Initial Results of Prototyping a 3-D Integrated Intra-Chip Free-Space Optical Interconnect

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***Abstract*—A new optical interconnect system for intra-chip communications based on free-space optics is summarized in this paper. All-to-all direct communications is provided using dedicated lasers and photodetectors, hence avoiding packet switching while offering ultra-low latency and scalable bandwidth.**

A board-level prototype for technology demonstration is built using fabricated germanium photodetectors, micro-lenses, commercial vertical-cavity surface-emitting lasers (VCSELs), and micro-mirrors. Measured from the prototype setup, transmission loss in an optical link of 10-mm distance is measured as 5 dB. Small-signal bandwidth of the link is 10 GHz.

I. Introduction

Continuing device scaling, if not compensated, degrades performance and signal integrity of on-chip metal interconnects, hence limiting the performance of multi-core microprocessors and high-speed systems-on-chip (SoC). The communication-centric nature of future high performance computing devices demands a fundamental change in intra- and inter-chip interconnect technologies. Optical interconnect exhibits inherent advantages in delay and bandwidth over electrical counterparts [1], [2] and thus receives increased attention as a possible substitute for electrical interconnects.

Using optical components only addresses the signaling portion of the issue. Applying a conventional packet-switching architecture to optical networks is unlikely to be an ideal solution for intra-chip environment: Packet switching incurs repeated electro-optic (E/O) and opto-electronic (O/E) conversions, diminishing the advantages of optical signaling. To avoid packet-switching, bus or ring structures can be used, which generally rely on wavelength division multiplexing (WDM) to achieve a large bandwidth [3], [4]. These systems, however, typically require precise E/O modulators with accurate wavelengths and minimal transmission losses, hence poses significant fabrication challenges and constraints.

An alternative approach is to use free space optics instead of waveguides. Vertical-cavity surface-emitting lasers (VCSELs) and normal-incidence photodetectors (PDs) are typically linked by a free-space optics fabric made of mirrors and lenses. For example, systems based on planar optics [5], macro-optics [6], [7], and microoptics [8], [9] have been demonstrated for inter- and intra-chip applications.

From a multidisciplinary angle, we have analyzed the capabilities and challenges in different layers of the design stack and have proposed a new optical interconnect system specifically developed for intra-chip communications in multi-core microprocessors and SoCs based on free space optics [10]. In this paper, we recap the technological tradeoffs of the design and present some preliminary prototype measurement results.

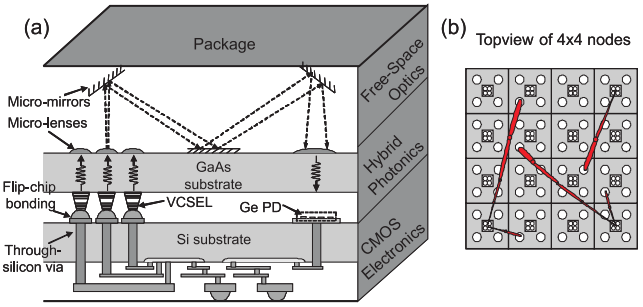

Fig. 1. (a) Cross-sectional and (b) top view of an intra-chip free-space optical interconnect system in a 3-D integrated chip stack. The VCSEL arrays are in the center and the photodetectors are on the periphery within each node.

II. Intra-Chip Free-Space Optical Interconnect

In the proposed intra-chip optical interconnect system, GaAs photonics and free-space optics layers are placed on top of the CMOS electronics layer via 3-D integration (Fig. 1). VCSELs in the GaAs photonics layer serve as light sources, hence removing the need for external multi-wavelength lasers used in WDM systems. Each light beam from the digitally modulated backside-emitting VCSELs is collimated through a dedicated micro-lens, built at the back of GaAs substrate, transparent at the target wavelength. The collimated light bounces from a series of micro-mirrors, implemented on the chip package using low-loss metal coatings. Then, it is focused by another micro-lens onto a PD, built with a thin germanium (Ge) layer on the silicon substrate. In the CMOS layer, the transmit and received electrical signals are converted from/to digital data by the transceiver electronics.

This *free-space optical interconnect* (FSOI) system uses point-to-point links to construct an all-to-all intra-chip communication network. A single transmission medium (free space) provides links between every VCSEL-PD pair. In comparison with applying a conventional network architecture, this design has a number of advantages.

First, it avoids packet-switching and the associated intermediate routing and buffering delays in electrical networks or packet-switching optical networks. Hence, it permits the signal propagation delay to be extremely low – approaching the ultimate lower bound. Eliminating packet switching also reduces energy overhead.

Second, it does not require external laser sources implied in many designs and also side-steps the challenges in waveguide

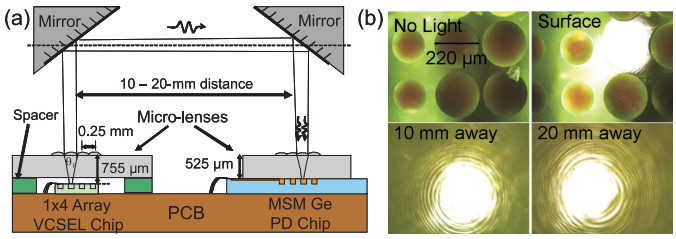

Fig. 2. (a) 2-D cross-section schematic, and (b) image of the beam collimated by the VCSEL lens at different distances. The VCSEL chip is 25 μm away from the focal point of the lenslet. The beam size is 240 μm at 1 cm and 250 μm at 2 cm, corresponding to 1.5 and 1.9-dB optical power clipping at 1 cm and 2 cm, respectively.

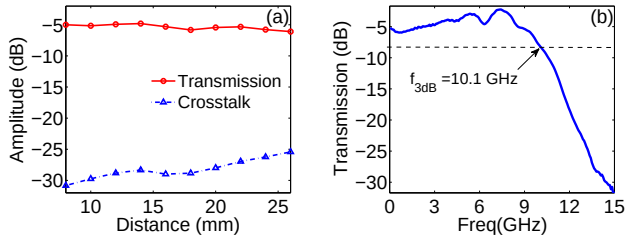

Fig. 3. (a) Transmission and crosstalk at different link distances, and (b) small-signal bandwidth at L=1 cm. Note that the optical transmission changes between -5 and -6.5 dB due to the little change in the beam spot size.

layout. In addition to making the design more feasible to implement, the design allows VCSELs to be powered down during idle time and fundamentally reduces energy waste. The signaling chain is comparatively simple and avoids issues such as thermal sensitivity, accumulating insertion loss of the often-used micro-ring modulators in WDM systems. The lack of waveguides eliminates loss and crosstalk due to waveguide crossings in densely routed waveguide-based optical interconnects, which limit the optical network performance.

Finally, the free space medium provides aerial freedom for scalability and low dispersion. The resulting good signal integrity simplifies optical transceiver electronics, e.g., removing the need for equalization as typically used in high-speed electrical interconnects. On the other hand, however, the introduction of a free-space layer does complicate the issue of heat dissipation.

III. Prototype and FSOI Measurement Results

A series of prototype components and subsystems are being developed to understand the feasibility and validate theoretical parameters used in the system-level study [10]. At the time of this writing, the only available results are measurements from a link prototype built on a PCB using micro-lenses, micro-mirrors, a 1×4 PD array, and VCSELs. The VCSELs are a commercial 1×4 array (Finisar HFE8004-103), with 2-mW optical power at 850 nm, 40% conversion efficiency, 30° full-angle beam divergence and 10-Gb/s speed. The micro-lenses are built on a 525-μm thick fused silica substrate by melting and reflowing the 10-μm thick and 220-μm diameter cylindrical photoresist. The resultant spherical shape has a 1.22-mm radius of curvature and a corresponding focal point of 730 μm from the surface of the lenslet. The fabricated PDs are 47×47-μm^2 metal-semiconductor-metal Ge PDs with a thin layer of undoped amorphous-silicon on the substrate, enabling low dark current and large bandwidth. The PD has a 0.23-A/W responsivity without any anti-reflection coating and a 13-GHz bandwidth at 7-V bias and 850 nm [11].

As shown in Figure 2, the VCSELs and PDs are wirebonded to the PCBs with 50-Ω transmission lines, connected to the instruments via RF connectors located at the input edge of the PCB. Two micro-lens arrays are UV-cured to spacers on top of the VCSELs with a sufficiently wide gap for the wirebonds, and directly onto PDs with 50-Ω 1-mm transmission line on the germanium substrate, respectively. The VCSEL chip is 230 μm from the back surface and 25 μm from the focal point of the lens. The mirrors with 96% reflectivity are mounted on top of the micro-lenses with a 45-degree angle approximately 1 mm from the lens.

To evaluate the dc properties, both the optical transmission for a specific link and the optical crosstalk of adjacent links are measured with respect to distance. As shown in Fig. 3, at 0.5-mW laser optical power, the transmission loss is 5 dB at a 10-mm distance and increases to 6.5 dB at 26 mm. The crosstalk power is -29 dB at 10 mm and increases to -25 dB at 26 mm. The small-signal bandwidth of the link is measured as 10-GHz does not change with distance.

Compared to the theoretically-calculated 2.6 db path loss used in system-level study [10], the larger loss measure is mainly due to the large divergence angle of the commercial VCSELs used. 1.25 dB and 1.5 dB of the optical power is clipped by the VCSEL lens and PD lens at 1 cm. To eliminate these losses, a VCSEL with a smaller beam divergence is possible, and/or a larger aperture size lenses with the same focal length can be used at both ends [8].

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