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Comparing Laser Hybrid-Integration and Fiber Coupling with Standard Grating Couplers on Si-PICs

L. Zagaglia, F. Floris, L. Carroll, and P. O’Brien

Abstract—We compare the simulated optical insertion-losses and fabrication-tolerances of a micro-optical bench (MOB) for laser hybrid-integration on the 220nm Silicon-on-Insulator (SOI) photonic-platform to standard fiber-to-grating coupling. Our millimeter-scale two-dimensional finite difference time domain (2D-FDTD) simulation captures (i) aberration, (ii) reflection, (iii) diffraction, and (iv) wave-guiding effects in a single-shot and completely self-consistent way, indicating that light from a laser-diode can be coupled to the SOI photonic integrated circuit (PIC) with a 2.8 dB insertion-loss at 1550nm. This insertion loss is just 1 dB higher than for a standard Fiber-to-PIC grating-coupler, and is due to a combination of interface-reflections and aberration-effects from the micro-optical elements in the MOB. We use further 2D-FDTD simulations to investigate the alignment and manufacturing tolerances of the MOB, and show that these are compatible with practical photonic-packaging processes for mass-manufacture.

Index Terms—Integrated circuit packaging, Laser applications, Optical fibers.

I. INTRODUCTION

Re-deployment of complementary metal oxide semiconductor (CMOS) technologies, which were developed and optimized for the electronics industry, for photonic applications has created a credible route to mass-manufacturable Si-photonic devices to address communications and sensing mass-markets [1, 2]. In addition, the growing availability of multi-project wafer (MPW) photonic-foundry services, which offer a rich catalogue of passive and active building-blocks, has served to de-risk the design and fabrication of photonic integrated circuits (PICs). In addition, the high refractive-index contrast of the silicon-on-insulator (SOI) platform allows for very small photonic components, which means that many devices can be harvested from a single dedicated SOI-wafer, e.g. \(10^7\) (2mm \(\times\) 2mm) devices can be realized on a 300mm wafer [3].

While Fiber-to-PIC edge- and grating-coupling are often useful means of delivering light to the SOI-PIC, for certain applications an on-PIC light-source is preferred, especially in the medical- and sensing-spaces, where (i) there is often no need to integrate the photonic device into telecom or datacom fiber-network and (ii) having a small and handy packaged device with its own embedded source is vital. Given that Si is an indirect band-gap material, it is not trivial to develop an efficient intrinsic, or monolithically-grown, light-source on the SOI-platform.

Different schemes for heterogeneous integration of III-V materials on SOI have been demonstrated, such as transfer-printing [4] or wafer-bonding [5, 6] and hybrid laser-integration can also be efficient and cost-effective due to a better scalability giving a further advantage for mass markets. In the hybrid approach, a stand-alone “known good” laser-diode is opto-mechanically coupled to the SOI-PIC, using either an edge-coupling scheme [7], micro-optic coupling to gratings [8, 9], or direct chip-to-chip coupling to gratings [10]. In the case of grating-coupling, a micro-optical bench (MOB) can be used to match the mode-field diameter (MFD) and numerical aperture (NA) of the diffraction-limited laser-diode emission to that of the approximately \(10\mu m \times 10\mu m\) acceptance-footprint of standard SOI grating-couplers available from the photonic-foundries. The MOB acts to relax hybrid laser-integration alignment tolerances to approximately \(\pm2.5\mu m\) (1dB) [11], which is compatible with practical manufacturing and photonic-packaging processes [12].

In this paper, we show how millimeter-scale two dimensional finite difference time domain (2D-FDTD) simulations can be used to capture the full physics of laser hybrid-integration on the SOI-platform, which consists of (i) the propagation of the laser-mode through the micro-optics of the MOB, and (ii) the diffraction of the MOB-mode, incident on the grating-coupler, into the waveguides of the SOI-PIC, all in a single-shot simulation. These simulations allow the whole laser-to-waveguide insertion-loss to be calculated, and compared to that of a standard Fiber-to-PIC grating-coupler. Despite the spherical-aberration introduced by the micro-lens and the interface-reflections from the micro-lens and micro-prism in the MOB, a Laser-to-PIC total insertion-loss of 2.8dB is possible, which is just 1dB higher than the Fiber-to-PIC insertion-loss, using exactly the same grating-coupler design. Further 2D-FDTD simulation campaigns are used to investigate the alignment and manufacturing tolerances of the MOB, and the results indicating that they are compatible with practical photonics-packaging processes, such as UV-curing gluing, flip-chip and precision PIC and place.

II. MOB DESIGN AND SIMULATION

Fig. 1(a) shows a scheme of Fiber-to-PIC, and MOB-based Laser-to-PIC coupling. Standard grating-couplers available from the process design kits (PDKs) of the photonic foundries are designed to accept
emission intensity profile with a MFD of 10.4 μm, which is the benchmark used to model the fiber emission through a Gaussian source in the 2D-FDTD simulation - see Fig. 1(b). These standard grating-couplers are not well-matched to accept the beam-profile from a typical laser-diode, which has a diffraction-limited emission from a waveguide region with a typical cross-section on the order of \( 2 \, \mu m \times 1 \, \mu m \) - see Fig. 1(c). The micro-optics of the MOB act to facilitate mode-matching between the laser-diode and the grating-coupler in two ways - (i) the ball-lens images the laser-mode on the grating-coupler with the required 10 μm–MFD - see Fig. 1(d), and (ii) the micro-prism ensures that the imaged laser-mode is incident on the grating-coupler with the required angle-of-incidence (AOI) of approximately 10°.

Fig. 2(a) shows the design-parameters of our simulated MOB - (i) a 110 μm thick laser-diode with full-angle (\(1/e^2\)) vertical-divergence of 28° [13], (ii) a 300 μm- diameter fused-silica (\(n_\text{FS} = 1.44\)) ball-lens, (iii) a 300 μm-height fused-silica micro-prism, polished to a 40° angle, and (iv) a 250 μm-thick AlN-ceramic sub-mount with a cut-out below the prism to allow the re-imaged laser-mode access to the grating-coupler on the SOI-PIC. These design-parameters are typical of an existing MOB designs [9].

The design-parameters of the grating-coupler in our simulations are – (i) a 220nm SOI-layer, (ii) a 160nm poly-Si overlay, (iii) a 230nm etch-depth, i.e. the full poly-Si overlay, plus 70nm of the SOI-layer, (iv) a 30% duty-cycle, (v) a 2.0 μm bottom-oxide layer (BOX), and (vi) a 1.3 μm top-oxide layer (TOX) – see Fig. 2(b). These parameters are known to be the basis for the standard 1550nm TE-polarized grating-couplers, designed for an angle-of-incidence (AOI) of 10° that are offered by the IMEC MPW Si-Photonic foundry service [14]. Ray-tracing software, such as Zemax™ [15], is typically used to model light-propagation through micro-optic systems, like the MOB [9]. However, these ray-tracing models use geometric-optic rules and empirical algorithms, rather than a true physics-engine, to generate solutions. In this work, we exclusively use 2D-FDTD simulations to optimize the MOB design, evaluate the Laser-to-PIC insertion-loss, and determine the alignment and manufacturing tolerances. An FDTD simulation makes no underlying assumptions or simplifications about the micro-optic elements in the MOB or the properties of the grating-coupler; it simply propagates light through the designated simulation-space in accordance with Maxwell’s equations. As a result, the accuracy of a properly defined FDTD simulation depends only on how finely “meshed” is the simulation-space, which is practically limited only by the memory and processing speed of the computer running the simulation. We used commercially available *Lumerical® FDTD Solutions™* [16] to run millimeter-scale 2D-FDTD simulations, to capture the full physics of the laser-mode propagation through the micro-optics of the MOB, and the diffraction at the grating-coupler, in order to evaluate the Laser-to-PIC Insertion Loss (IL) - see Fig 2.

A convergence test identified the minimum meshing-density needed for the simulations, and an auto-generated non-uniform mesh (on the order of 30nm × 30nm at the grating-coupler, and 80nm × 80nm at the micro-lens) was found to be adequate. The 850μm × 550μm 2D-FDTD simulation used to describe the MOB takes 3 hours to run on a PC with a liquid-cooled 16-core processor and 64GB of RAM. Clearly, this large 2D-FDTD simulation captures only the divergence of the laser-diode and the focusing-effect of the micro-lens in the x-y plane, but these are the parameters that most directly affect the Laser-to-PIC IL value, because they determine the phase-front of the focused mode across the diffractive-elements of the grating-coupler [17]. In contrast, divergence and focusing in
the “missing” x-z plane of the 2D-FDTD simulation only affects the size of the focused mode along the diffractive-elements of the grating-coupler, which can be easily managed by tuning the width of the coupler.

As shown in Fig. 2, light is “injected” into the 2D-FDTD simulation from a Gaussian-mode source with a MFD and NA consistent with that of a commercial laser-diode [13], propagates through the micro-optic ball-lens, undergoes total internal reflection (TIR) at the polished-facet of the micro-prism, exits and refracts at the bottom-facet of the micro-prism with an angle of \( \theta_{\text{GR}} = 14.5^\circ \), and is focused onto the TOX-layer of the PIC, where it undergoes a second refraction effect to be incident on the grating-coupler with an AOI of \( \theta_{\text{GC}} = 10^\circ \). To facilitate passive-alignment during its fabrication, the MOB design calls for the micro-prism to be pushed into physical contact with the ball-lens.

To reduce manufacturing costs, the MOB design should also use a “standard” AlN ceramic thickness, i.e. 250µm. As a consequence, the only design-parameter that can be used to tune the size of the focused-mode on the grating coupler is the Laser-to-Lens distance (P). A series of 2D-FDTD simulations were used to identify the value of P that offered the best Laser-to-PIC insertion-loss for the above MOB design. As shown in Fig. 3(a), the optimum MOB design, with P = 195µm, offers an insertion-loss of 2.8dB at 1550nm with a standard grating-coupler.

III. MOB INSERTION LOSSES AND TOLERANCES

Fig. 3(a) compares the spectra of both Fiber-to-PIC and Laser-to-PIC coupling using identical standard grating-couplers.

Fiber-to-PIC coupling offers an insertion-loss of 1.8dB at the target wavelength of 1550nm, indicating an MOB performance-penalty of 1.0dB. Thanks to our millimeter-scale 2D-FDTD simulation, able to capture the whole physics behind aberration, reflection and diffraction in the light propagation in the MOB, we can attribute this approximately 20% reduction in coupling to two effects: (i) reflections at the multiple air-to-glass interfaces for about 12%, and (ii) reduced modal-overlap of the focused-mode on the grating-coupler due to spherical-aberration effects for around 8%.

The losses from interface-reflections can be easily minimized by using suitable anti-reflection coatings while designing a grating-coupler that can accommodate the extended spot-size and variable phase-front of the spherically-aberrated focused mode will be more challenging. However, the same particle swarm optimization and genetic-algorithm techniques that have been successfully used to develop chirped and apodized grating-couplers can likely be repurposed to this task [18, 19].

The Laser-to-PIC coupling spectrum in Fig. 3(a) is for a perfectly fabricated MOB that is perfectly aligned over the grating-coupler. To investigate the alignment tolerances of the MOB, and compare them to direct Fiber-to-PIC coupling, a campaign of 2D-FDTD simulations were used, in which horizontal (\( \Delta x \)) and vertical (\( \Delta y \)) offsets were applied to the ideal MOB (and fiber) positions.

Fig. 3(b) shows that both the MOB and Fiber have a comparable 1dB horizontal alignment tolerance of \( \pm 5.2 \mu m \), which is compatible with epoxy-bonding of the MOB to the surface of the PIC, after an active-alignment step. The 1dB limit in the tolerances is considered being the benchmark for alignment processes in packaging.

Fig. 3(c) shows that the MOB has a 1dB vertical alignment tolerance of \( \pm 8 \mu m \), which is outside the \( \pm 5\% \) manufacturing tolerances that are typical for a 250µm-thick AlN-substrate. However, it is always possible to re-align along the x-direction the GC compensating the wrong impinging position taking advantage of the extended MOB-focal region (i.e. 65µm). Note that the Fiber-to-PIC alignment data are only shown for positive values of \( \Delta y \), because the fiber cannot be pushed “through” the PIC surface. These results show that the 1dB alignment tolerances of the MOB are similar to those of a fiber for grating-coupling, and are compatible with existing practical alignment processes.

Fig. 4 illustrates the effect of fabrication tolerances on the MOB coupling performances. A campaign of 2D-FDTD simulations were used to investigate the effect of an horizontal offset (\( \Delta P \)) affecting the laser best horizontal position (P) and a vertical offset (\( \Delta Q \)) affecting the micro-lens best vertical position (i.e. Q=0µm, so the lens optical-axis is properly aligned with respect to the laser exit slit - see Fig 2(a)).

Fig. 4(a) shows that 1dB laser-to-lens horizontal alignment tolerance is \( \pm 20 \mu m \), which is well within the capabilities of either flip-chip or precision pick-and-place processes for attaching the laser-diode to the AlN-substrate. Fig. 4(b) shows that 1dB laser-to-lens vertical alignment tolerance is significantly tighter, at \( \pm 5 \mu m \) / 15 µm. The asymmetry in this tolerance is due to the fact that a symmetric \( \pm \Delta Q \) results in an
MOB are shown to be compatible with practical photonic-packaging processes. The fabrication tolerances the ball lens height ceramic substrate. b) Fig. 4. (a) Behavior of the IL value due to a laser misalignment on the ceramic substrate. b) Variation in the IL as a function of a misalignment in the ball lens height. (a) and (b) represent the consequences in the IL value of the fabrication tolerances.

asymmetric change in both the optical path-length and propagation-direction through the micro-prism. It also changes the AOI of the focused-mode arriving at the surface of the PIC, and displaces the focused-mode across the propagation-direction through the micro-prism.

In practice, there are two potential origins of fabrication tolerances reported in [9], the -15μm 1dB alignment tolerance is technically within the variations introduced by this effect, even though the margin is rather tight; however, the +5μm 1dB alignment tolerance is outside of the manufacturing tolerances, around 12 μm. Therefore, not only care must be taken to ensure that these components are manufactured to a high-degree of their nominal specification, but also improvements in the fabrication processes must be introduced.

The difference of 1.0dB in the IL of the Fiber-to-PIC and MOB-to-PIC coupling can be divided into two different contributions the light back reflected at each surface of the optical components (0.6dB), which can be eliminated with suitable anti-reflective coatings, and the spherical-aberration (0.4dB), which can be accommodated through custom non-uniform grating-couplers. This suggests that the MOB can potentially be a reasonable alternative to the fiber in order to couple light directly into a PIC. However, it is to be considered that a full 3D model is needed to capture the entire complexity of the real MOB features.

IV. CONCLUSION

Millimeter-scale 2D-FDTD simulations are demonstrated to be a practical solution for optimizing MOB designs for efficient Laser-to-PIC hybrid integration. Compared to direct Fiber-to-PIC coupling, a basic MOB suffers from a performance-penalty of just 1.0dB compared to a fiber-coupling. Both alignment and manufacturing tolerances of the MOB are shown to be compatible with practical photon-packaging processes.

V. REFERENCES


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