Multi-channel optical intra-chip interconnections based on free-space modules: towards manufacturable solutions.

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We report on the use of a free-space optical module to establish multi-channel intra-chip optical interconnections on an opto-electronic field programmable gate-array (OE-FPGA). The optical component was prototyped and replicated in our labs to provide 2x8 parallel channels. After careful alignment of the free-space module on the OE-FPGA 4 channels were interconnected with sufficient data quality to ensure at least 10 Mb/s per channel. We present our latest results with a new optical interconnection module, composed of a glass prism and in-house made lenslet arrays capable of interconnecting up to 330 channels.

Introduction

Moore's law still dictates the evolution of the transistor count in digital IC's. However, the downscaling of the interconnect feature size deteriorates the signal quality and worsens the design complexity of the link. Advanced detection techniques should be used in order to circumvent this interconnect aspect ratio limit, imposed merely by the dimensions of the link wiring[1]. After the introduction of optics as a "wire replacing technology"[2], a lot of effort has been put in determining the potentialities[3] of optical interconnects. The trend for the introduction of optical interconnects in the lower levels of the interconnect hierarchy has been set, possibly reaching the on-chip interconnection level. The latter approach is the subject for many frenzy discussions and the outcome is as yet unclear.

Despite the ongoing debate, we fabricated and replicated a free-space micro-optical interconnection module (OIM) and used it to establish for the first time to our knowledge a working multi-channel interconnect within a chip. The module interconnects photonic I/O's on an OE-FPGA, fabricated within the EC project "Optically Interconnected Integrated Circuits"[4]. In this paper we discuss the link experiments with this intra-chip optical interconnect as well as our efforts to build a 3D optical block with a higher channel count and density using a mechanically aligned glass prism.

The micro-optical pathway block

The micro-OIM we propose uses micro-optical beamshaping and beamdelivering structures[5], as shown in Figure 1, to interconnect emitters and detectors on the same chip via free space. A microlens array collects and collimates the light coming from a flip-chip bonded multimode VCSEL array. As the light travels through the structure, it encounters a microprism which reflects the light back to the substrate. A second microlens focuses the light onto the detector surface. The OIM containing the necessary features to implement the mentioned functionalities was designed and fabricated in our photonics labs.

We used deep lithography with protons (DLP)[6], an in-house technology, to seperately fabricate a microlens array and a microprism. Both components were assembled with index matching glue to form the OIM. Figure 2 depicts the prototype OIM assembly and the dimensions of the different features. As can be seen, the prism with the two micromirrors is plugged into two alignment holes on the baseplate containing the two 2x8 microlens arrays with a diameter of 200 µm on a pitch of 250 µm.

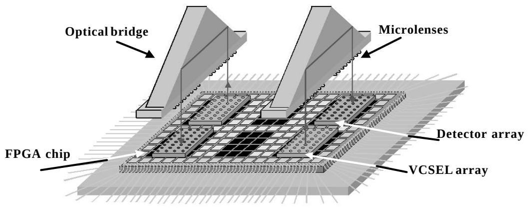

Figure 1: The concept of the OIM.

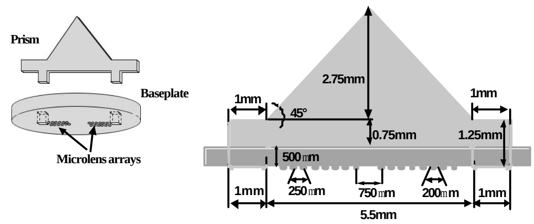

Figure 2: The dimensions of the OIM

DLP is a rapid prototyping technique but is not suited for low-cost mass-production. We used vacuum casting to produce several replicas of our OIM[7]. The resulting OIM (see Figure 3) is a monolithic bloc in poly-urethane (PU) containing the microlens arrays and the prism. We used this OIM for our multilink experiments.

The dimensions of the microlensarrays were chosen according to the position of the detectors and emitters on the OE-FPGA. Only 2 rows of microlenses could be implemented since the status of our DLP-technology limits the prism thickness to 500 µm. Therefore, we studied the use of a commercially available 3D-glass prism with larger lateral dimensions. The thickness of the glass prism is 5 mm, which guarantees a fully interconnectable OE-FPGA (see Figure 4).

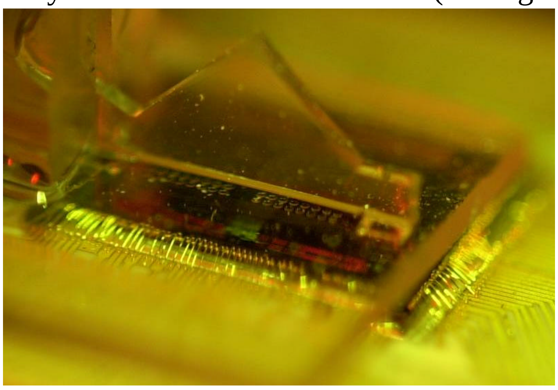

Figure 3: A side-view photograph of the replica of the 2x8 channel OIM aligned on the OE-FPGA. The two arrays of microlenses are clearly visible.

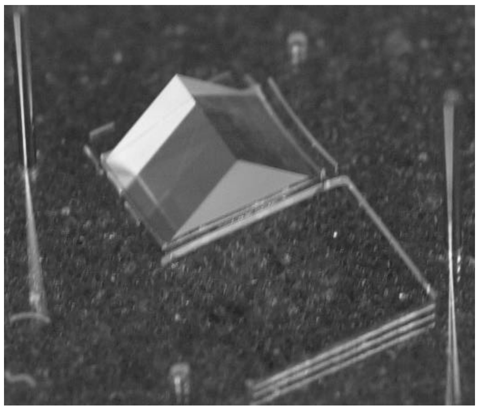

Figure 4: Prototype OIM with mechanically aligned glass prism. The second glass prism is to be aligned in front of it using visual/active alignment.

An extensive study[8] has been conducted in order to define the lens dimensions according to the system specifications and to establish the tolerancing values for different geometrical and alignment errors.

Intra-chip multilink experiments

Using the above described OIM, we were able to demonstrate a multi-channel intra-chip interconnection. 4 of the 16 channels present on the module were interconnecting

VCSEL- and detector arrays that were flip-chipped on the OIIC OE-FPGA. The link speed was 10 Mbit/s, limited by the chiptester. We found no indications for cross-talk or optical efficiency problems with these 4 links.
The tolerancing behaviour was very similar to the results obtained from our modeling study[8]. Indeed, the lateral alignment tolerance of ±4 µm and the working distance tolerance of ±35 µm demanded a careful alignment for correct operation.
Non-uniform lens heights and quality problems with the micromirror surfaces limited us to 4 working channels out of 16. The other channels clearly showed severe cross-talk and/or too low efficiencies for successful operation.

3D micro-optical pathway block

The use of the DLP technology at 8.3 MeV sets a limit for the thickness of the irradiated structures to 500 µm. This limits the amount of rows in a microlens array. As a new approach we used a commercially available glass prism with a thickness of 5 mm. Moreover, by reducing the pitch from a standard 250 µm, to 175 µm, and by reducing the lensdiameter from 200 µm to 123 µm we investigated the effects of a higher channel density on the optical performance of the complete system.
Indeed, simulation software reveals that it is possible to design an OIM with the desired efficiency (88 %) and cross-talk (<-25 dB). The reduced pitch however leads to tighter mechanical tolerancing values. Cross-talk arises quicker because a slight misalignment easily causes light to be coupled into the wrong exit lens. The reduced lensdiameter lowers the maximum amount of light that can be coupled in. Typically, in comparison with the 250 µm pitch approach, alignment tolerances are reduced by a factor 2.

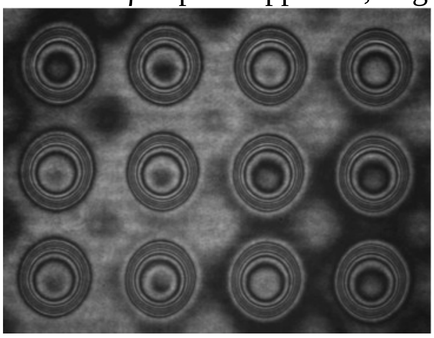

Figure 5: Spherical wave illumination of the prototyped PMMA baseplate showing the lens uniformity. The pitch is 175 µm, diameter 122 µm and the average height is 10.3 µm.

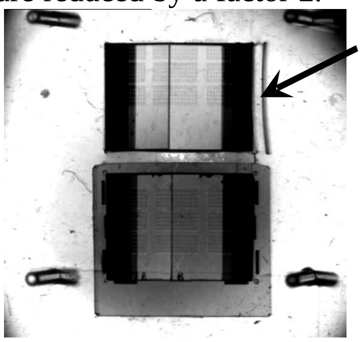

Figure 6: Top view of a fully assembled 660 channel module. A preliminary visual alignment of the lower prism has been carried out. The mechanical spring structure of the upper prism is clearly visible at the right (see arrow).

Our first prototype of the 3D optical pathway block comprises a PMMA baseplate with 3 groups of 5x11 channels, with a total channel count of 165 for a prism with 5 mm sides. The baseplate is equiped for 2 prisms (totalling 330 channels). Using a non-contact profilometer and a Mach-Zehnder interferometer, we were able to assess the quality and uniformity of the microlenses on the baseplate. It turned out that the lensarray is performing much better than the earlier mentioned 2x8 channel OIM: the lenses are more uniform (8% variation) and closer to specification (see Figure 5). As can be seen in Figure 6, one prism is aligned using a mechanical spring structure while the other prism is aligned visually along several marks on the baseplate. Replication through vacuum casting will allow us to obtain a complete monolithical system in PU.
The optical properties of the OIM with one mechanically aligned glass prism were investigated in our labs. The OIM shows efficiencies between 20 and 26 % and a cross-

talk close to –20 dB. Although the lensarrays showed promising characteristics, the total yield of this OIM is low in comparison with our earlier experiments. We found several causes for this lower efficieny. Besides the additional air gaps and different indexes of refraction (almost 22% extra loss), and the longer focal length of the lenses due to the lower refractive index of the PMMA material, the most important source of error is the lateral misalignment of the glass prism with respect to the baseplate. This effect leads to off-axis light input into the output lens. Ray-tracing simulations reveal that a misalignment of 30 µm is enough to cause the observed efficiency drop. We have no indications of other alignment errors, although it is difficult to make accurate measurements on the completed OIM.

Conclusion

We demonstrated an intra-chip optical link with 4 adjascent channels. The OIM we fabricated contained several errors, preventing us to obtain a full 16 channel interconnection. We discussed the possibilities of using a glass prism. The first results show that despite the more uniform characteristics, the OIM has lower efficiencies due to misalignment errors between the glass prism and the lensarrays. In near future studies we will try to alleviate these problems by redesigning our alignment systems.

Acknowledgments

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