Free-space optical modules for interconnecting 2D-photonic VLSI circuitry over inter-chip distances.

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In this paper we present different configurations for a compact free-space optical interconnection (FSOI) module by combining two radial gradient refractive index lenses (GRIN) and/or two arrays of refractive microlenses. Based on our findings with ray-tracing and radiometric analysis we discuss how we select the proper optical system configurations and how we choose the different design parameters to optimally accommodate VCSEL and detector arrays for bridging inter-chip distances, while maximizing optical coupling efficiencies and misalignment tolerances and minimizing inter-channel cross-talk.

Introduction

The present-day Optics in Computing community strongly promotes the use of photonic technologies to overcome the input/output data communication bottlenecks of future generation Si-VLSI chips predicted in the International Technology Roadmap for Semiconductors [1]. To this end 2D parallel photonic pin-outs have been proposed through the use of emitter and detector arrays flip-chip mounted on CMOS circuitry and interconnected by optical pathway blocks (OPB) [2]. In this paper we study different configurations for a compact FSOI module to transfer the firehose optical data streams between two neighboring chips.

Design of a free-space micro-optical bridge

We have developed in our lab a micro-optical bridge [3] to optically interconnect a VCSEL and a receiver array flip-chip mounted on a FPGA chip [4]. The base-plate of this optical bridge, features two precision alignment holes and two 2x8 arrays of spherical microlenses: one to collimate the light from a VCSEL-array and the other to refocus the beams on their respective detectors. A top prism is mounted on this baseplate and integrates two micromirrors at a right angle to fold the 8 mm long light path over 180° (Figure 1). We have already reported on the design, the tolerance analysis [5], the rapid prototyping with deep proton lithography in Poly MethylMetAcrylate of such an optical bridge for intra-chip interconnects and on the opportunities for its low-cost mass-replication through injection molding [3]. This scalable 'optical bridge' concept allows for an increase in channel densities by using smaller lens diameters. However the maximum interconnection length L that we can bridge with this microlens relay approach is limited by the diffraction of the VCSEL beam and as a consequence depends on the lens diameter ϕ_{lens}. For a confocal system where the waist is located in the center of the system and where a 99% optical

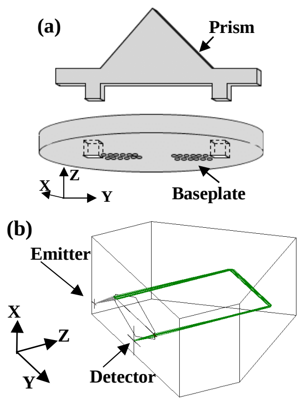

Figure 1: (a) Base plate with spherical lenses and prism with alignment features, (b) Ray-tracing drawing of the OPB

throughput is demanded, the minimum lens diameter for an interconnection length L is limited to $\phi_{lens} = 3.\sqrt{\frac{\lambda}{\pi}.L}$ (1) and the interconnection density to N = 1/(ϕ_{lens})² (2).

We can conclude from (1) and (2) that we can trade-off interconnection length for channel density. In our case the bridge is used to interconnect an 8x2 array of VCSELs and receivers over an optical path length in the OPB of 8mm. These VCSELs are 980 nm through substrate emitters with a FWHM emission angle of 12°. The detectors have an area of 150 µm. According to expression (1) the minimum lens diameter to achieve at least 99% optical throughput while avoiding cross-talk is 123 µm. We have chosen for a lens diameter of 200 µm, i.e. the maximum possible lens diameter of our proton mask if a pitch of 250 µm is desired [3]. To calculate the optical throughput of this FSOI we have simulated the system via ray-tracing and radiometric calculations using the photonics design software SOLSTIS. An efficiency of 90% is reached for a working distance of 500 µm and a focal number for the lenses of 2.6 while the cross-talk for a neighboring channel is less than–40dB [3].

Micro-optical bridge with relay lenses

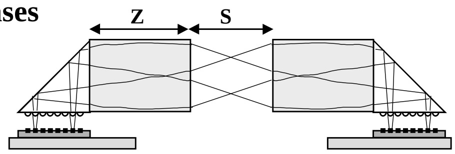

Figure 2: Hybrid micro-optical bridge.

As pointed out before, the throw that can be achieved with the FS OPB is limited by the diffraction of the laser beam. We can extend the throw of our optical bridge and broaden its application domain from the intra-chip interconnection to the inter-chip interconnection level by inserting a relay lens in the system. To maintain the compactness and ease of assembly of the system we have chosen for NSG SELFOC GRINs as relay optics. The concept of this hybrid system is shown in figure 2. The microlenses are integrated with the prism. Because we want a sufficiently large field of view the best candidates are the SLW4.0 type lenses that have a diameter of 4 mm. These lenses have an on-axis NA of 0.46 and will be used in combination with 4 mm prisms. The working distance of these GRINs should be large enough such that the VCSELs can be placed at a convenient distance from the interconnection module. Therefore we have selected a pitch P for the GRINs of 0.14 that corresponds to lens lengths of Z = 5.88 mm and a working distance of 3.21 mm. We opt for a telecentric configuration to minimize distortion and coma. In addition it prevents the emerging beam from the second GRIN lens to be oblique with respect to the optical axis of the microlens, thus avoiding a decrease of the optical system's transfer efficiency through vignetting at the microlens aperture. This means that a fixed distance S of 6.42 mm is necessary between the two GRIN lenses equal to twice their working distance. We have performed a radiometric analysis to find the optimal focal length and working distance for the microlenses. Our study resulted in a design featuring microlenses with a focal number f# = 3.25 and a working distance of 320 µm. We have calculated the optical throughput of the system for 5 different off-axis VCSEL positions along the diagonal of a 10x10 array with a device pitch of 250 µm and for two detector diameters of 150 µm and 50 µm respectively. Figure 3a shows the optical throughput of the system for the 5 off-axis VCSEL positions (1-5). The efficiency is higher than 99.5 % for all VCSELs. The microlenses adjust the divergence of the VCSEL beams such that it matches the NA of the GRIN lens even for radial distances up to 1.6 mm. They also focus the light emerging from the second GRIN to a smaller spot onto the detector.

There is no difference in system performance if we shrink the detector diameter from 150 µm to 50 µm. We have also studied the effect of a change in spacing S between the GRINs on the performance of the link. The results are shown in figure 3b. Only the results of the three most off-axis devices are shown, because for the other ones the efficiency is at least 99.5%. The optical efficiency is constant for S ranging from 5.4 to 6.5 mm. In this domain the beam diameter and its inclination are such that no vignetting at the microlens aperture occurs. We have selected 6 mm as a nominal value for the GRIN separation because this results in the most tolerant configuration.

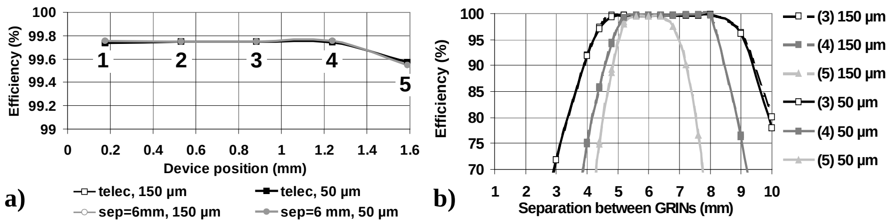

Figure 3: The efficiency as a function of a) radial distance, b) the separation between the GRINs.

The problem of vignetting at the microlens aperture is not present if the system consists of only GRINs and prisms. In that case the distance between the GRINs is not so critical and can be adjusted to accommodate even better for differences in throws between OE-VLSI chips. Therefore we have also designed a pure GRIN based interconnection module. We have calculated via radiometric simulations the optical throughput of the system for a 630 µm spacing between the prism and the emitter. The results are plotted in figure 4a. For the devices close to the optical axis the efficiency of the link is higher than 99%. The drop in optical throughput for the corner elements of a 10x10 array reaches a level of 30%, due to the decreasing NA of the GRIN with radial distance. We have also studied the effect of the spacing S between the GRINs on the performance of the link. In order not to overload figure 4b only the results for the three most off-axis devices (3,4,5) in the array are shown because the efficiency of the other ones is at least 98% over the whole range of S. We can conclude that the best efficiency can be achieved for S equal to 4.5 mm, which is a shorter distance than in the telecentric configuration. The first GRIN lens vignettes the laser beam of the corner element of the array and introduces a loss of 13%. For a telecentric configuration we get twice this loss because of the symmetry of the system. Using an interconnection module with S = 5 mm will improve the uniformity of the power impinging on the detector array to 17%.

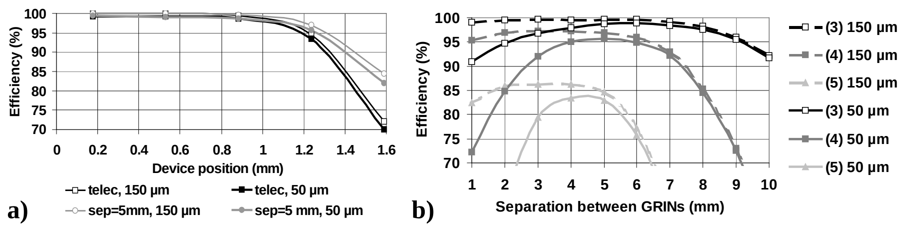

Figure 4: The efficiency as a function of (a) the radial distance, (b) the separation between the GRINs.

Comparison of the interconnection systems

We have compared the three types of interconnection modules: the monolithic micro-optical bridge, the pure GRIN system and the hybrid system (see table 1). To determine the tolerances on longitudinal and lateral misalignments of the emitter and detector array and on the interconnection length we demand that the efficiency should not drop below 85% of its maximum value. From the results displayed in table 1 we can conclude that for very short interconnection lengths, i.e. for intra-chip interconnection modules, the monolithic micro-optical bridge is the only feasible solution, because the other two systems require the chips to be separated by at least twice the GRIN's length. The GRIN-based approaches however are very well suited for inter-chip interconnects because they allow variations in the inter-chip distance up to a few millimeters. Also if we look to the alignment tolerances of the VCSEL and detector array (diameter 50 µm) we see that the GRIN lens based systems are far more tolerant than the monolithic OPB.

System:	**Monolithic**	**GRIN**	**Hybrid**
Working distance	500 µm	630 µm	320 µm
Focal number microlens	2.6	No microlens	3.25
Maximum efficiency	90%	100%	99.75%
Cross-talk	<-40 dB	No cross-talk	No cross-talk
Non-uniformity	Perfectly uniform	17 %	0.2 %
Path length L in OPB	8 mm	24.26 mm	25.76 mm
On-chip throw	4.25 mm	20.26 mm	21.76 mm
Tolerance on L	± 0.5 mm	± 2 mm	± 1.4 mm
Longit. Tolerance em/det	± 35 µm	± 60 µm	± 80 µm
Lateral. Tolerance emitter	± 7 µm	± 14 µm	± 18 µm

Table 1: Performance of the micro-optical bridge, the GRIN- and the hybrid-bridge

Conclusions

In this paper we have analysed different free-space optical modules to interconnect OE-VLSI chips placed in a co-planar configuration. We made use of a combination of GRIN lenses and arrays of refractive microlenses to design optical interconnection systems that show many attractive features such as compactness, high efficiency, good uniformity, acceptable tolerances for misalignments and many more. Our study therefore shows that these types of FSOI modules should be considered as valuable candidates to help alleviate the electrical off-chip interconnection problems that the semiconductor industry will face in the years to come.

Acknowledgments

The work reported here is funded the European Commission ESPRIT-MELARI project 22641 "OIIC", by DWTC IUAP 13, by FWO, GOA, IWT-ITA II GBO and the OZR of the Vrije Universiteit Brussel.

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