Enabling Volume-Compatible Photonic Medical Devices Through Hybrid Integration Assembly

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***Abstract* — A highly integrated and compact photonic module is realised using state-of-the-art wafer-level assembly processes, paving the way for volume production. This advancement opens new avenues for cost-effective and user-friendly point-of-care medical devices, facilitating early detection of cardiovascular conditions.**

***Keywords* — cardiovascular disease monitoring, Laser Doppler Vibrometry, photonic integrated circuit, hybrid laser integration.**

I. INTRODUCTION

Cardiovascular diseases (CVD) are the leading cause of death globally, with approximately 17.9 million deaths reported each year [1]. Early healthcare interventions involve monitoring CVD symptoms using affordable and accessible methods or devices [2,3]. Recently, the CARDIS project investigated and developed a non-invasive optical sensor based on Laser Doppler Vibrometry (LDV) for early detection of CVD [4]. This diagnostic tool utilised hybrid integration techniques to combine state-of-the-art silicon-based photonic integrated circuits (PICs) with an on-chip source. Hybrid integration allows for low power consumption, high signal integrity, and a compact package design, making it highly suited for medical diagnostic devices.

CARDIS validated the concept and InSiDe carried forward the efforts by focusing on functional improvements and manufacturability to lower healthcare costs and enhance patient experience. The system encompasses discrete lasers, sub-millimetre free-space optics, and a PIC, all housed within a single package. Sub-assemblies compatible with scalable production techniques were developed due to the substantial level of photonic integration in the InSiDe project [5].

The focus of this paper is on the development of volume-compatible techniques for micro-optical bench (MOB) assembly and integration. An automated wafer-level assembly of MOBs is presented alongside a semi-automated volume-compatible method for integrating the MOB into a photonic subsystem. These approaches leverage the already established manufacturing capabilities within the electronics packaging industry, enabling a faster time-to-prototype with streamlined volume production.

II. WAFER-LEVEL MICRO-OPTICAL BENCH ASSEMBLY

A micro-optical bench assembly is a technology platform that offers a method for integrating a laser source on silicon PICs instead of relying on externally plugged sources. As shown in Figure 1a, the MOB consists of a discrete laser source and free space micro-optics to focus light towards an on-chip grating coupler. The dual ball-lens configuration collimates and focuses the expanded optical beam, while the micro-prism steers the focused beam onto the PIC grating couplers at a predetermined angle (10°) and working distance. The MOB is designed to minimise spherical aberrations, while the expanded spot size allows for relaxed alignment tolerances during the MOB-to-PIC integration process.

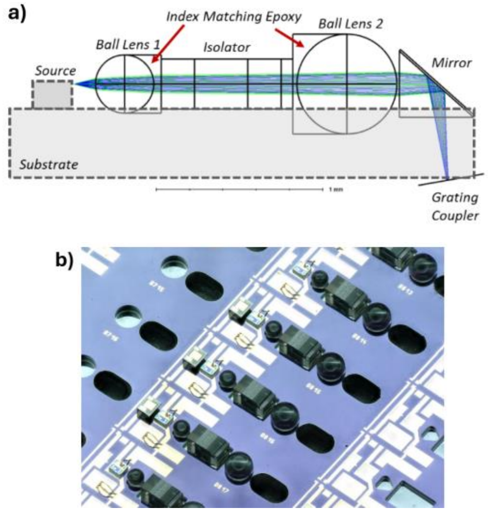

Figure 1: (a) Layout of the proposed MOB configuration. (b) Wafer-level micro-optical bench assembly on a silicon substrate.

To ensure compatibility with volume production processes, silicon was chosen as the MOB substrate platform. Cavities and recesses were etched into the silicon wafer to enable passive alignment of optical components at precise coordinates using standard pick-and-place procedures. The diode lasers were individually soldered to ensure optimal mechanical and thermal connections, facilitating efficient heat dissipation.

By moving to wafer-level assembly of the MOB rather than individual assembly, a factor of 30x improvement in MOB assembly throughput was realised during the InSiDe project when compared to previous work. Further refinement of the process and creating a dedicated production line for multi-wafer assembly will result in an even higher throughput.

III. Volume-Compatible MOB Integration

The hybrid integration of MOB to PIC was the most complicated assembly step of the photonic subpackage in the InSiDe project. The alignment process required both passive and active steps. This was achieved using an advanced alignment station equipped with 6-axis piezoelectric-controlled actuators and transimpedance amplifiers for optical power monitoring. Figure 2a compares the MOB-to-PIC alignment tolerance to a simulated setup of direct laser-to-PIC integration, demonstrating the relaxed alignment tolerance that the MOB platform offers.

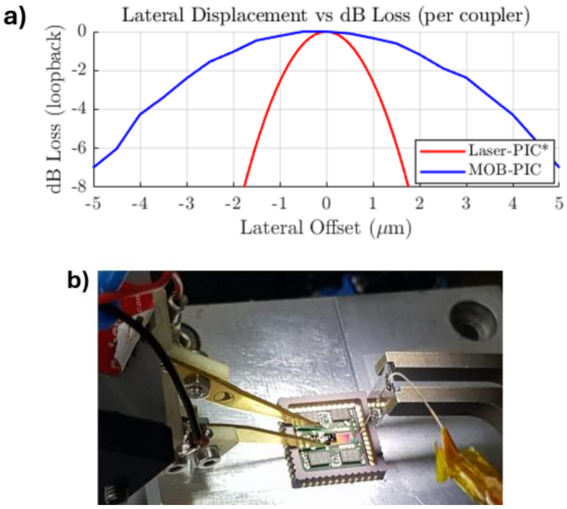

Figure 2: (a) Displacement tolerance for MOB-to-PIC integration (measured) compared to laser-to-PIC integration (simulated). (b) Active alignment of MOB to PIC inside a Kyocera package.

The main sensing module consists of the source (MOB), the PIC, and an electronic PCB interposer populated with trans-impedance amplifiers (TIA) and electrostatic discharge (ESD) protection for the laser diode. These components are assembled sequentially into a QSFP Kyocera ceramic sub-package to allow for pluggability to the main controller module. To facilitate the alignment process of the MOB to the PIC, electrically conducting grippers were used to grip metallic structures on the MOB. The metalised pillars on the MOB provided electrical connections for powering the laser diode during alignment.

Once the focused light from the MOB was coupled to the PIC input grating-couplers, the signal from the on-chip output antenna was continually monitored with an optical fiber. This signal is amplified with a TIA and employed as a feedback signal to optimize the lateral and angular positions of the MOB, overall enhancing the coupling efficiency. After active alignment, the MOB was secured on top of a heat-sink using a UV-curable epoxy. To address epoxy shrinkage and movements during the curing process, an adaptive curing technique was developed, resulting in enhanced control throughout the process.

IV. Discussion

The volume-ready wafer-level MOB assembly process presented in this paper has the potential to be further scaled up in a dedicated production line. However, during the InSiDe project, MOBs were individually characterised for beam profile and working distance, and those not meeting the specification requirements were rejected. Implementing a wafer-level probing step to characterise and sort functional MOBs would further enhance production capacity. During the InSiDe project, the PICs were fabricated as part of a multi-project wafer run, so were not compatible with wafer-level MOB alignment processes. Introducing a wafer-level process would be beneficial for high-volume manufacturing.

Both the MOB and overall package design are well-suited for high volume production, and the wafer-level MOB assembly process can be easily adapted to accommodate a wafer of PICs. It is estimated that utilising specialised tools enables the reduction of cycle time for fully automated processes at the wafer level from 2 hours to just 2 minutes. This includes MOB pick-up, active alignment, UV epoxy dispensing, epoxy curing, and final coupling measurement, thereby establishing a competitive edge with industry standards [6]. Transitioning to a wafer-scale integration process will not only facilitate high-volume production, but also leads to reduced packaging costs, ensuring that the final product remains highly competitive in terms of both performance and cost.

V. Conclusions

An automated passively-aligned wafer-level assembly of micro-optical benches was developed and is presented alongside a semi-automated MOB-to-PIC hybrid integration process. The hybrid integration combines a discrete laser on MOB, silicon PIC, and an electronic interposer in a photonic subpackage which is implemented in a medical device. The enhanced volume-ready MOB assembly process showcases significant potential for commercialising micro-optical benches in medical devices and other sectors. Further refinements and automation in the integration of MOBs into photonic integrated circuits are set to expand the scalability of photonic subpackage assemblies. Integrating these photonic modules into larger systems enhances scalability, reliability, and compactness – a notable improvement over the previous CARDIS project. This advancement underscores the growing viability of photonic technologies in the medical device market.

Acknowledgment

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