INTEGRATION OF OPTICAL INTERCONNECTS ON CIRCUIT BOARD

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Abstract: *Hybrid integration of polymer-based micro-optical technologies allows implementing high-bit-rate optoelectronic interconnects. The target is communication between surface-mounted integrated circuit packages on printed circuit board through embedded optical waveguides. Different kinds of optical elements for coupling between transmitters/receivers and waveguides are studied, including microlens arrays, microlenses integrated on VCSELs, surface-mountable beam deflecting elements, optical pillar structures, and waveguide structures patterned by laser ablation. Integration experiments by the use of ceramic packaging substrate as well as results of the coupling efficiency and alignment tolerance characterizations are presented.*

1. Introduction

As operation frequencies, I/O counts and densities of integrated circuits continue to increase, the physical constraints on the development of off-chip interconnects are becoming more and more severe. Integration of optical interconnects into printed circuit board (PCB) is viewed as a potential solution to overcome the performance limitations encountered with electrical interconnections. Embedded polymeric waveguides with similar physical topography and dimensions to electrical strip-lines can be regarded as the most promising approach, since the polymeric waveguides in PCB have the potential of fulfilling integration and compatibility requirements of electronics manufacturing processes. In recent years, a number of optical chip-to-chip interconnections based on embedded-waveguide approach has been demonstrated, e.g. in Refs. [1,2].

One of the biggest challenges in the introduction of optical interconnects at the board level is the need to implement a feasible and reliable optical coupling between the transmitter/receiver and the optical waveguide. High coupling efficiency is required by the narrow loss budget of the high-bit-rate VCSEL-based transceivers, the technology enabling high density integration. Moreover, to achieve compatibility with conventional, high-volume electronics manufacturing and semiconductor packaging technologies, all optical, optoelectronic and electronic components should be suitable for pick-and-place mounting procedures in such a way that passive optical alignments lead to low coupling losses. In addition, all materials should withstand the reflow soldering temperatures.

In this paper, some results of recent research work on board-level optical interconnects by VTT together with several collaborators is presented. Of particular interest are the aspects of in-coupling efficiency and alignment tolerances using different kinds of micro-optical coupling structures suitable for high-channel-density transmitters and receivers.

2. Integrating high-speed multi-channel transmitters and receivers

Hybrid integration allows incorporating photonic devices and micro-optical components into surface-mountable IC packages. On the other hand, the packaging is also challenged by signal integrity issues tied up with high-density optoelectronics, i.e. the multi-channel VCSEL drivers and photodiode amplifiers, capable of >10 Gb/s channel data rates. To address these challenges, the feasibility of transmitter and receiver packaging with multilayer ceramic substrates for optical interconnects has been studied at VTT. Low-temperature co-fired ceramics (LTCC) substrate technology is used because of the possibility to implement precision structures for optical alignment directly onto the electronics packaging substrate. The accuracy of the through hole structures and small cavities on LTCC can be on the order of few micrometers [3], thus enabling passive optical alignment of multimode waveguides. LTCC has also many other properties advantageous for high-speed optoelectronics, including good high frequency and thermal properties, high packaging density, stability, reliability, as well as possibility for passive-component integration and bare-chip encapsulation (as reviewed in Ref. [4]).

3. Optical coupling with microlens arrays

Microlens arrays are often proposed for hybrid-integrated multi-channel optical interconnects, and have been used in many demonstrators, e.g. in Ref. [5]. Microlenses enable enhancing optical coupling, extending the separation between components, and loosening the required alignment accuracies.

We have used microlens-based coupling in our earlier board-level optical interconnect demonstrators [6, 7]. The latter demonstrator (shown in Fig. 1) was a

4x10 Gb/s optical interconnect completely integrated on a standard FR4 PCB [7]. The optical link demonstrator consisted of 4-channel surface-mounted transmitter and receiver modules built on LTCC substrates as well as of four parallel multimode optical waveguides fabricated on the PCB.

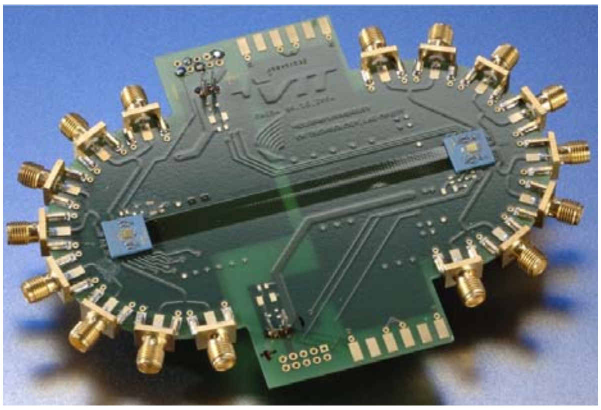

Fig. 1. Optical interconnect demonstrator on FR4 board [7]. Optical waveguide layer is on the board between the (blue) transmitter and receiver components.

In the demonstrator, the coupling between the flip-chip mounted VCSEL/photodiode array and the waveguide array is made of two microlens arrays and a micro-mirror, as illustrated in Fig. 2. One lens array was mounted into a cavity on the ball-grid-array (BGA) side of the LTCC substrate, whereas the other one and the mirror were mounted on the PCB. With this design, an expanded and collimated beam was obtained between the two microlens arrays, i.e. between the transmitter/receiver component and the board; thus, reducing the sensitivity to the potential alignment errors in the BGA board assembly. The characterized transversal alignment tolerances of the BGA-mounted components were ±40…60 µm with 1 dB loss margin, and the total loss of the link was estimated to be around 19 dB. [7]

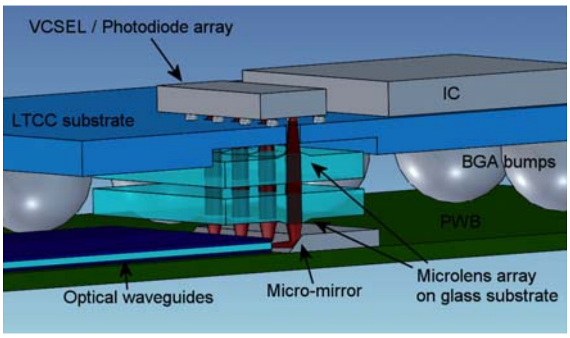

Fig. 2. Schematics of the optical coupling and device packaging structures of the demonstrator in Fig. 1.

4. Coupling with integrated microlens and out-of-plane coupler

An alternative optical coupling structure for the demonstrator described in the previous chapter was implemented by the use of novel micro-optical technologies available within the European Network of Excellence in Micro-Optics (NEMO) [8].

Assembly of the discrete microlens array that collimates the VCSEL beam requires high accuracy. This placement step can be avoided by fabricating microlenses directly on top of the VCSEL wafer (Fig. 3) by the use of wafer-scale replication process, which combines UV-casting and lithography and was developed at the Centre Suisse d'Electronique et de Microtechnique (CSEM) [9]. Such so-called i-VCSELs used in this work were measured to reduce the far-field FWHM-divergence to around 6º (at 1 mW emitted power). Fig. 3 shows a 4-channel i-VCSEL array chip with 250-µm pitch wire-bonded onto the bottom of a cavity on an LTCC-based packaging substrate.

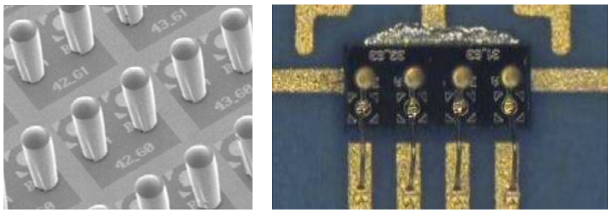

Fig. 3. (left) i-VCSELs on wafer; (right) i-VCSEL array chip mounted on the bottom of the cavity on transmitter substrate.

Multimode optical waveguides were fabricated on the top of the demonstrator PCB (presented in Section 3.) at the Ghent University. Truemode Backplane™ polymer material (by Exxelis Ltd.) was spin-coated on the PCB. Waveguides were patterned by excimer laser ablation and had a cross-section of 50 µm x 50 µm (Fig. 4) and NA of 0.3. For a detailed process description see Ref. [10]. After spin-coating of the top cladding, a micro-cavity (Fig. 4) was ablated to the waveguide layer in order to enable mounting of a coupling element in the front of the waveguide facets.

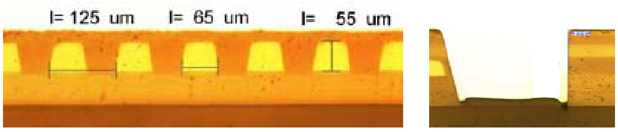

Fig. 4. Laser-ablated optics on PCB: (left) cross-section of waveguide array; (right) cavity on waveguide layer.

To bend the output beam of the i-VCSEL by 90º towards the optical waveguides, we used a pluggable micro-optical component (Fig. 5) incorporating a 45º micro-mirror facet. It was fabricated of PMMA material using deep proton writing (DPW) technology at the Vrije Universiteit Brussel. In addition to the total internal reflection (TIR) mirror, the component has a curved facet, which acts as a cylindrical lens surface. The fabricated coupling components are potentially suitable for low-cost mass production since the DPW technology enables fabrication of molds for standard replication techniques, such as hot embossing and injection molding [11]. In addition, the replication could enable to make the component of another material than PMMA in order to enable standard surface-mount assembly of the module with reflow soldering process.

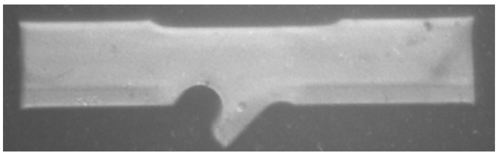

Fig. 5. Micro-optical out-of-plane coupler.

The principle of the optical coupling and the structure of the transmitter package are illustrated in Fig. 6. It is intended for BGA assembly on PCB. The transmitter was built on a LTCC substrate equipped with a cavity for the die-bonded i-VCSEL array. The cavity enables to adjust the separation between the VCSEL and the PCB so that the optical components fit in between them. The out-of-plane coupler has a mechanical alignment structure with laser ablated cavity edge and can be assembled either by a die bonder or by a pneumatic gripper on a precision alignment station. The component was attached with UV-cured adhesive.

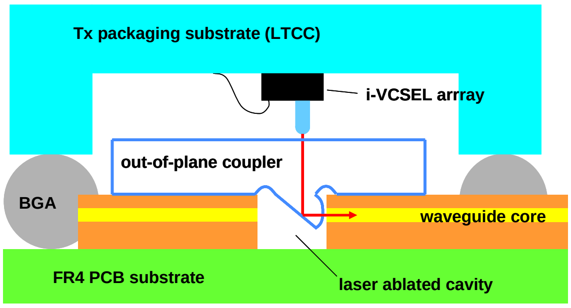

Fig. 6. Schematics of the optical coupling and transmitter packaging structures.

Optical loss of the implemented demonstrator structure (Fig. 6) was measured by butt-coupling the output light from the waveguides with polished ends to a 200-µm-core-diameter fiber with 0.22 NA. The average insertion loss was 8 dB. The propagation loss of the ablated waveguides is 0.12dB/cm [11]. By subtracting the waveguide propagation and out-coupling losses, the in-coupling loss is estimated to be 6…7 dB. This loss was mostly due to the divergence of the i-VCSEL beam, which hinders the complete deflection of the beam by the TIR mirror and makes the beam too large to completely fit into the waveguide aperture when incident to the waveguide facet. Thus, the loss may be significantly reduced by coating the facet with metal and making the optical path between the i-VCSEL and the mirror shorter.

Alignment tolerances were also characterized (before the BGA assembly of the transmitter) by measuring the out-coupled optical power as a function of transversal misalignments of the transmitter component. -1 dB alignment tolerances were ±15 µm and ±10 µm depending on the axis of displacement, and the -3 dB alignment tolerances were ±30 µm and ±20 µm, respectively.

When comparing to the earlier demonstrator with double microlens arrays (Fig. 1), the i-VCSEL-based coupling structure requires higher alignment accuracy, because it does not provide expanded beam concept. However, the structure includes fewer components; thus, the assembly process is potentially easier. Optical coupling efficiency performance between the two demonstrators can be considered quite similar, although measurements were not entirely comparable.

5. Coupling with optical pillars

Alternatively to the microlens-based optics, the coupling between the o/e device and the waveguide with mirror facet can be enhanced with an integrated vertical lightguide [12], possibly having a pillar shape (see Fig. 7). Since free-space lens optics is avoided, coupling with optical pillars may enable very dense interconnects to a flip-chip mounted o/e device. Moreover, when fabricated of polymer material that is flexible enough to enable bending of the pillar without deformation, the optical pillar may also compensate for small displacements of a flip-chip mounted device [13].

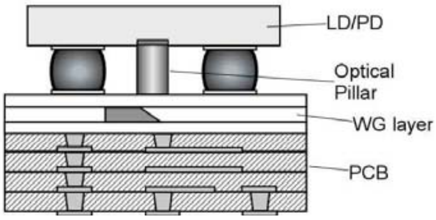

Fig. 7. Mounting of o/e device on opto-PCB with optical pillar.

To study the feasibility of the optical pillar coupling, arrays of pillars were fabricated on metallized surfaces of glass substrates equipped with lithographically patterned circular openings behaving as apertures. Pillars made by UV lithography of direct-patternable Ormocore™ material (by Micro Resist Technology Gmbh) are presented in Fig. 8. By using these test structures and a lensed fiber as a source, the pillars were characterized to improve the coupling efficiency by more than 2 dB when compared to the coupling without pillars, i.e. to free-space coupling with same separation.

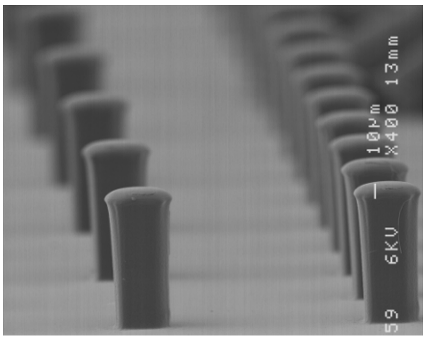

Fig. 8. SEM image of optical pillar array. Pillar height is 100 µm and diameter ca. 28 µm.

6. Conclusions

Micro-optical coupling structures and optoelectronics packaging schemes were presented and characterized aiming feasible implementation of optical interconnects on PCB with embedded waveguides. The hybrid-integration of coupling structures and high-speed multi-channel optoelectronics based on LTCC multilayer ceramic substrates was used. With double microlens array concept, relaxed surface-mounting placement tolerances were demonstrated. Also, a novel coupling scheme was presented, consisting of a transmitter with VCSEL array equipped with integrated microlenses; of a pluggable out-of-plane coupling component made with the DPW technology; as well as of laser ablated polymer waveguides and cavities. In addition, improvement of coupling efficiency by the use of optical pillars was demonstrated; potentially enabling even higher density and bit-rate interconnects.

Acknowledgement

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