Polymer Waveguide-coupled Co-packaged Silicon Photonics-die Embedded Package Substrate

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Abstract: We propose a next generation co-packaged substrate using Si photonics dies, a polymer optical waveguide, and a optical connector to achieve beyond 10 Tb/s and WDM optical links. The two micro-mirrors and polymer waveguides were integrated, and their optical characteristics were evaluated.

1. Introduction

Data centers and high-performance computer systems must evolve to cope with exponential growth in the demand for data storage, processing, and accessibility. Bottlenecks in system bandwidth density require the development of new architectures [1]. Optical interconnection shows promise as a solution to eliminate input-output (I/O) communication bottlenecks due to increasing data rates by reducing energy and latency compared with conventional electrical wiring. A bandwidth breakthrough would require converting electrical and optical signals as efficiently as possible to large-scale integrated circuits. For an extreme reduction in the length of high-data-rate electrical links, co-packaging technologies of optics chips (e.g. silicon (Si) photonics) and high-performance large-scale integration (LSI) chips have attracted considerable attention. For example, Rockley Photonics showed a switch application specific integration circuit (ASIC) containing co-packaged Si photonics chips at OFC 2018; it was connected to a dozen ribbon optical fiber cables [2]. Such massively parallel optical input/outputs (I/Os) will be necessary for high performance LSIs like upcoming high-capacity switch ASICs for 25.6 and/or 51.2 Tbps. Recently, as one of the next generation co-packaging solutions, we proposed a new package substrate using a polymer waveguide and silicon photonics transceiver modules. We proposed an optical and electrical hybrid active optica package (AOP) using Si photonics dies, a polymer optical waveguide, and an optical connector. The AOP package has high bandwidth of 10 Tb/s and WDM optical links. The AOP substrate is an organic package substrate where Si photonics dies are embedded, as shown in Figure 1. On the surface of the substrate, fan-in/out polymer optical waveguides, connecting high density Si-photonics I/O, and a low density single-mode fiber (SMF) array are integrated. The polymer waveguides and the SMF are connected using an optical connector at the edge of the AOP substrate [3]. However, a surface optical I/O is required for the optical I/O of the embedded Si photonics dies. We have proposed and demonstrated the Si-photonics vertical I/O with an integrated curved micro-mirror [4]. In this study, we determined an AOP substrate and some key technology for an AOP substrate. The two micro-mirrors and polymer waveguides were integrated, and their optical characteristics were evaluated.

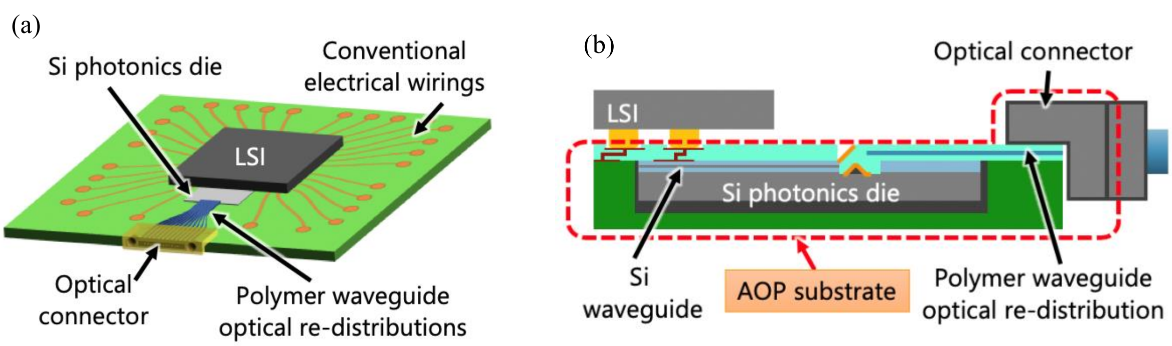

Fig. 1: (a) The bird's-eye view and (b) cross-section schematics of the co-packaged optics using AOP substrate.

2. Mirror-based optical coupler between Si and polymer waveguides

For the optical I/O of the embedded Si photonics dies, a surface optical I/O is required. Grating couplers are popular surface optical I/O devices; however, it's difficult to use WDM systems due to their large wavelength and polarization dependences. To overcome these problems, we have proposed mirror-based vertical optical coupling. A close-up cross-sectional schematic of the optical coupling between Si and polymer waveguides is shown in Figure 2(a). The coupling was composed of bottom-side and top-side mirrors. The bottom-side mirror was integrated in the Si photonics die layer, and the top-side one was integrated in the polymer waveguide layer. The spot-size diameters of the Si and polymer waveguides are different. To connect these waveguides efficiently, the bottom-side and/or top-side mirrors were curved micro-mirrors. Thus, a lens-less optical connection between Si and polymer waveguides could be realized. Last year, we demonstrated the Si-photonics vertical optical I/O with the bottom-side curved micro-mirror [3]. The vertical optical I/O of the Si waveguide with a standard SMF was demonstrated, and a low wavelength-dependent loss of approximately 1 dB was obtained for a full O-band wavelength. The polarization-dependent loss was 1.1 dB on average. In this study, we demonstrated the optical coupling of the Si and polymer waveguides using the two micro-mirrors as shown in Figure 2(a). Owing to the curved surface of the bottom-side mirror, the beam waist diameter of the light from the mirror was approximately 10 µm. The light was reflected again by the flat-surface topside mirror and coupled to the polymer waveguide with a mode field dimeter (MFD) of approximately 10 µm. Smooth surfaces of 45° were obtained for the bottom- and top-side mirrors. The optical loss, composed of the coupling loss (between the Si and polymer waveguides) and the polymer waveguide propagation loss, was measured as shown in Figure 2(b). For the measurement, a super-luminescent diode was used as a broadband optical source covering the S, C, and L bands. The light, passed through the Si waveguide, mirrors, and polymer waveguide, was received by a standard SMF with 10-µm MFD and cleaved end facet. As shown in Figure 2(b), broadband optical characteristics were obtained over the wavelength range of 1460 to 1540 nm, and the minimum optical loss was approximately 4 dB. The optical signal transmission of 28 Gb/s on-off keying (OOK) was also demonstrated at a 1550-nm wavelength. There was negligible signal distortion and the 28 Gb/s OOK signal was successfully transferred through the Si waveguide, the mirror coupling structure, and the polymer waveguide shown in Figure 2(c).

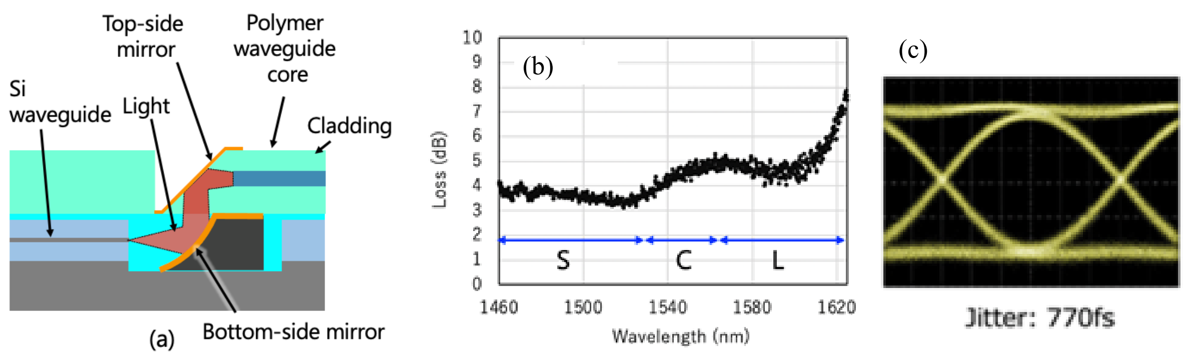

Figure 2. (a) Schematic of a mirror-based vertical optical coupler between Si and polymer waveguides. (b) The measured optical loss of an optical coupler and polymer waveguide. (c) A 28Gb/s OOK transmission at 1.55 µm.

3. Optical connector for polymer waveguide and single mode fiber

For a single-mode polymer waveguide on the AOP substrate, a polymer-waveguide integration process on a glass-epoxy substrate was developed [4]. The waveguide material was silicate-based organic-inorganic hybrid resins, and the waveguide was integrated based on optical lithography processes. A low propagation loss of 0.44 dB/cm and a coupling loss with an SMF of 0.99 dB were obtained for the 1.31-µm wavelength. For such polymer waveguides, we also proposed and developed an MT-connector-compatible optical connector [5]. Cost-efficiency, scalability, and the manufacturing volume of photonic packaging are important factors to consider during development [6]. To assemble the optical connector to the AOP substrate at low cost, the assembling process is based on self-alignment, and the alignment structure of the connector is guided mechanically by the connectors of the AOP substrate as reported in the previous work [5]. The precise alignment structure was fabricated for the AOP substrate by the photolithography process of the polymer waveguide core. Thus, there was no additional cost for the fabrication of precise alignment structures. Polymer waveguides were fabricated on a glass epoxy substrate on which the optical connector was passively assembled. Photographs of the substrate after the connector assembly are shown in Figure 3(a). Using the assembled connector, the polymer waveguide array was butt-coupled with a 12-channel MT fiber connector. To evaluate the coupling loss penalty of the connector, the insertion losses with and without the use of the assembled connector were measured, as shown in Figure 3(b). Each SMF was actively aligned to each polymer waveguide. The coupling loss penalty was calculated by subtracting the insertion loss measured without the connector from that measured with the connector. The measured coupling loss penalty is shown in Figure 3(b). Compared with the active alignment, there was a coupling loss penalty of approximately 3 dB on average. The alignment structures and assembly/gluing processes will be optimized in future research, and more efficient optical coupling will be achieved.

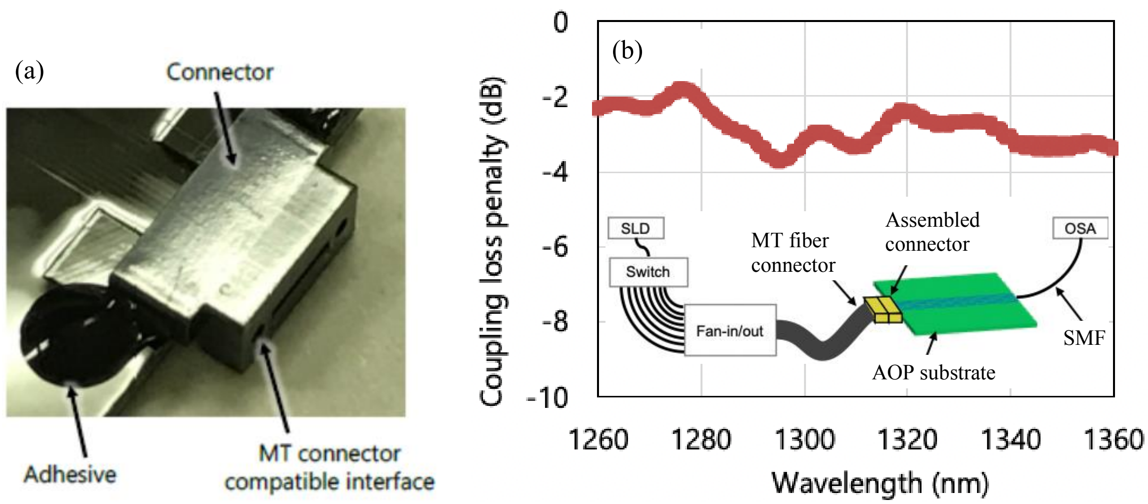

Figure 3. (a) Photographs and (b) measured coupling loss of the connector assembly.

4. Summary

To provide co-packaging technology for Si photonics dies that is compatible with standard LSI packaging processes, we have proposed a next-generation co-package substrate called the AOP substrate. Two coupling technologies for the AOP substrate were developed in this study and their results were presented. The mirror-based coupling technology of the Si and polymer waveguides was developed, and the broadband coupling characteristics over the S, C, and L-bands were demonstrated. We also demonstrated integration and assembly of the single-mode polymer waveguide and low-cost MT-connector.

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