Design of free-space microlens-relay optical interconnects: A focus on optical efficiency and scalability

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We analyze the potentialities of microlens based optical interconnects to Silicon. We model and compare the performances of different microlens-relay configurations. We show that their scaling performance exhibits a different behavior depending on the beam divergence of the VCSEL sources and on the minimum optical efficiency that is needed. Only when VCSELs are used with FWHM divergences less than 7 degrees, spherical aberration becomes important. The use of real ray-tracing or beam propagation methods is then imperative to properly design the microlens system.

Introduction

Near-future inter- and intra-chip data communication bottlenecks [1] can be solved through the use of 2D-photonic pin-outs by way of flip-chip mounting VCSEL and detector arrays on Si-CMOS. Low-cost free-space micro-optical pathway blocks [2] are needed to link up these photonic pin-outs with the outside world. This approach potentially offers higher channel densities, higher bandwidths, lower latency and lower power dissipation. The question however remains as to whether VCSEL-operated micro-lens relay modules could fulfill the requirements on pin-out density and interconnection length in practice.

In this paper we will investigate the relationship between channel density and interconnection length for a microlens-based free-space optical interconnect system (FSOI). This study leads to the scaling behavior of practical microlens-relay interconnection modules that link the diameter of the microlens and therefore the channel density to the maximum achievable optical pathway length. We will show that this scaling performance exhibit a different behavior depending on the beam divergence of the VCSEL sources and on the minimum optical efficiency that is needed.

The concept of a free-space micro-optical bridge

The free-space optical pathway block (OPB) that we have designed and modeled consists of two components. A first component 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 a 90° angle prism. Figure (a) shows the individual components while figure 1 (b) displays the assembled optical bridge positioned on top of a VCSEL and detector array that are heterogeneously integrated with a VLSI chip. 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. The free-space ‘optical bridge’ concept allows increasing the channel density by using smaller microlens diameters. Since there are no major theoretical fabrication limitations to obtain short focal lengths for very small lens diameters [3], we may say that our FSOI approach has the potential advantage of being scalable with the diffraction of the VCSEL beam as main limitation for the minimum lens diameter and the interconnection length. We can simplify the modeling by omitting the 90° deflections at the prism surfaces and considering only the curved air-PMMA interfaces of the microlenses, separated by a distance *L*, as shown in figure 1 (c). The beam waist of a VCSEL with radius ω_o, located at a working distance d_o, is then imaged by the input microlens with focal length *f* at an image distance d'_o.

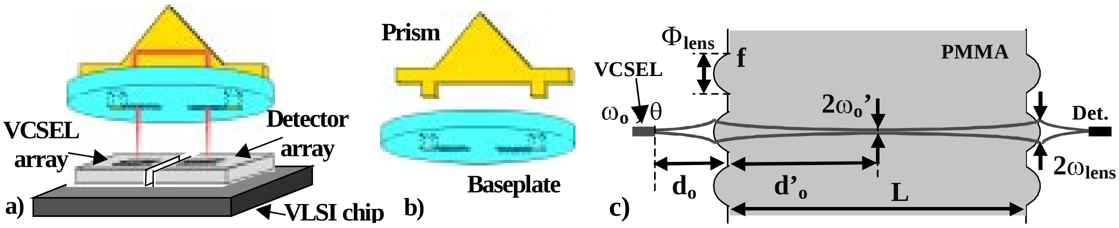

Figure 1: (a) Concept of a multi-channel micro-optical bridge (b) and its sub-components. (c) Model of our optical system.

We will only consider symmetric systems. Hence the path length *L* in the OPB equals to twice the image distance d'_o, and the focal length of the output microlens is identical to that of the input microlens. For this reason the detector is placed at a working distance d_o behind the output microlens.

Design methods used

We used three different methods for the design of this micro-optical bridge. First we did an analytic Gaussian beam propagation (GBP) calculation, which satisfies the paraxial Helmholtz equation. This results in a first order layout of the system, and gives us the diameter of the lenses, their focal length and working distance, depending on the beam parameters and on the requirements imposed on the interconnection length and optical efficiency of the module. Once these design parameters are known, we modeled the optical component with the photonics design software SOLSTIS [4] and evaluated its performance. Therefore we have simulated the system via ray tracing and radiometric calculation (RAD). It is based on a Monte Carlo method, in which real rays are emitted from the source in a quasi-random manner in accordance with the emission probability of the source and are propagated through the optical system. In this case also the aberrations are taken into account. The latter method however has no inherent support for the optical characteristics of coherent light and since we also wanted to identify the effect of the diffraction of the laser beam on the system performance, we carried out a beam propagation analysis method (BPM) where laser modes are propagated through the optical system. The emitted fundamental mode of the VCSEL is represented as a superposition of plane waves. To simulate the coherent source a Monte Carlo method is used that generates the plane waves in agreement with the source emission pattern. The Fresnel-Huygens law is used to propagate the elemental fields to the analysis plane where they are integrated to result in the image wave front. In this case both aberrations and diffraction phenomena are considered.

Practical guidelines for micro-optical relay system design

To study the scaling properties of the micro-optical relay system, we have considered different design layouts and we have evaluated these designs via RAD and BPM simulations for VCSELs with FWHM divergences ranging from 1° to 20° and for path lengths (L) in the OPB between 4 mm and 20 mm [5].

If we want to design an efficient micro-optical relay systems, we can apply the rule-of-thumb that the diameter of the microlens should be at least three times the beam waist radius at the lens, allowing a 99% energy throughput through the lenses. The obvious system layout for such an interconnection module is a Rayleigh design, where the path length between the two microlenses equals twice the Rayleigh distance. This minimizes the required lens diameter for a given interconnection length, resulting therefore in the highest possible channel density. In figure 2 we have plotted the optical efficiency (obtained with a GPB, RAD and BPM analysis) as a function of the FWHM angle of the VCSEL and this for a Rayleigh system that bridges a path length (L) of 8 mm. It is clear from this graph that for this system the 98% optical efficiency, predicted by simple analytic GBP, cannot be reached for VCSELs with FWHM divergences larger than 5°. This is because the GBP analysis does not take into account the lens aberrations, which deteriorate system performance if small focal numbers are implemented. Because of the smaller focal lengths needed for the more divergent VCSELs, the optical system starts suffering from large spherical aberrations (SA). As a consequence it has an efficiency that is much lower than expected. This means that a first order layout of the optical system via paraxial Gaussian optics will not result in the expected system performance and more elaborated simulation models are compulsory to design these systems.

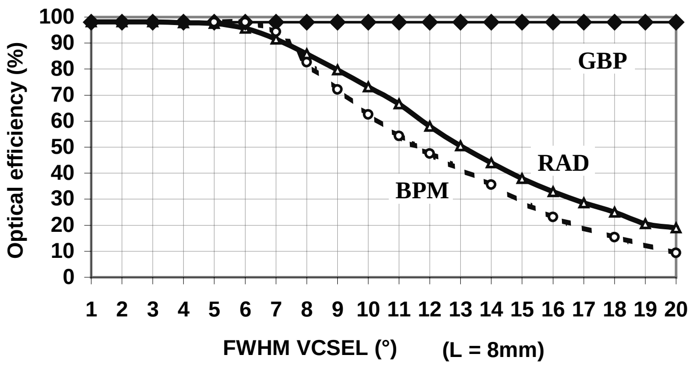

Figure 2: Efficiency as a function of VCSEL divergence angle for a Rayleigh system with L = 8 mm

In a next step we have investigated more general symmetric system layouts, where the lens diameter is not optimized for a given path length. This results in systems with larger lens diameters but also with longer focal lengths and larger focal numbers. Consequently these slower lenses introduce less spherical aberration and will allow a higher optical throughput of the system for higher divergent VCSELs. We have deduced the scaling behavior of this type of micro-optical relay systems. In figure 3 the practical required lens diameter is given as a function of pathway length considering the aberrations in the system. If both the minimum efficiency level, which has to be reached is given (85% in case of figure 3) and the divergence of the VCSEL, the scaling plots then give the required diameter for the microlenses. Once we know the diameter for the lenses we can calculate the focal length and the working distance, using simple analytic GBP. Since we already took care of the aberration effects at the moment we selected the value for the lens diameter, the calculated design parameters will result in an interconnection system that has the predicted system performances.

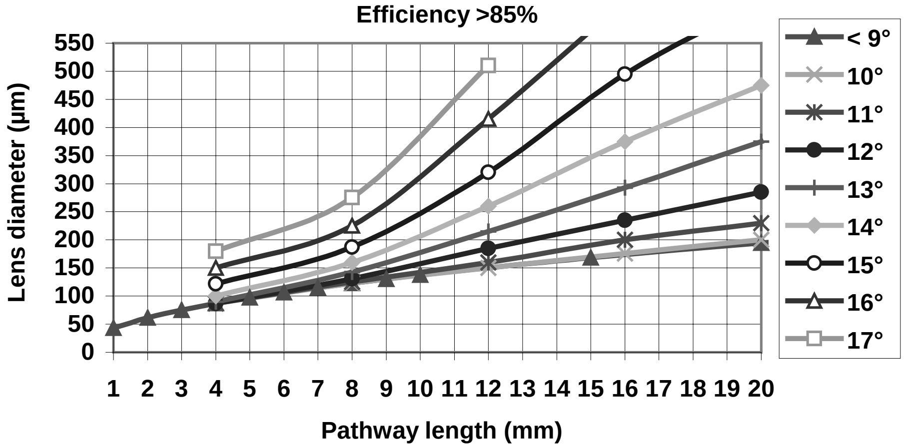

Figure 3: Lens diameter versus pathway length for system efficiency of 85% and for different VCSEL FWHM divergences

Conclusions

We have shown that the scaling performance for practical microlens-relay interconnection modules exhibits a different behavior depending on the beam divergence of the VCSEL sources and on the minimum optical efficiency that is needed. Only when VCSELs are used with FWHM divergences less than 7°, spherical aberrations can be neglected and channel densities can be derived reliably with a first-order layout. For VCSELs with a divergence larger than 7°, a simple analytic Gaussian beam propagation method is not adequate to design microlens relay-based optical systems and the achievable channel densities are much lower because of aberration deteriorations.

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