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Expanded-Beam Backside Coupling Interface for Alignment-Tolerant Packaging of Silicon Photonics

Nivesh Mangal, Bradley Snyder, Joris Van Campenhout, Geert Van Steenberge, and Jeroen Missinne

Abstract—We demonstrate an alignment-tolerant backside coupling interface in the O-band for silicon photonics by generating an optimized through-substrate (downward) directionality beam from a TE-mode grating coupler and hybrid integrating the chip with backside silicon microlenses to achieve expanded beam collimation. The key advantage of using such an expanded beam interface is an increased coupling tolerance to lateral and longitudinal misalignment. A $34\ \mu\text{m}$ beam diameter was achieved over a combined substrate thickness of $630\ \mu\text{m}$ which was then coupled to a thermally expanded core single-mode fiber to investigate the tolerances. A 1-dB fiber-to-microlens lateral alignment tolerance of $14\ \mu\text{m}$ and an angular alignment tolerance of 1° was measured at a wavelength of $1310\ \text{nm}$. In addition, a large $\pm 2.5\ \mu\text{m}$ 1-dB backside alignment accuracy was measured for the placement of microlens with respect to the grating. The radius of curvature of Si microlens to achieve a collimated beam was $480\ \mu\text{m}$, and a 1-dB longitudinal alignment tolerance of $700\ \mu\text{m}$ was measured for coupling to a single-mode expanded core fiber. The relaxation in alignment tolerances make the demonstrated coupling interface suitable for chip-to-package or chip-to-board coupling.

Index Terms—Optical Interposer; Silicon Photonics; Microlenses; Collimator; Expanded Core Fibers; Grating Couplers.

I. INTRODUCTION

WITH a growing need for higher capacity and performance in the datacenters, single-mode optics is projected to surpass the multimode-optics based solutions in the next decade for short-reach distances. Silicon photonics technology will be at the forefront to cater to this demand bringing single-mode transmission, dense integration and wavelength division multiplexing capabilities along with it. There has been a rapid increase in the number of CMOS-based wafer-scale manufacturing fabs providing access to silicon photonics design services [1] and this investment is in sync with the expectation of the volume of silicon photonics based components needed, out of which a significant portion is going to be absorbed in the datacenter market [2]. Packaging is one of the primary contributing factor in increasing the overall cost of a silicon photonics based transceiver [3], [4]. Several processes such as manual assembly, fiber attachment, reliability testing etc. contribute to a throughput that is far less than the practical requirement [5], [6]. Thus, a significant

price point advantage gained from a CMOS-like wafer-scale platform, is totally lost. For example, a typical fiber attachment process on a photonics die consists of actively aligning an optical fiber array to edge couplers or grating couplers, and then glue-cure it to the die, which is time-consuming and affects the throughput of a manufacturing facility looking to ship thousands of components a day. This is because an optical signal when coupled out of a grating coupler, that is usually mode-matched to a standard single-mode fiber, at best, provides a $\pm 2.5\ \mu\text{m}$ lateral alignment tolerance [7] that necessitates an active alignment driven fiber-array packaging. Similarly, a photonics chip assembled via a solder-reflow based approach can easily encounter several microns of lateral displacement that can impact the coupling performance of the component if the receiving end of the coupling component is fixed (e.g. a readout system for sensing or a detector for chip-to-board coupling), although some efforts have been made towards solder reflow compatibility recently [4].

Hence, a passive alignment based strategy is needed that can be low-cost, scalable, generic to any material platform, mass deployable and if possible, enable solutions for pluggable optics as well. In order to realize this, the optical mode from the coupling interface needs to be expanded to achieve a relaxed lateral alignment tolerance. As shown in Fig. 1, one can obtain a 3x improvement in the lateral alignment tolerance with an expanded mode diameter of $34\ \mu\text{m}$ when compared to a standard fiber mode diameter of $9.2\ \mu\text{m}$. It is also well understood that this comes at the expense of an increase in sensitivity to angular misalignment, which is however relatively easier to control than lateral misalignment with an appropriate mechanical design during assembly as long as it is above a 0.1° -limit [8]. For fiber-coupled lasers, beam expansion/collimation is usually achieved by integrating hemispherical lenses at the tip of the fiber [9], [10] or with the use of a ball lens [11], [12]. On-chip beam expansion has been recently demonstrated using both edge couplers with 3D-printed optics [13] and grating couplers combined with mounted microlens array blocks [14], ball-lens [15] or polymer microlens [16]. In order to truly leverage the expanded beam concept, a more scalable approach is required in which the optics can be incorporated monolithically at a wafer-scale using passive alignment.

Therefore, we have proposed to integrate microlenses at the backside of an integrated photonics chip to collimate the expanded beam resulting in a relaxed tolerance to both lateral and longitudinal misalignment (Fig. 2a) [16], [17]. Additionally, by using such a through-substrate coupling scheme, the device side (top-side) of the chip remains accessible for any additional

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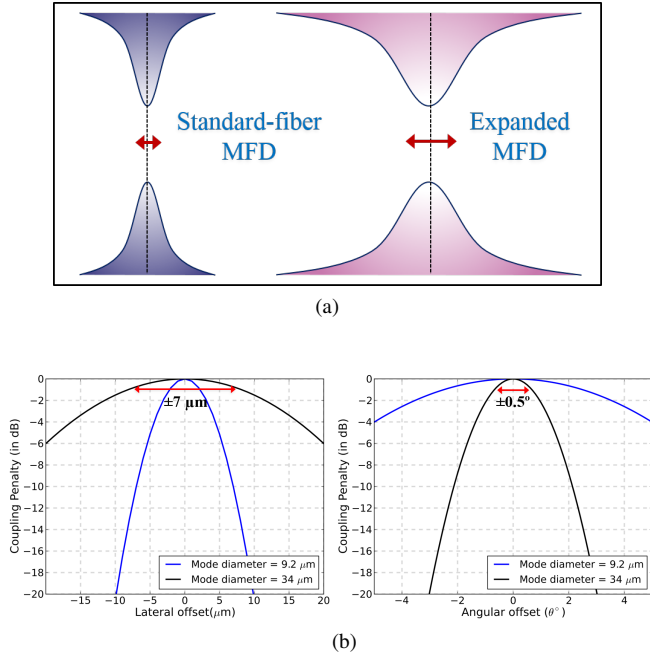


Fig. 1: An expanded mode-field diameter provides a few orders (2-3x) of improvement in lateral alignment tolerance at the expense of a reduced (0.25-0.5x) angular alignment tolerance.

fiber-array packaging and die stacking for 2.5D/3D electro-optic integration (Fig. 2b). Alternatively, such an interface can be utilized for coupling to a lensed fiber array with relaxed alignment tolerances (Fig. 2c). Finally, this approach would be beneficial for various sensing applications since the device topside can be kept clear to allow the photonic circuit to interact with biomarkers or trace gas molecules. Although we have presented initial results for monolithically integrated microlenses in combination with C-band grating couplers earlier [17], the current paper (i) targets O-band grating couplers and (ii) aims at investigating in detail the tolerances and individual contributions to the coupling loss of such a backside expanded beam interface. This is achieved by hybrid integrating a silicon microlens and a photonics chip consisting of a downward directionality based O-band grating coupler. (Fig. 3).

II. DESIGN FOR EXPANDED BEAM COUPLING

The hybrid integrated photonics chip and microlens assembly is comprised of a $100 \mu\text{m}$ thinned and backside polished silicon photonics chip and a separately fabricated silicon microlens array on a dual-side polished silicon substrate of $530 \mu\text{m}$ thickness (Fig. 3). The grating couplers fabricated on the topside of the chip diffract the TE-polarized waveguide mode at an angle of 2.81° in silicon in a downward direction through the SOI wafer substrate. To achieve downward directionality, Ti/Al metal reflectors were deposited on the oxide cladding above the grating at a particular oxide thickness to obtain a constructive interference between the downward diffracted and metal-reflected mode. An optimal oxide thickness of $2 \mu\text{m}$ between the grating and the metal reflector was used to achieve

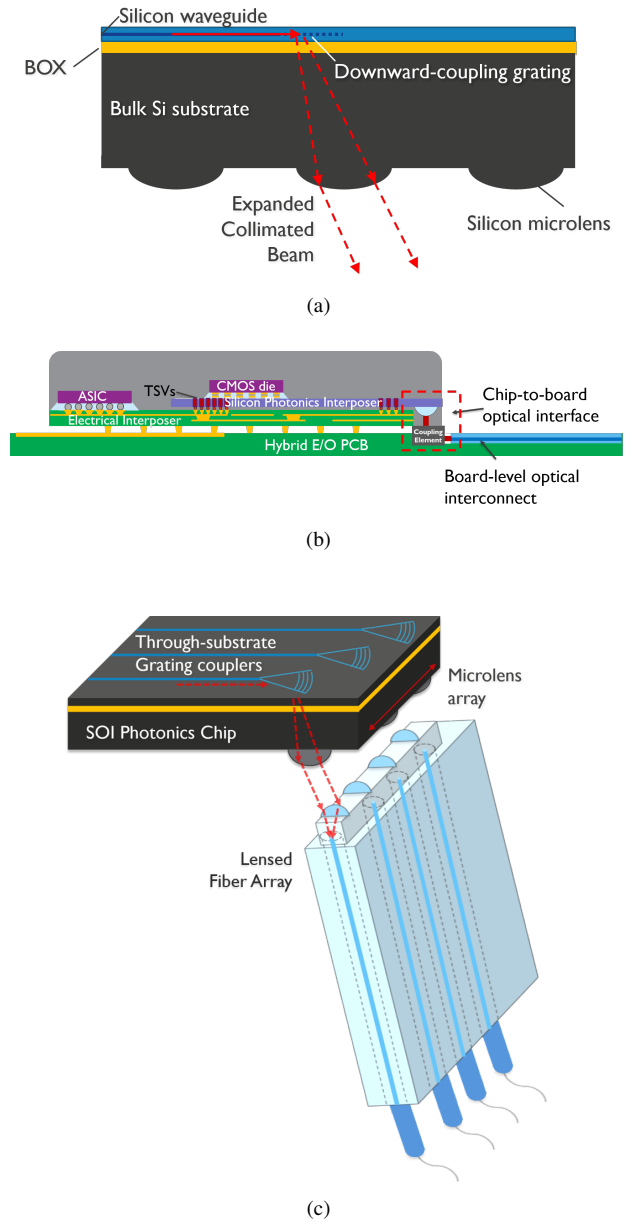


Fig. 2: (a) An overview of photonics chip expanded-beam coupling interface; (b) Application example 1: 2.5D/3D face-up integration of silicon photonics with lensed-backside coupling interface for chip-to-board coupling; (c) Application example 2: Photonics chip-to-microlensed fiber-array coupling.

this constructive interference for a wavelength of 1310 nm which was derived by performing 2D finite-difference time-domain (FDTD) simulations [18].

In order to derive the parameters of the microlens for expanded beam collimation, a ray-trace model was developed using Zemax. A $650 \mu\text{m}$ thickness of the Si substrate was taken as a total thickness of the chip substrate and microlens-fabricated Si substrate in the model, which allows for sufficient expansion of the incoming diffracted beam from the output grating coupler. The far-field divergence and primary angle of diffraction of the output grating coupler obtained via FDTD

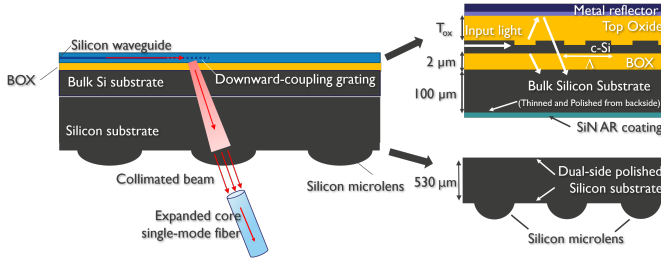


Fig. 3: Hybrid integration of silicon microlenses with a photonics chip comprised of through-substrate grating couplers. The expanded-collimated beam is coupled into a thermally expanded core single-mode fiber to investigate various alignment tolerances.

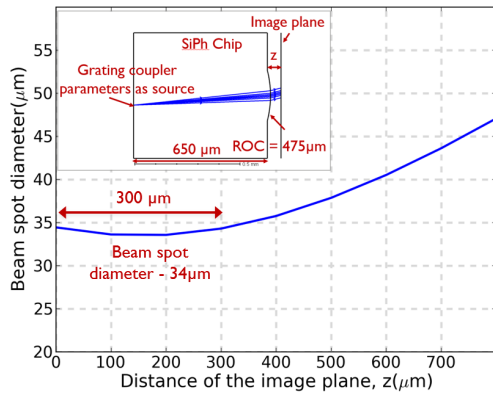


Fig. 4: A 475 μm radius of curvature was determined from the ray-trace model to result in a collimated range of 300 μm for a constant expanded beam diameter of 34 μm (Rayleigh range - 700 μm). From a single-mode coupling standpoint, a 300 μm range provides for a relaxed longitudinal alignment tolerance for chip-to-board coupling with a negligible coupling loss.

simulations, was defined in the ray source of the model. Although the field profile from a uniformly periodic diffraction grating is exponentially decaying, it was assumed to be Gaussian in the ray-trace model. Using the beam-propagation analysis within the ray-trace model, a parameter sweep for the radius of curvature (ROC) of the lens was performed to yield an optimal value of 475 μm for a lens diameter of 250 μm and achieving a collimation distance of 300 μm with a beam waist diameter of 34 μm . The Rayleigh range of the beam is about 700 μm , with the waist of the beam placed 150 μm away from the vertex of the lens. With the typical chip-to-board distance ranging between few hundreds of microns, this scheme for expanded beam collimation can help in achieving negligible coupling loss due to reduced mode mismatch in the longitudinal (mode-propagation) direction (Fig. 4).

III. DEVICE FABRICATION

The photonic die used to perform the grating coupler measurement was obtained from a wafer fabricated in imec's 200 mm Si Photonics pilot line. The die was further post-processed to deposit 5 nm Ti + 200 nm Al reflector on the

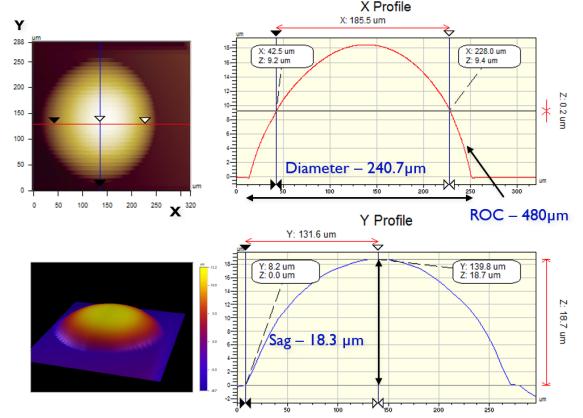


Fig. 5: A 2D surface profilometry scan of microlens post-etch was performed to determine the resulting diameter, sag and radius of curvature of the microlens.

top oxide above the grating. The die was then temporarily bonded onto a glass carrier to perform substrate-side lapping and polishing starting with a thickness of 650 μm to a final value of 100 μm . After releasing the die from the glass carrier, a 170 nm SiN anti-reflective (AR) coating was deposited on the polished backside of the chip. For the fabrication of microlenses, Microchem AZ4562 resist was spun on top of a 530 μm thick dual-side polished silicon substrate. After UV-patterning and development of the exposed resist, the obtained cylindrical structures were thermally reflowed, followed by a hard-bake. The reflowed microlens profiles in resist were then transferred to silicon by a reactive-ion etch (RIE) process with an optimized composition of SF₆ and O₂ [17]. A 3D-surface white light profilometry was performed to verify the fabricated microlenses, which had a diameter of 240.7 μm , lens height (sag) of 18.3 μm and a radius of curvature of 480 μm , which corresponded very closely to the desired specs obtained from the beam propagation simulations in the ray-trace model (Fig. 5). Also, the rms surface roughness of ~ 10 nm was obtained over the fabricated microlenses in silicon.

IV. EXPERIMENT AND RESULTS

An angled-polished fiber was glue-cured to the input grating coupler from the topside on the photonics die by performing active alignment and UV-curing NOA-61 underneath it [19]. The input fiber attachment to the photonics chip enabled us to investigate the alignment tolerance of the output grating with the fabricated microlenses. A broadband O-band SLD source was used to launch the optical signal into the input fiber. The fiber-attached photonics die was then flipped and brought underneath the substrate on which the microlenses were fabricated (Fig. 6a). A thermally expanded core single-mode fiber (TEC40 - 34 μm mode field diameter) was brought close to the microlens to couple the output signal to a fiber beam-splitter connected to a power meter and an optical spectrum analyzer. A thermally expanded core (TEC) fiber has an enlarged mode field diameter obtained by locally heating a single-mode fiber at high temperature, which causes a redistribution of dopants while maintaining the condition for

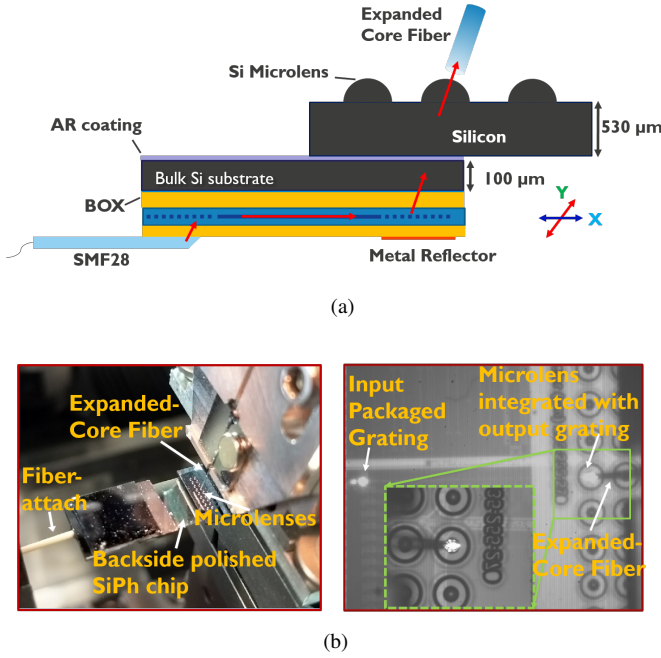


Fig. 6: (a) By actively aligning the photonics die with the far-side of the microlens-fabricated silicon substrate, coupling analysis of the optical output from the microlens with an expanded core single-mode fiber was performed; (b) (Left) An expanded-beam collimation experiment with a microlens-integrated Silicon Photonics module. (Right) IR image seen from the backside of the integrated assembly.

single-mode operation [20]. By actively aligning both the fiber and the photonic chip with respect to the microlens, an optimal coupling efficiency was obtained (Fig. 6). As shown in Fig. 7, the fiber-to-microlens coupling efficiency was compared to the case when a standard single-mode fiber (SMF28) was directly coupled to the output grating coupler from the backside of a 100 μm thinned photonics chip, keeping the same input conditions on the packaged grating coupler. A 3 dB drop in the coupling efficiency was measured, out of which a 1.85 dB loss contribution was due to the Fresnel reflections from the silicon-air and fiber-air interface. This can be corrected by the use of an anti-reflective coating on the microlenses, similar to what was done on the polished backside of the photonics die. In addition, the thickness of the AR coating deposited on the backside of the photonics chip was off by -30 nm from the target value (170 nm) resulting in some ripples in the spectrum. Also, the two actively aligned components were not bonded in order to study the respective alignment tolerances. This would have resulted in the presence of a very narrow air gap between the two components contributing to some additional loss. Lastly, a decrement in the fiber-to-fiber spectral bandwidth can be attributed to a low NA (0.02) of the TEC40 fiber. Although the focus of the paper is to investigate the alignment tolerances, it is interesting to tabulate the measured and estimated optical loss distribution across the expanded beam interface, listing the corrective measures needed for further improvement (Table I).

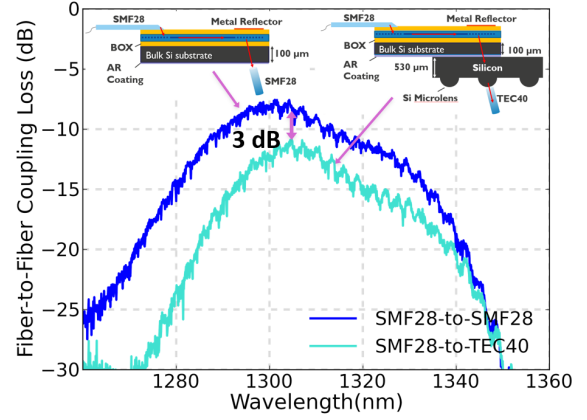


Fig. 7: A 3 dB drop in coupling efficiency was measured after hybrid integrating the microlens on the backside of the chip. Out of this, a 1.85 dB Fresnel loss occurred from the Si microlens-air and air-fiber interface.

TABLE I: Optical loss distribution across the expanded beam interface

Interface	Loss (dB)	Estimated Loss After Further Optimization (dB)	Corrective Measures
Fiber-attached input grating	4.5	2.5	Raised Grating Couplers [21]
Output Grating	3.5	1.5	Improvement in directionality [22]
Fresnel Loss	1.85	0	AR coating on microlenses
Loss due to phase mismatch/microlens	1.15	1	Needs further investigation
Net Loss	11	5	

In order to investigate the tolerances arising out of the placement of the microlens with respect to the output grating coupler, if it were to be monolithically fabricated on the chip backside [17], a lateral alignment of the photonic chip was performed with respect to the microlens substrate, keeping the output fiber position fixed. A $\pm 2.5 \mu\text{m}$ lateral 1-dB alignment tolerance was measured between the grating and the microlens (Fig. 8a). From a standpoint of fabricating microlenses monolithically on the backside of a silicon photonics wafer, a relative misalignment between the grating and microlens will result in a lateral and angular shift of the optical beam relative to its optimum coupling position, thereby contributing to an additional coupling loss and an undesirable shift in the grating coupler spectrum. In this context, a large value of $\pm 2.5 \mu\text{m}$ holds good considering a sub-100 nm level overlay accuracy acceptable with the dual-sided aligners used in conventional lithography processes in wafer-scale manufacturing [23]. Next, with an optimum microlens to grating alignment, the tolerances (lateral and angular) arising out of coupling an expanded mode diameter of 34 μm to a thermally expanded core fiber (TEC40) were investigated. A $\pm 7 \mu\text{m}$ lateral and a $\pm 0.5^\circ$ angular 1-dB alignment tolerance was measured between the

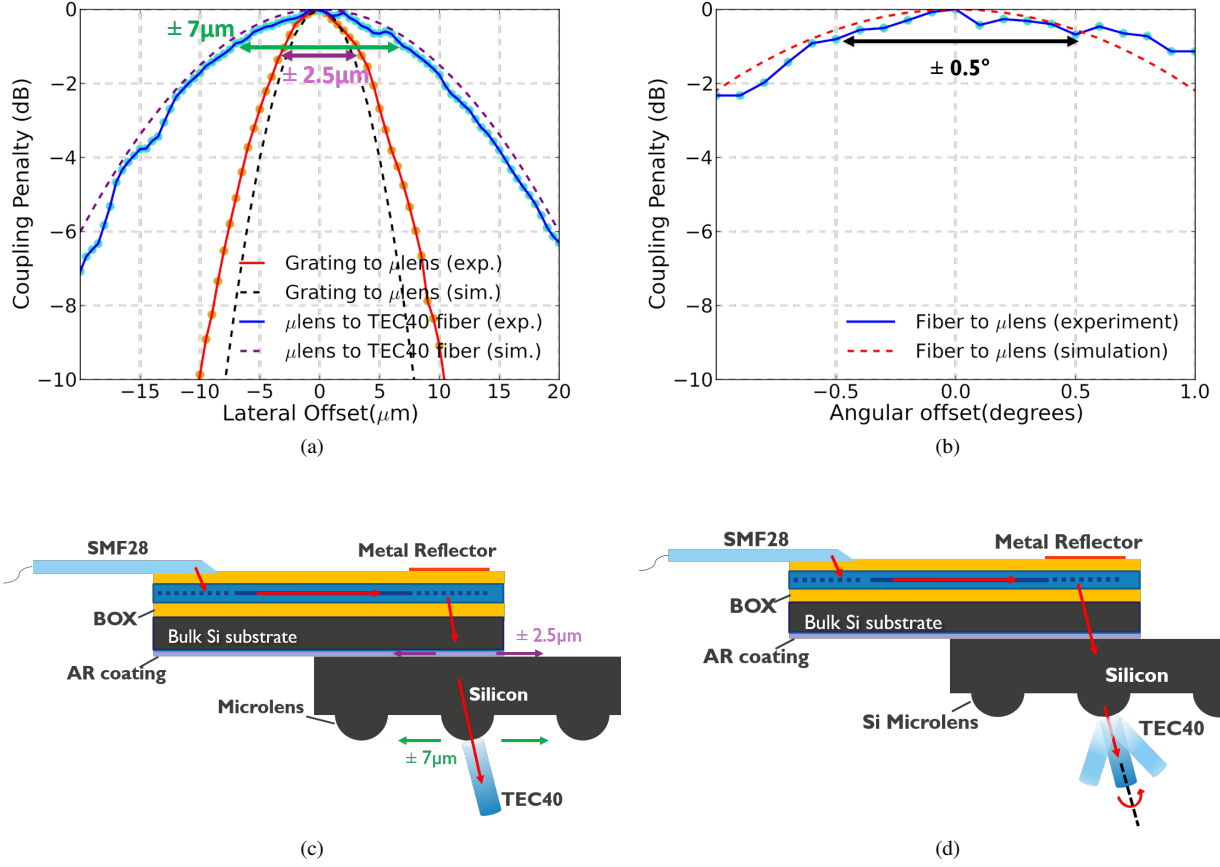


Fig. 8: (a) A $\pm 7\mu\text{m}$ lateral and (b) $\pm 0.5^\circ$ angular 1-dB alignment tolerance was measured between an expanded mode coupled from the microlens to a single-mode expanded-core fiber; Schematics (c) and (d) illustrate the methodology of the corresponding measurements.

microlens and the expanded core fiber (Fig. 8a and 8b). A 3-dB lateral alignment tolerance extends this limit to $\pm 12.5\mu\text{m}$. These values match well with the expected alignment tolerance (lateral and angular) simulated under the Gaussian approximation.

Lastly, the expanded core fiber was retracted away from the microlens vertex successively in steps of $100\mu\text{m}$ along the axis of the output beam and the fiber-to-microlens coupling efficiency was recorded at a fixed wavelength of 1310 nm . Fig. 9 shows that a negligible drop in the coupling efficiency was measured over a distance of $300\mu\text{m}$, which indicates that the expanded beam was collimated. An additional point to note here is that the NA of the expanded-core fiber (TEC40) was 0.02 compared to 0.14 of a standard single-mode fiber (SMF28). This implies that an expanded core fiber would have been far more sensitive to couple to a divergent beam and hence, a drop in coupling efficiency would have been measured in the range of the specified distance here, if the optical beam from the microlens wouldn't have been collimated. Moreover, a 1-dB longitudinal alignment tolerance over a distance of $700\mu\text{m}$ was measured as expected from the Gaussian beam propagation simulations in the ray-trace model.

Hence, a longitudinal tolerance range of this magnitude makes the demonstrated coupling interface an attractive proposition to perform chip-to-board coupling for face-up integration of silicon photonics interposer in the future (Fig. 2b).

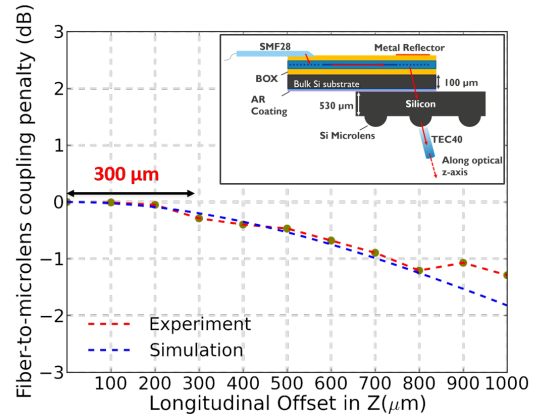


Fig. 9: By retracting the fiber along the axis of propagation of the collimated beam, a negligible drop in the coupling efficiency was measured over a distance of $300\mu\text{m}$.

V. CONCLUSION

We have reported for the first time a detailed investigation of the tolerances involved in hybrid integrating silicon microlenses on the backside of a photonics chip comprised of an O-band grating coupler with downward directionality. The microlenses with a low rms roughness were fabricated on a dual-side polished silicon substrate. An expanded beam of 34 μm mode-field diameter was achieved that was collimated over a distance of 300 μm with a negligible drop in coupling loss when coupled to a thermally expanded core single-mode fiber. A 1-dB fiber-to-microlens lateral and longitudinal alignment tolerances of $\pm 7 \mu\text{m}$ and 700 μm respectively were obtained at a wavelength of 1310 nm. We also show that a downward directionality based expanded beam coupling interface is compatible with wafer-scale manufacturing process owing to a relatively large measured $\pm 2.5 \mu\text{m}$ 1-dB backside alignment accuracy between a grating and microlens. These relaxed alignment tolerance values pave the way for monolithically integrating these microlenses at the backside of a photonics chip in the near future.

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