Edge-Coupled Active and Passive Wafer-Scale Measurements on 300mm Silicon Photonics Wafers

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Abstract: We perform wafer-scale measurements of silicon photonics components using broadband (100nm+) edge couplers and reflecting optical fiber probes for the first time. We demonstrate <1dB/cm waveguide loss and 25GHz+ micro-ring modulators on 300mm wafers.

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1. Introduction

Optical Characterization of Photonic Integrated Circuits (PICs) is performed using either on-chip edge couplers or grating couplers to couple light from the fibers. The grating couplers allow for out-of-plane coupling of light onto PICs using a fiber positioned above the wafer surface, enabling simple scaling to full wafer characterization [1]. However, the grating couplers are formed using 1-dimensional periodic perturbations which trade-off optical bandwidth for insertion loss (IL). Further, optical communications require receiver PICs to operate with both polarization states of light which further reduces performance in complex 2-dimensional grating couplers [2]. The edge couplers address these performance trade-offs and limitations by facilitating in-plane coupling of light onto PICs using a horizontal fiber positioned at the die edges. Photonic foundries provide narrow etched areas around the dies as dicing trenches/streets for singulation which can be used to access edge couplers. The drawback is that the die edges are not fully accessible to a horizontal fiber on a complete wafer before die singulation. Previous attempts to address this drawback bent light by 90° using a 45° angle polished planar lightwave circuit (PLC) [3], or a 3D-printed optic on fiber [4]. Both of these probes are demonstrated on die-scale measurements with an IL of 5.7 dB [3] and 2.23 dB [4], respectively. Therefore, a solution that uses standard fiber arrays and demonstrates edge-coupled wafer-scale characterization is desired.

In this work, we demonstrate this solution, and present wafer-scale characterization of edge coupled silicon photonic devices on an undiced 300mm wafer for the first time. We build customized optical probes consisting of two angled polishes on a fiber array, which facilitate in-plane coupling to edge coupler, and minimize beam diffraction without additional optical elements. This probe was measured with a mean IL of 2.95 dB coupled to silicon photonics waveguides, and 0.03 dB polarization dependent loss (PDL) when it is butt-coupled to another probe. When two probes are used to edge-couple in and out of the die, the IL was repeatable within ±0.15 dB, enabling active (thermo-optical, electro-optical) and passive statistical characterization of to-be-packaged PICs. With these optical probes, we measure polarization dependent waveguide loss, and micro-ring modulators with tunable heaters across the 300mm silicon photonics wafer. We extract wafer-scale distributions of quality factors, thermo-optic (TO) and electro-optic (EO) parameters of these modulators, including record high EO tuning efficiencies at 9.39 GHz/V at -5 V across O-Band, and uniform bandwidth of ~25 GHz.

2. Optical Probe Design for Edge Coupling to Silicon Photonic Wafers

A schematic of the optical probe used for this work is shown in Fig. 1(a), where a common fiber array design consisting of a glass "frame" with v-grooves and "lid" is used. We polish through the frame and fiber at a 40.3° angle, reflecting light in-plane with the waveguide layer, allowing us to lower the probe into a dicing trench, and inject light into an edge coupler. To minimize mode mismatch to the edge coupler, we polish at 8° through the lid and fiber cladding, leaving <20 µm of cladding in the beam path. Probes are mounted onto XYZ piezo actuators on 6-axis hexapod positioners and lowered into place (Fig. 1(b)). This simple process can be scaled immediately to multiple and/or polarization maintaining fibers, seen in the next iteration of our design, a 16-channel probe with single-mode fiber, in Fig. 1(c). Future work will use this to probe PICs with complex optical I/O, and PIC arrays in parallel.

To measure the repeatability of the probe and system, we conduct a controlled experiment to mimic normal operation of automated wafer probing. We perform a custom semi-automated 6-axis power coupling optimization for each probe, and step the probes 15 µm from the chip facet. We then use machine vision to align the wafer reticle, optimize coupling lateral to the chip facets, measure insertion loss of the setup, move the wafer many reticles away, back into position, and repeat this custom automated sequence. This yields the normal distribution in Fig. 1(d) with $\sigma = 0.06$ dB; 98.1%

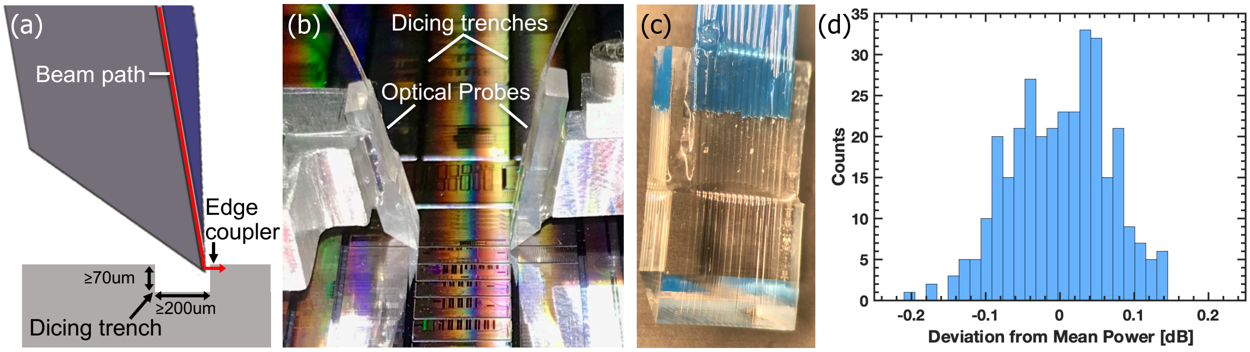

Fig. 1. *Optical Probe and Repeatability* (a) Optical probe side-view schematic showing first (40.3°) and second (8°) polishes. Light reflected from the polished facet is directed in plane with the waveguide layer and edge coupler. (b) Photograph of single-fiber probes in trenches. (c) Front-view photograph of 16-channel optical probe. (d) Histogram showing distribution of 2-probe automated return-to-position coupling loss repeatability.

of measurements are within 0.15 dB of the mean. The deviation may be the result of the chip-to-chip variations, mechanical misalignment of two optical probes, and the distance between the optical probes to the chip facet, leaving room for further optimization. To extract probe loss, we subtracted the mode-mismatch losses of the test site edge couplers (2xSMF28 to Chip ~2x3 dB), the waveguide losses (0.5 dB), and the fiber connector losses (2.1 dB) from the total (mean, wafer scale) setup loss (14.5 dB). The single probe loss is determined to be 2.95 dB. This edge coupler mode size was optimized for UHNA1 fiber, and future work will include using SMF28 fiber optimized to reduce coupling efficiency to 1 dB/facet [4].

To extract PDL and wavelength dependent loss (WDL) of the probes, we butt-coupled two optical probes to each other, adjusted input polarization, and measured spectra from 1250-1350 nm. We found the maximum WDL to be 0.02 dB/nm for both probes, and a maximum PDL of 0.06 dB per probe, with a mean of 0.03 dB per probe. When coupled to SMF28 fiber, optical probe IL was 1.1 dB, maximum WDL was 0.01 dB/nm, and PDL was below the ~0.1 dB noise floor, each of which are the lowest reported for any probe for this application, to date. The low WDL and PDL of these probes is ideal for broadband and dual polarization testing. An Analog Photonics Silicon Photonics PDK component library development site was laid out using a customized process at AIM Photonics on 300 mm silicon-on-insulator wafers [4], with wafer-scale measurement results of this test site using the optical probes found in the next section.

3. Measurement Results on 300 mm Silicon Photonic Wafers

We now move to wafer-scale electro-optic measurements of photonic components using the optical probes on 300 mm silicon-on-insulator wafers. We begin by taking the passive TE spectra of waveguides across the wafer. In Fig. 2(a), we see the results of a cutback measurement for Si rib waveguide width variations. The width of the top portion of the rib waveguide is varied (see inset). The narrower waveguides were found to have higher propagation loss, indicating the loss is induced by the fundamental TE mode interaction with the waveguide sidewalls [5]. We plot the same dataset as a function of radial position on the wafer in Fig. 2(b), for which each loss value is the mean loss across the spectrum (1240-1380 nm). We observe stronger radial dependence in narrow waveguides, depicted by a steeper fitted slope,

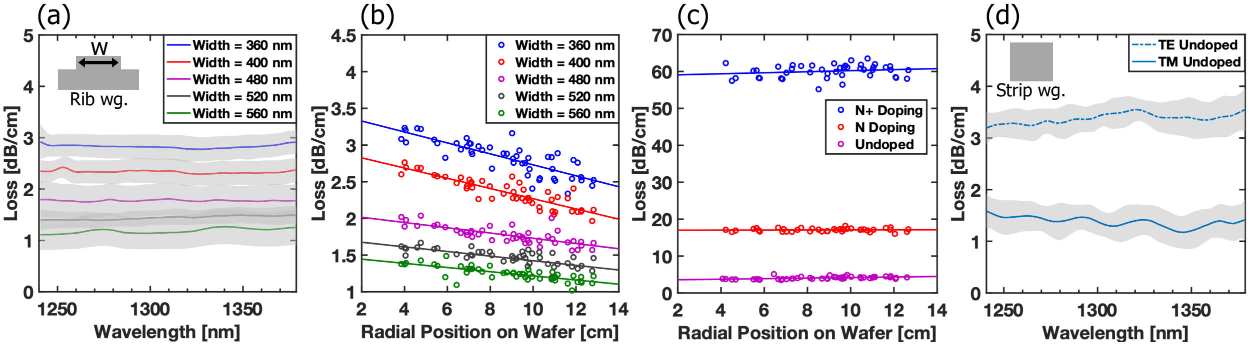

Fig. 2. *Wafer-scale waveguide measurements* (a) Rib Si waveguide loss for width variations. Inset: rib waveguide width diagram. For (a,d), each line denotes the wafer-scale mean loss over the measured wavelength range, and grey fill denotes ±1 std. dev. across wafer. (b) Rib Si waveguide width variation loss vs. radial position. (c) Strip Si waveguide doping loss vs. radial position. For (b,c), each data point represents a wafer reticle, averaged over wavelength. (d) Dual-polarization measurements for undoped strip Si waveguides.

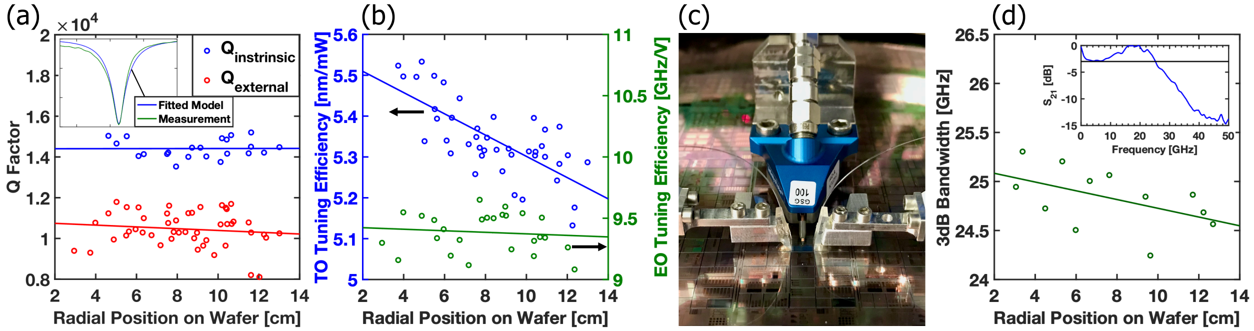

Fig. 3. *Wafer-scale micro-ring modulator measurements* (a) Micro-ring Q factors. Inset: example transmission spectrum with fitted model to extract Q factor. (b) Micro-ring modulator EO and TO tuning efficiencies. (c) Photograph of high speed EO measurement setup. (d) Micro-ring EO 3 dB bandwidth. Inset: S_{21} curve from single reticle; horizontal line shows 3 dB cutoff threshold. For (a,b,d), each data point represents a wafer reticle.

and higher variation of loss in narrow waveguides ($\sigma_{nonradial,360nm}$ = 0.13 dB/cm, $\sigma_{nonradial,560nm}$ = 0.06 dB/cm), again indicating mode-sidewall interaction. Importantly, waveguide loss for a 560 nm wide rib core was measured to be <1.5 dB/cm across the O-Band on the 300 mm wafer.

Waveguide loss vs. doping concentration is shown in Fig. 2(c). We observe a uniform distribution of waveguide loss for the doped waveguides across the wafer. The implant conditions are maintained well across the wafer which is also verified separately by sheet resistance measurements. In Fig. 2(d), we demonstrate the capability of the optical probes to couple both TE and TM light into edge couplers and test components for both polarization states, here using strip waveguide cutback structures. The polarization dependent loss on strip waveguides across the O-Band are measured to be ~2 dB using the optical probes, paving the path to use edge couplers for production chipsets.

Next, we measure custom micro-ring modulators with integrated EO junctions for modulation and TO heaters for tuning. In Fig. 3(a) (extracted from passive spectra), the radial dependence of both coupling ($Q_{external}$) and intrinsic losses due to waveguide roughness, radial bend, junction and heater ($Q_{intrinsic}$) are uniform across the wafer. A -5 V bias was applied to junctions, and a 4 V bias (a mean of 7.6 mW) to heaters, with extracted ring resonance tuning efficiency shown in Fig. 3(b). The mean large-signal EO tuning efficiency across the wafer (9.39 GHz/V) is the highest measured in O-Band at 47 GHz, to date. The mean TO tuning efficiency is found to be 5.3 nm/mW. Both TO and EO efficiencies exhibited weak radial dependencies. The TO tuning efficiency's more noticeable but small radial dependence (0.24 nm) is on par with non-radial variation (0.23 nm) which we attribute to measurement inaccuracy.

Finally, we demonstrate wafer-scale high-speed EO testing using a 3-pin RF probe and two optical probes (Fig. 3(c)). S-parameters were extracted for a wavelength offset of +0.082 nm from the resonance dip (i.e. minimum power), selected to optimize RF power at 25 GHz. A -1 V DC bias and 0.8 Vpp RF signal was applied to the EO modulator of the device using a Keysight N4373D LCA, yielding EO S21 measurements as shown in the inset of Fig. 3(d). 3 dB bandwidth of the RF response was extracted to be 25 GHz across the wafer. We see a radial dependence of 0.43 GHz, and a non-radial variation of 0.78 GHz, showing good uniformity of modulator bandwidth across the wafer.

4. Conclusion

We have demonstrated high-repeatability usage (±0.15 dB) of an edge-coupling optical probe on the wafer-scale. This probe was created using a double-polished fiber array that offers efficient edge coupling with low polarization dependence. In conjunction with electrical probes, we can reliably measure EO characteristics of arbitrary photonic devices and systems, and did so using micro-ring modulators with record high performances. This work realizes an industry-first method for wafer-scale silicon PIC yielding, enabling rapid testing of the complete set of devices included in final packaging of product. This method can be extended to measure statistical variations of PDK component libraries and silicon photonic products with edge couplers on any undiced wafer.

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