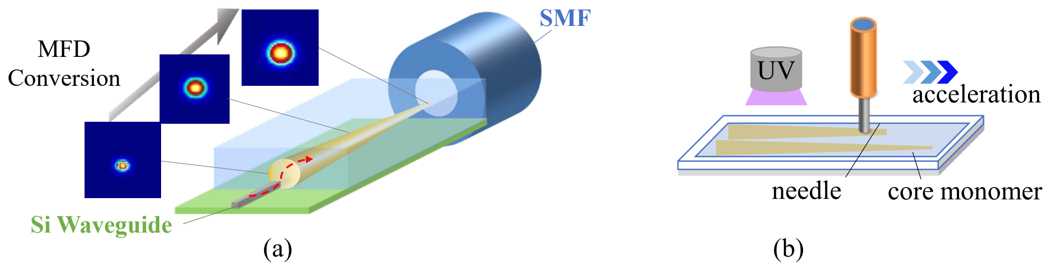

Fig. 2 (a) Design of tapered polymer waveguide SSC (b) formation method of a tapered core

Fig. 3 shows cross-sectional photos and near-field patterns (NFPs) measured at 1.55 µm from both ends of a fabricated tapered waveguide[7]. We visually confirm that a circular tapered core is formed, and the MFD increases from the larger core to the smaller core sides, as designed. When the fabricated tapered waveguide shown in Fig. 3 is inserted in two SMFs with different MFDs (4.0 µm and 8.5 µm) keeping the direction to match the MFDs of the waveguide with both SMFs, an insertion loss of 1.83 dB is observed at 1.55 µm. Meanwhile, when the waveguide is inserted in the opposite direction to show mismatches in the MFDs at both ends, the insertion loss increases higher than 10 dB. From these results, we verify the SSC ability in the fabricated tapered waveguide.

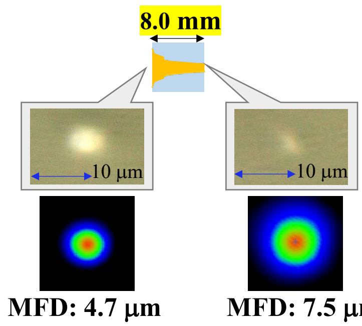

Fig. 3 Cross-sections and output NFPs of a fabricated tapered polymer optical waveguide.

2.2. Waveguide Couplers for Multicore and Few-mode Fibers

Fig. 4 shows a design of fan-in/-out waveguide for a multicore fiber (MFC with 7 core) in which a hexagonal core arrangement on one end is reconfigured to one dimensional array on another end[8]. In this design, the horizontal pitch of the seven cores is expanded to 250 µm from the MCF side to 1-D array side, while the core height difference is vanished. Fig. 4 also shows the cross-sectional photos of a fabricated FIFO waveguide for 7-core MCF. Although the core arrangement is not accurate enough to couple to actual MCF and SMF array, it is visually confirmed that the designed three dimensional fan-in/-out structure is successfully formed. The insertion loss of the fabricated 4.5-cm long FIFO waveguide is 4.0 dB at 1.31 µm on average. Currently, the lowest insertion loss of 1.4 dB is observed for a 2-cm long 4-core FIFO waveguide. Although several other methods to fabricate similar three-dimensional core patterns have been reported, those are dedicated to the core pattern formation, resulting in just naked cores formed.

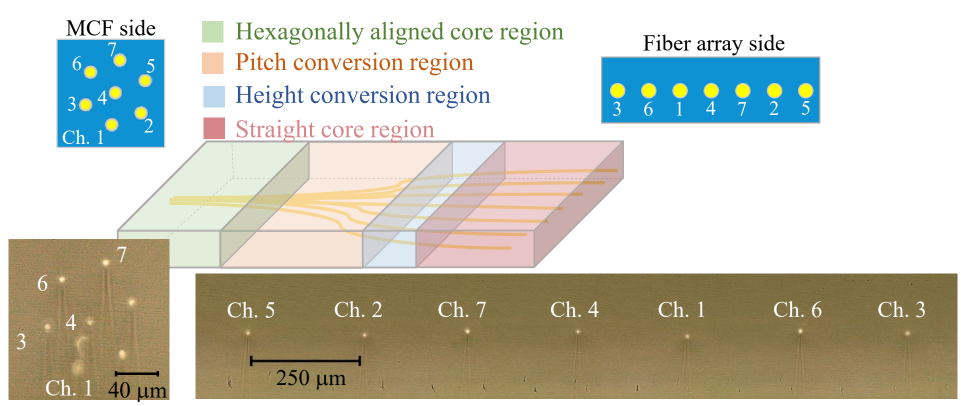

Fig. 4. Design of three-dimensional fan-in/fan-out polymer waveguide for a multicore fiber (7-core) and cross-sectional phots on both ends of a fan-in/fan-out waveguide fabricated using the Mosquito method.

Meanwhile, it is another strong advantage of the Mosquito method that both core and cladding are simultaneously formed just after curing, where a wide variety of polymers can be selected for the core and cladding. Thus, we can control the MFD by adjusting the index difference between the core and cladding, as well as the core diameter.

As another coupler device, top-view and cross-sectional photos of an *asymmetric Y-branched polymer waveguide* fabricated using the Mosquito method are shown in Fig. 5[9]. Because liquid core is dispensed in another liquid cladding, Y-branched cores are not formed by a simple needle scan. So, we employ a specific needle-scan path: a unicursal scan in which the needle starts scanning from core (A) to (C), and then the needle scans back to core (B) without pulling it off from the cladding monomer. In this Y-branched waveguide, the diameter of core (A) is designed to be slightly larger than that of core (B), although both cores (A) and (B) satisfy the single-mode condition. Meanwhile, core (C) is designed to support two modes (LP_{01} and LP_{11} modes), by which the input light from core (A) and (B) are coupled to LP_{01} and LP_{11} modes in core (C), respectively. From the measured NFPs at 1.31 μm in Fig. 5, the input light to cores (A) and (B) are coupled to different order modes in core (C), as designed. Thus, we confirm that the waveguide works as a MUX for MDM with an FMF. Because of the circular core, LP_{11a} and LP_{11b} modes can be separately launched by forming a three dimensional branching structure.

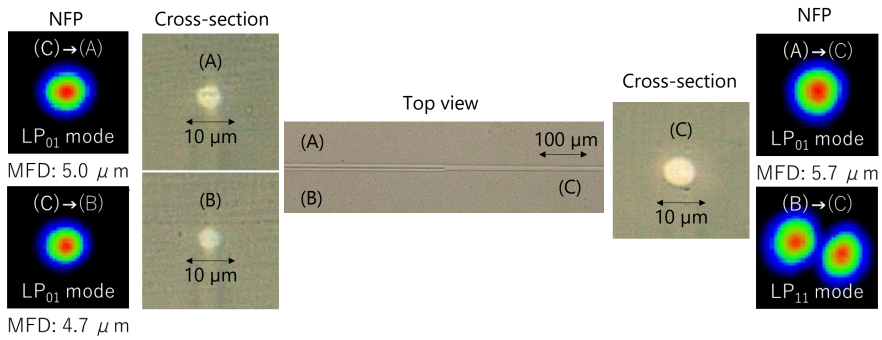

Fig. 5. Top-view and cross-sectional photos of asymmetric Y-branched polymer waveguide. NFPs measured at 1.31 μm show the ability of MUX device for a few-mode fiber.

3. Conclusion

Applying the Mosquito method for UV curable resins, we succeeded in fabricating several unique polymer optical waveguide devices that are axially tapered core waveguide SSC for Si photonic chips, three-dimensionally aligned core fan-in/-out waveguide for MCF, and asymmetrically branched core waveguide for MDM links with FMF. Since the Mosquito method allows to form circular cross-sectional cores in the waveguides, high connectivity to the conventional optical fibers is possible: for instance, the waveguides can exhibit the same mode power profiles as those in FMF. Hence, low connection losses at both ends of the waveguides are expected, resulting in low insertion loss. For high speed and high density optical links, the Mosquito method will pave the way for great advantage in creating unique optical devices. This research is partially supported by Japan Society for the Promotion of Science (JP18H05238), and research grant from the Foundation for Technology Promotion of Electronic Circuit Board.

3. References

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