Free-Space Micro-Optical Interconnection Modules: The Missing Link for Photonics in Computing.

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ABSTRACT

We report on the design, the fabrication, the characterization and the demonstration of scalable multi-channel free-space interconnection components with the potential for Tb/s.cm^2 aggregate bit rate capacity over inter-chip interconnection distances. The demonstrator components are fabricated in a high quality optical plastic, PMMA, using an ion-based rapid prototyping technology that we call deep proton lithography. With the presently achieved Gigabit/s data rates for each of the individual 16 channels with a BER smaller than 10^{-13} and with inter-channel cross-talk lower than –22dB the module aims at optically interconnecting 2-D opto-electronic VCSEL and receiver arrays, flip-chip mounted on CMOS circuitry.

Keywords: Micro-Opto-Mechanical-Systems, optical interconnects, VCSELs

1. INTRODUCTION AND RATIONALE

Fibre-optics and free-space opto-electronic technologies have been widely investigated as means to alleviate data communication bottlenecks at the machine-to-machine, back-plane and board-to-board interconnection level [1-3]. Recent breakthroughs in the fabrication of spatial arrays of opto-electronic emitters and detectors [4,5] and their heterogeneous integration with Si-CMOS electronic chips [6-9] now also encourage the use of photonics as a wire replacement technology at the inter- and intra-Multi-Chip-Module (MCM) interconnection level [10]. With this approach one aims at increasing the communication functions between the latter electronic processing modules relaxing their bandwidth

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limitations. These limitations are primarily imposed by fundamental electrical signal propagation issues and the limited number of electrical chip pin-outs [11].

The requirements on these short range interconnect fabrics in high-performance systems are spelled out in the SIA Semiconductor road map [12]. The main thrust in this evolution is that, over the next 7 years, high-performance ASIC or processor chip sizes are expected to grow to 520 mm^2 (implying lateral dimensions of 22.8 × 22.8 mm), and that they will need up to 4000 connections to their environment (chip package or high-density substrate), of which 3000 will carry high-speed signals. Locally on the chip, frequencies will grow as high as 3.5 GHz, and across-chip frequencies are expected to hit values ranging from 0.9 to 2 GHz. Chip-to board frequencies will reach roughly half that frequency, driving buses with widths of 256 bits and more. In order to interconnect chips to their interconnection substrates, area flip-chip bonding techniques will have to be developed that will reach down to a 100 μm pitch on the chip. The substrates themselves will require track widths and spacings as low as 20 μm in order to access two rows of bumps per wiring layer. Reaching these goals will require significant research and development, as existing galvanic interconnection technology is currently not capable of providing the required performance. The road map document indeed marks several key requirements as "Research Required" or "Development Underway", "Solutions Being Pursued", or even as having "No Known Solution”. Research groups all over the world are therefore presently exploring various optical schemes to interconnect densely-packed photonic pin-outs regularly distributed over entire CMOS chip areas. Key-considerations here are the relative positions of the CMOS chips to be interconnected, the available overhead-space, the distances to be bridged, the interconnection configuration, the photonic pin-out densities, the overall power budget, the high signal integrity to be achieved at high aggregate bit rates, and the power dissipation and packaging issues. Different schemes are possible to realize these interconnection systems in practice. Most of these implementations are based on a beam-guiding approach. A second route is the use of free-space beam-shaping and beam-delivering micro-optical structures combined in compact hybrid or monolithic modules [13].

In this paper we report on the design, fabrication and demonstration of such a prototype micro-optical free-space multi-channel interconnection module. Fabricated with deep proton lithography [14] in PolyMethylMethAcrylate (PMMA) the component can be mass-produced at very low cost by injection molding replication techniques in highly advanced optical plastics agreeable to the wishes of the semiconductor industry. We start by introducing the concept of this free-space MCM interconnection component and the parameters involved in its design. We then describe the basic principles of deep proton irradiation of PMMA and shows how we apply this deep etch lithographic technique to fabricate the micro-optical structure for short distance optical interconnects, integrating refractive micro-lenses, micro-mirrors and passive alignment features. We highlight typical optical characteristics of the micro-optical structures and surfaces thus obtained. The next part of the paper is devoted to the experimental set-up and the performances of this multi-channel module. The last two sections are devoted to a sensitivity analysis for misalignments and fabrication tolerances and to fabrication issues related to the mass-replication of these components through injection-molding techniques with high optical quality plastics.

2. THE CONCEPT

2.1 Our free-space approach

The optical pathway block that we describe in this paper is an optical bridge consisting of two components. The first one is a base plate featuring two arrays of spherical micro-lenses and a pair of alignment holes. The second component integrates the counterpart mounting features and two micro-mirrors. Figure 1 shows the individual components as well as the assembled optical bridge aligned above a VCSEL and a detector array heterogeneously integrated with a CMOS chip. The concept is based on the idea that the micro-lens array positioned above the emitters would act as a beam collimator, while the second micro-lens array should refocus the beams onto the detectors. Each micro-mirror surface should make an angle of 45° with respect to the optical axes of the lenses in order to deflect the collimated beams by 90°. For our interconnection module we will only consider VCSELs as sources because for this free-space micro-lens relay concept low divergence angle emitters are imperative to avoid cross-talk between adjacent channels. Contrarily to “ individual fiber ”-based schemes, where the diameters of the fiber claddings limit the maximum channel density of the optical interconnects, the free-space bridges that we propose have the advantage that there are no major technological fabrication limitations for small lenslet diameters at different focal lengths. We only have to take care that the diameters of the lenslets are smaller than the channel pitch. This provides the free space approach with the potential advantage of being scalable because lower lens diameters imply higher channel densities and consequently higher total aggregate bit-rates.

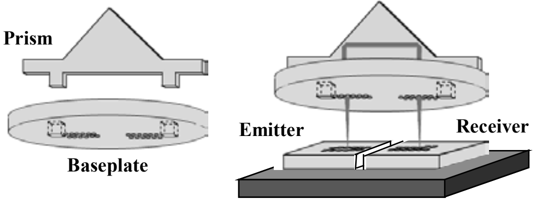

Fig. 1. Concept of a 16-channel micro-optical bridge and its components

2.2 The Gaussian beam model.

The minimum lens diameter needed to bridge a geometrical interconnection length L in this component is determined by the diffraction of the VCSEL beam which is characterized by a Gaussian angular intensity distribution, a beam waist w_O, a beam divergence θ and a wavelength λ_0. From the minimum lens diameter we can calculate the maximum channel density as a function of the distance traveled in the optical pathway block (OPB), assuming that the pitch of the channels equals the lens diameter.

We apply the rule that the laser beam must always be smaller than 2/3 of the lens diameter so that more than 99% optical throughput through the lenses is achieved and cross-talk is absent in the system. For a confocal system, where the waist is located in the center, the minimum lens diameter ϕ_{lens} for an interconnection length L is limited to

$$\phi_{lens} = 3.\sqrt{\frac{\lambda_0}{n\pi}.L} \qquad \textbf{(1)}.$$

and the maximum geometrical pathway length that can be traveled in the bridge is:

$$L_{max} = 2L = \frac{n\pi}{\lambda_0} \frac{\phi_{lens}^{2}}{9} \qquad \textbf{(2)}$$

This requirement on the minimum size of the lens diameter will restrict the device density to

$$N = \frac{1}{(\phi_{lens})^2} \qquad \textbf{(3)}$$

in case power dissipation considerations do not play an even more severe limiting role.

2.3 Channel density versus interconnection length trade-offs

For VCSELs with a FWHM angle of 12° or a beam divergence $\theta = 10°$ and a wavelength $\lambda_0 = 980$ nm this would mean that the focal number of the lenses will have to have a value $f/\# \geq 1.33$. With this simple analytical model we have calculated the allowed channel density N as a function of the geometrical pathway length L_{max} for different lens diameter sizes. The results are displayed in figure 2. From this graph we can conclude that we can trade-off pathway length and therefore interconnection length for channel density. Indeed one can increase the interconnection length by using larger diameter micro-lenses but this goes at the cost of lower channel densities. For example a micro-lens with a diameter of 100 µm could yield a channel density of 10^4/cm^2. This density however only allows a pathway length L_{max} of 5.2 mm and a array size of 26x26. With a micro-lens diameter of 200 µm in a 52x52 lenslet array on the other hand we can bridge lengths up to 21 mm, but at the cost of a lower channel density of 2.5 10^3/cm^2. A very important characteristic of these optical data transmission modules is their total data throughput capacity. The data throughput per chip area of a data link is defined as the bit-rate per channel multiplied by the channel density in the interconnection module. In general the channel densities and the bit-rates that can be achieved are primarily limited by the maximum allowed power dissipation of the opto-electronic emitters and receivers and their CMOS or bipolar drivers. Usually power dissipation densities are limited to 10W/cm^2 for air-cooled silicon or to 100W/cm^2 when the chip is actively-cooled. As stated above an additional limiting factor in the particular case of free-space OPBs is the diffraction of the laser beams rather than their attenuation in the optical medium. This causes the channel density to drop with increasing interconnection length and limits the total throughput per chip area for an interconnection length beyond a couple of centimeters [15]. Notwithstanding these and other types of limiting factors it is important to notice that for this type of free-space interconnection modules all the different performance analyses converge to the same conclusions: interconnect densities of 10^3/cm^2 at around 1 Gb/s bit rate can be achieved for passively cooled chips, which corresponds to an aggregate throughput capacity of 1Tb/s.cm^2, while actively cooled systems could even perform aggregate bandwidths of several Tb/s.cm^2 over future inter- and intra-MCM interconnection distances [15-17]. The performances of both plastic optical fiber wave-guide and free-space optical pathway blocks have previously been compared [15]. As a general conclusion one can say that while both approaches have the potential for Tbits/s.cm^2 fire-hose data handling capacity the rigid free-space module and the more flexible guided-wave approach are complementary in that the first is better suited to bridge distances smaller than a few centimeters while the latter is more appropriate for interconnection lengths of several centimeters and more [15].

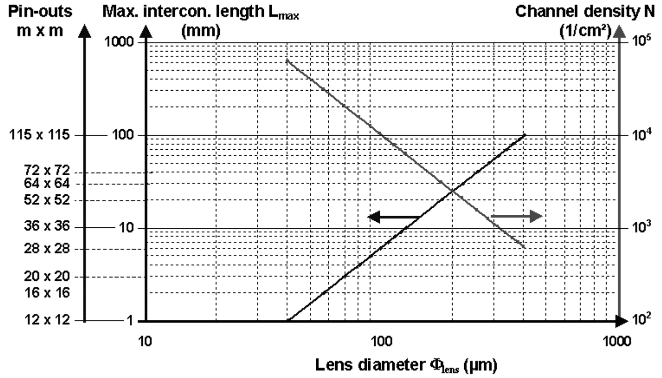

Fig. 2. Channel density versus interconnection length

3. DESIGN OF THE OPTICAL BRIDGE

In this case-study we have based the design of our prototype free-space OPB on the lay-out and the characteristic dimensions of the photonic chip proposed and fabricated within the European Community funded MEL-ARI project “Optically Interconnected Integrated Circuits ”. In this specific case the optical bridge will be used to interconnect an 8x2 array of 250 µm-pitched 980 nm VCSELs with an 8x2 array of 150 µm diameter InP receivers. The geometrical distance L_{max} to be traveled inside the OPB for this configuration is 8 mm. Using the analytical model describing the confocal micro-lens relay we estimate that for this distance a minimum lens diameter of 115 µm is needed to achieve 99% transmission efficiency while avoiding cross-talk. We have opted for a lens diameter of 200 µm which is the maximum possible lens diameter obtainable with our non-contact deep proton lithographic LIGA-mask while respecting the device pitch of 250 µm. To calculate the focal number of the micro-lenses and to optimize the optical throughput of this system we have used ray-tracing simulations and radiometric calculations using the photonics design software SOLSTIS. In doing so we have generalized the simple Gaussian beam confocal model. Here optical throughput has been defined as the ratio of the optical power received by the detector to that emitted by the VCSEL. The inter-channel cross-talk is calculated as the ratio of the power that falls on the adjacent detector to that impinging on the targetted one. The fixed reflection and absorption losses of the OPB are not included in the calculations. We have performed radiometric simulations of OPBs with microlenses of focal lengths ranging from 340 µm to 560 µm and for different working distances between the lenses and the emitter and detector array. For the single mode VCSEL we assumed a circular geometry with a Gaussian emittance and a Gaussian angular intensity distribution with a FWHM angle of 12°. The VCSEL is simulated using a Monte Carlo method. This way rays are emitted from the source in a quasi-random manner in accordance with their emission probabilities. These rays are propagated through the system and their intersection with the detection plane is calculated. Efficiencies as high as 96 % can be achieved. For our design we have selected a focal length for the microlens of 520 µm, because in this case the link still has an efficiency of 90% and the system is very tolerant with respect to changes in the working distance. A practical working distance was chosen in the middle of the flat region of the efficiency curve and has a value of 500 µm (see figure 3a). For these optimized design parameters an optical cross-talk of smaller than –40 dB was calculated. Based on these design characteristics we have fabricated the two basic micro-optical bridge components with dimensions as displayed in figure 3b, using deep proton lithography.

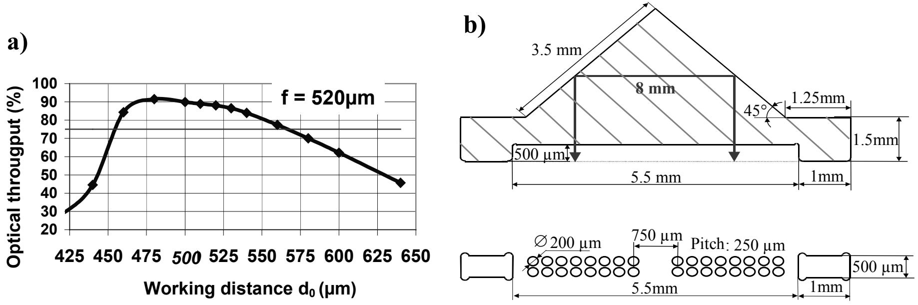

Fig. 3. a) Optical throughput of the free-space approach using single mode VCSELs
b) Dimensions of the free-space OPB

4. PROOF-OF-PRINCIPLE DEMONSTRATION

Figure 4a shows the side view of the assembled free-space 2-D multi-channel interconnection module. We have used all 16 channels individually to establish an optical link between a single-mode pigtailed 1 mW CW 680nm laser and a multi-mode pigtailed silicon detector. Here the single mode input fiber with a NA=0.11 was used to mimic the emission characteristics of a VCSEL source whereas the multi-mode fiber with a NA=0.2 and a core diameter of 50 µm simulated the photo-detector. The distance traveled within the bridge is 8 mm and corresponds to a maximum on-chip interconnection distance of 4.2 mm. The optical transfer efficiencies for the 16 channels were measured to be in the range of 40% to 46% with a cross-talk between neighboring channels of –22dB to –27dB. To demonstrate the potentialities for high bandwidth intra-MCM data communication we connected the single mode input fiber to a standard telecommunication card operating at 1300 nm on the OC-12 SONET carrier level, providing us with a quasi-random 622Mb/s bit stream and reliable data transmission with a bit error ratio less than 10^{-13} was obtained (see figure 4b). Because of the short interconnection distances neither dispersion nor absorption will play a limiting factor on the maximum achievable bit rate. We have indeed already reported on the demonstration of a 2.48 Gb/s one-dimensional multi-channel module based on cylindrical micro-lenses fabricated with deep proton lithography [13]. In both cases we were only limited in bit-rate by our testing equipment. Although the experimentally obtained optical transfer efficiencies of 40-46% are sufficiently high and the cross-talk acceptably low to obtain reliable short distance parallel data transmission, it is clear that with this first prototype component we do not reach the calculated maximum transmission efficiency of 83 % and the –40dB cross-talk. We can impute this partly to a combination of geometrical and optical fabrication imperfections, partly to misalignment errors and partly to the fact that the input and output fibers are only approximate imitations of the VCSEL source and the photo-detector.

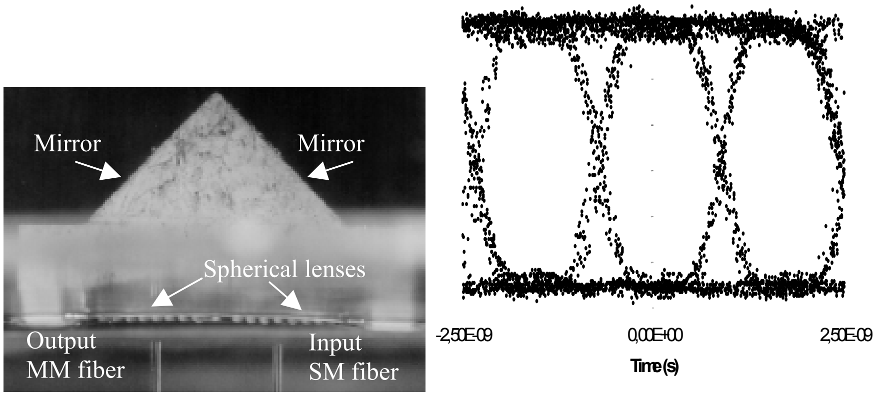

Fig. 4. a) Assembled free-space 2D multi-channel interconnection module, b) Eye-diagram for data communication through a single micro-optical channel at 622 Mb/s and 1300 nm

5. CONCLUSION

In this paper we reported on the concept of a scalable multi-channel optical data-link with Tb/s.cm^2 aggregate bit rate capacity for inter- and intra-chip module interconnection distances. A simple prototype module was designed. The individual components were fabricated with deep proton lithography in PMMA and their optical characteristics were measured. With the assembled module we demonstrated the potentialities for intra-MCM data communication at high bit rates for 16 channels @ 622 Mbit/s per channel with a BER smaller than 10^{-13} while the cross-talk between neighboring channels was lower than –22dB.

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