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Electro-optical integration for VCSEL-based board-level optical chip-to-chip communication

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ABSTRACT

This paper discusses the technology development for integration of parallel optical interconnects on board-level, including the active and passive optical components as well as the electrical integrated circuitry. The inter-chip link is based on planar polymeric optical multimode waveguides with integrated out-of-plane coupling optics and optical transceiver subassemblies based on glass interposer. Integration of polymeric waveguides on flexible substrates will be shown since the realization of an overlay optical substrate enhances the yield and testability of the final hybrid electro-optical printed circuit board (EOPCB). Realized on-board waveguides feature low insertion loss (minimum attenuation coefficient of below 0.1 dB/cm). For short planar waveguides ($L_{\text{waveguide}} = 9$ cm) error free transmission (BER < 10⁻¹²) up to 30 Gbit/s was achieved. The development of glass interposer passive optical coupling structures for VCSEL-based short-distance links will be described.

Keywords: optical packaging, board-level optical interconnects, passive alignment, polymeric optical waveguides, glass interposer, out-of-plane coupling optics, optical characterization, parallel optical interconnects

1. INTRODUCTION

Current high-performance computing (HPC) systems and data centers mainly suffer from chip-to-chip interconnect bottleneck. A promising approach to increase the inter-chip bandwidth in future links are integrated optical interconnections [1]. Board-level optical interconnects are especially interesting for applications like high performance computers or data centers where the channel density and power consumption become critical. Recent advances in the silicon photonics confirm the emergence of this technology [2, 3]. The challenge for optical interconnects at board- and backplane-level is the cost competitive implementation in standard electrical substrates. In comparison to fiber-based optical interconnects the integrated planar optical waveguides enable a higher channel density and the routing of the optical path by integration of passive optical structures. Different materials for the integration of optics in electronic systems on board- and module-level have been proposed: silicon [4], silica glass [5] and polymer [6, 7, 8]. The lack of robust assembly routines which are compatible with standard assembly processes avoids optical boards to be widely applied nowadays. In order to accommodate the typical assembly tolerances of SMT-processes, adapted transceiver assemblies with integrated micro-optics are needed. This enables low-loss redirection of the optical signal and coupling of active and passive optical components at the same time.

In this paper, an approach for electro-optical integration of VCSEL-based board-level optical chip-to-chip communication is investigated. The development of planar polymeric waveguides with out-of-plane optics on flexible substrate and glass interposer for optical transceiver systems is described. An approach for assembly of optical transceiver components with passive alignment is discussed.

2. VCSEL-BASED BOARD-LEVEL OPTICAL CHIP-TO-CHIP LINK

In order to achieve the high accumulated processing power of future exascale computing systems [9] an array of computing nodes is expected. Hence the optical links need to provide a high bandwidth density to enable the communication between computing nodes within a HPC. Therefore, a multichannel optical network system is targeted. In this work, a parallel optical link for high-performance computing application is discussed. Each VCSEL-based channel consists of four main blocks (Figure 1 (a)):

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- electrical driver and receiver circuitry: multiplexer/demultiplexer (MUX/DEMUX) including clock distribution and retimer, laserdiode driver (LDD), transimpedance amplifier (TIA) and limiting amplifier (LA), clock- and data recovery (CDR),
- electro-optical (E/O) converters (optoelectronics): laser (VCSEL), photodetector (PD),
- optical coupling elements, and
- the optical on-board integrated waveguides.

Figure 1. VCSEL-based optical chip-to-chip link: a) schematic block diagram of the main components of the link, b) schematic of packaging concept based on polymeric overlay optical waveguides with micro-mirrors used as out-of-plane coupling optics and direct bonded glass interposer.

In Figure 1 (b) a packaging concept of the board-level optical link is depicted. This optical interconnect is based on polymeric optical multimode waveguides (WG), which are manufactured on flexible substrate, which realizes an additional optical layer attached on top of the electrical printed circuit board (PCB) – so called overlay-technology for realization of electro-optical PCB. This approach features an increased yield and simplified testability in comparison to inlay-technologies because of separate fabrication of optical and electrical PCB layer. Additionally using flexible substrate mechanical decoupling of optical and electrical layers is applied, which enhance the reliability at alignment-sensitive coupling interfaces. Using glass interposer the optical transceiver components, which are manufactured in different semiconductor technologies (driver and receiver ICs in SiGe- or CMOS-technology, optoelectronic ICs in III-V-technology), can be vertically stacked using 3D integration like through silicon vias (TSVs) and flip-chip assembly in order to shorten the electrical interconnects and hence lowering the power consumption and increasing performance at high data rates.

In previous work [10, 11] for realization of out-of-plane optics a glass interposer with integrated waveguides and micro-mirrors was incorporated (see Figure 2 (a)). That earlier approach featured increased losses caused by two additional coupling interfaces between polymer and glass waveguides. In this work, direct integration of 45° micro-mirrors into polymer waveguides used as out-of-plane coupling optics is investigated. This approach features reduced coupling interfaces and hence lower losses are expected. In Figure 2 the comparison of these two approaches for a VCSEL-based optoelectronic transceiver subassembly is shown.

Figure 2. Comparison of two approaches for a VCSEL-based optical transceiver subassembly with out-of-plane optics: a) realized in glass interposer with integrated waveguides, earlier approach [10] and b) integrated in polymer overlay waveguides, this work.

For the second approach discussed in this work (see Figure 2 (b)) a glass interposer for assembly of optical transceiver components (E/O converters and electrical driver/receiver circuitry) is bonded on this flexible substrate with waveguides

direct above the micro-mirror array. The light is redirected with micro-mirrors and couples into/from E/O-converters (PD or VCSEL) through the transparent flexible substrate and glass interposer. For assembly of E/O-converters a flip-chip (FC) bonding is deployed as a precise and surface mount compatible process. FC-assembly features low-parasitic interconnects, which makes this contacting method especially suitable for high bandwidth electrical interconnects.

3. ON-BOARD OPTICAL WAVEGUIDES WITH OUT-OF-PLANE OPTICS

The planar polymer single mode [12] and multimode [7] optical waveguides are often discussed as very promising approach for optically functionalized hybrid EOPCB. In this work multimode waveguides are discussed since relative large core dimensions (30 – 50 μm) lead to relaxed alignment tolerances, which are essential for incorporation of a passive alignment scheme. The planar strip waveguides were fabricated usingOrmocere® inorganic-organic hybrid material, which features high transparency in a wide spectral transmission range (from visual range 600 – 900 nm up to telecommunication wavelengths 1310 nm / 1550 nm), high thermal stability and excellent structuring properties. The commercially available material combination for the waveguide fabrication (Ormoclad and Ormocore) has an index contrast of $\Delta = 0.014$ ($n_{\text{core}} = 1.550$ and $n_{\text{cladding}} = 1.528$) at the target wavelength of $\lambda = 850$ nm which yields to a numerical aperture of $\text{NA} = 0.26$. This corresponds to an acceptance angle of 15.3° . Mixing of both materials enables tuning of the numerical aperture NA in the range from 0.26 down to 0.14. Further this material can be structured using UV-photolithography (negative type). In this work mask-based UV-photolithography was applied for the structuring of core and cladding material [13].

In order to enable structuring of waveguides in subsequent photolithography processing steps the flexible substrate has to be temporary bonded on a rigid carrier substrate. For the selection of suitable substrate material thermal and chemical resistivity have been used [10]. Because of excellent thermal and chemical stability of the temporary bond, heat-stabilized polyethylene-naphthalate (PEN - Teonex® Q65H) foil has been used for this work. This foil is pretreated on one side and can therefore be laminated on a carrier wafer. The used foil has a thickness of 50 μm and features a smooth surface ($R_a = 0.7$ nm) and high transparency making it suitable for optical application. After the temporary bonding of the PEN-foil the cladding and core layers were subsequently deposited on 6" carrier wafer with flexible substrate using spin coating. The core pattern was UV-structured by a proximity exposure followed by a post exposure bake and an immersion developing step. Finally, the covering of the core with the upper cladding polymer and hard baking of the layer sandwich were performed. In Figure 3 (a) an optical layer on a PEN-flexible substrate temporary bonded on Si-carrier wafer is shown.

Figure 3. Overlay flexible optical waveguides: a) structured on PEN-flexible substrate temporarily bonded on 6" Si-wafer, b) waveguide array on PEN-foil after debonding and c) cross section of single waveguide core

This photograph shows optical waveguide arrays with 250 μm pitch and with different number of channels. The result of the waveguide manufacturing after debonding from carrier wafer is shown in Figure 3 (b). For demonstration of its flexibility the substrate was folded, while typically there is no intrinsic mechanical tension. The advantages of a photolithographic waveguide manufacturing are high accuracy, high surface quality ($R_a \leq 20\text{nm}$) and an easy control of a core cross section shape and height-to-width aspect ratio. In Figure 3 (c) an exemplary cross section of single waveguide core is shown. The only disadvantage is the maximum length of the waveguides which is limited by the wafer size which can be processed with the spin coater and mask aligner. For longer structures or a mask-less fabrication, additive processes needs to be considered.

For the optical performance characterization straight waveguides including 8-channel waveguide arrays with the variation of its core width from 30 μm to 50 μm and waveguide numerical aperture NA in the range from 0.26 down to 0.14 (for a detailed description of NA tuning refer to [14]) were used. In [14] low optical attenuation coefficients below

0.05 dB/cm have been measured, which proves the applicability of the fabricated waveguides for low-loss on-board optical data transmission. Additionally the usability of the on-board waveguides for high-speed optical data transmission at a wavelength of 850 nm was verified with commercially available VCSEL and PIN-PD modules specified for data rates up to 25 Gbit/s [10]. For short planar waveguides ($L_{WG} = 9$ cm) error free transmission ($BER < 10^{-12}$) up to 30 Gbit/s was achieved. No significant distortion of the eye diagram could be observed by the insertion of planar waveguide in comparison to the reference back-to-back (B2B) measurement. Furthermore the bandwidth limitation above 30 Gbit/s of the used Tx/Rx test module has been observed - at 35 Gbit/s no error free transmission can be achieved - $BER_{B2B} > 10^{-3}$ could be achieved. An impact of the NA on BER was detected - decreased BER for waveguides with lower NA have been measured.

The micro-mirrors for out-of-plane coupling have been fabricated by wafer dicing (sawing). Since for this work 90°-light redirection is aimed, a dicing blade with double-side 45° profile was chosen. In Figure 4 (a) a top view of the diced mirror trench in with a goal depth of 50 μ m is shown (from substrate side – through the PEN-foil). An illuminated mirror slope with out-coupled and redirected light from the waveguide core can be seen. The profile characterization using confocal and optical microscopy shows that the geometrical dimensions of the realized mirror approximate the desired values regarding the trench depth and angle. The roughness of the mirror surface of $R_a = 51$ nm (using 2000 mesh blade) confirms an optical surface quality ($R_a < 0.1 \lambda$).

Figure 4. Micro-mirror diced into the polymer waveguides on PEN-foil for 90° out-of-plane coupling: a) top view of the diced mirror trench with illuminated waveguide core, b) optical characterization of mirror loss.

In order to evaluate the quality of the mirror the insertion loss of the optical link which consists of two diced mirrors and a short (3 mm long) polymer waveguide (U-turn) have been measured. In the upper picture of Figure 4 (b) a schematic view of the measurement setup is shown. In order to minimize the losses at the in-coupling interface the light from a 850 nm laser diode launched into few-mode fiber with core diameter of 10 μ m and numerical aperture of $NA = 0.1$ was chosen as an optical source. At the out-coupling interface, a large core (diameter of 200 μ m), large numerical aperture ($NA = 0.39$) step index multimode detection fiber was used. In the lower picture of Figure 4 (b) the light redirection is demonstrated by coupling of red light into polymer U-turn. Scattered light at mirrors depicts the losses. From the measurement results an insertion loss of -3.9 dB has been derived.

4. GLASS INTERPOSER FOR OPTOELECTRONIC TRANSCEIVER SUBASSEMBLY

Because the packaging concept described in Section 2 requires a transparent substrate in the targeted wavelength range from approximately 800 nm up to 1600 nm as interposer, thin glass was chosen as material (see Figure 2 (b)). In comparison to on silicon, glass enables a wider range of wavelength from UV to near IR. As depicted in Figure 2 (b) the glass interposer includes a metallization for the assembly of the integrated circuit (IC) components on top of the

interposer. The optical transceiver subassemblies can be manufactured on wafer- or panel-level using precise processing suitable for high-volume production. For first implementation of transceiver packages the transmitter Tx and receiver Rx with optoelectronic converters (VCSEL and PD) and electronic transceiver ICs (laser diode driver LDD and transimpedance amplifier TIA) are considered (Figure 5).

Figure 5. Chip components of optical transceiver: a) VCSEL- and PD-chips, b) LDD- and c) TIA-chip micrograph.

As optoelectronic converters commercially available chips from VI Systems GmbH have been chosen (Figure 5 (a)). These chips are single channel top-emitting VCSELs and top-detecting GaAs PDs with chip areas of $(250 \times 250) \mu\text{m}^2$ and with $50 \mu\text{m}$ diameter pad openings. Since in this work increased performance and energy adaptivity of the optical inter-chip on-board links is aimed for, required electronic transceiver ICs (LDD and TIA) are individually designed and manufactured in Fab. The performance/energy adaptivity means the ability to scale the data rate of each link during runtime while reducing the power consumption at the same time. Figure 5 (b) and (c) show micrographs of VCSEL-driver and transimpedance amplifier [15].

Interposers for a single channel transmitter Tx and receiver Rx have been designed and interposer realization includes the definition of metallization on the thin glass substrates, which has been processed on carrier Si-wafer with using temporary bonding foil RevAlpha®. The structuring of the metallization has been performed using a lift-off photolithographic process. Precise definition of pads for assembly of E/O devices is guaranteed, because of a high accuracy of this wafer-level process - mask exposure of lift-off resist using mask aligner. Figure 6 shows the top view of the glass interposer for the transmitter Tx (a) and receiver Rx (b) module after fabrication with marked areas for component placement.

Figure 6. Top view of glass interposer after fabrication with marked areas for component placement: a) transmitter Tx module, b) receiver Rx module and c) detailed picture of pad area for placement of active optoelectronic converter (VCSEL)

The next fabrication step includes singularization of the transceiver interposer. After placement and adhesive bonding of glass interposer using UV-curable adhesive. An illuminated mirror slope with out-coupled and redirected light from the waveguide core can be seen in Figure 6 (c).

For the assembly of chip components thermosonic FC-bonding using an equipment (FINEPLACER® lambda) with high placement accuracy (down to $\pm 0.5 \mu\text{m}$) and a special tool for the handling of small components has been implemented. This FC-method features a flux-free assembly process, which is particularly important for optical devices in order to ensure clean optical coupling surfaces. The electrical interconnect is based on Au stud bumps bonded on the component pad. In order to optimize the bonding process of E/O-converters on the glass a test assembly with $(350 \times 250) \mu\text{m}^2$ VCSEL-chips and glass substrates without integrated WGs have been performed. Optimized process parameters ($T = 120^\circ\text{C}$, $F = 1 \text{ N}$ (3 bumps), $P_{\text{US}} = 1 \text{ W}$ and $t_{\text{puls}} = 500\text{ms}$) have been found.

5. CONCLUSIONS

The paper presents an approach for electro-optical integration of VCSEL-based board-level optical chip-to-chip communication within a high-performance computer system. A packaging concept for fabrication and assembly of link components, which enables passive alignment have been described. An alternative approach for realization of out-of-plane optics with direct integration of 45° micro-mirrors into polymer waveguides which features reduced coupling interface number and hence lower losses is shown. A hybrid optoelectronic subassembly, which combines polymer waveguides with out-of-plane optics, glass interposer and silicon and GaAs chips is proposed in order to integrate different components into one package. The used wafer dicing for micro-mirror features an easy and quick process, but it enables only the realization of straight cuts and therefore no possibility for selective mirror fabrication is targeted for future work. Currently, improvements and alternative manufacturing methods are evaluated for selective mirror fabrication. The described technological platform is suitable for additional integration of another link components (MUX/DMUX chips, electronic chips for digital signal processing, e.g. FPGAs and processor/memory chips) using 3D-stacking, which enhances the performance of the package by shortening the electrical interconnects. In the future work, we will evaluate the performance of the complete link by optical characterization, transmission tests and reliability analysis.

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