Soft-lithography-based Inter-chip Optical Interconnects

Wei Ni\textsuperscript{1}, Rubing Shao\textsuperscript{1}, Jing Wu\textsuperscript{2}, and X. Wu\textsuperscript{1}

\textsuperscript{1}State Key Laboratory of Modern Optical Instrumentation, Department of Optical Engineering
Zhejiang University, Hangzhou 310027, China
\textsuperscript{2}University of California at San Diego, La Jolla, CA 92093, USA

Abstract — The increasing performance of microprocessors leads to higher bandwidth requirements for the data flow to and from the processor. Today, all signaling on a PCB is performed electrically, using copper lines that are integrated in the board. However, issues such as propagation loss and inter-channel crosstalk limit the scalability of electrical interconnects to ever higher bandwidth densities. Optical interconnects feature a higher bandwidth \times length product, are more power-efficient and enable a higher bandwidth density than electrical interconnects do. This paper describes a kind of two-dimensional monolayer optical interconnects providing interconnections between chips on conventional PCB. We have designed a soft-lithography-based, versatile coupling structure with a 45° total internal reflector (TIR), a beam duct, and a polymer waveguide in order to vertically couple light beams between transmitter (or receiver) and the waveguide layer. This proposed integrated architecture of a polymeric optical interconnection has been demonstrated to be advantageous in the aspects of misalignment tolerance, ease and low cost of fabrication, as well as relative simplicity in deployment. We also investigated the characteristics of in-plane connections including cross-over and branching nodes in the optical interconnects with experimental and theoretical analysis. The theoretical crosstalk, as calculated by a function of crossing angle, was determined for a set of interconnect pairs with varying cross-sections, and was compared with experimental measurements. Furthermore, a suitable branching angle was found for branching node and the effects of short-distance mode scrambling in highly multimode polymer waveguides were studied in detail in this paper too.

1. INTRODUCTION

Photonic technologies have been widely accepted as a way to alleviate bottlenecks in platform-to-platform, machine-to-machine and board-to-board interconnections [1]. Recent breakthroughs in the fabrication of spatial arrays of optoelectronic emitters and detectors and their heterogeneous integration with Si-CMOS electronic chips now encourage the use of optics as an electronic wire replacement technology also at the chip-to-chip and on-chip interconnection level as in Figure 1. The main objective for introducing two dimensional photonic pin-outs at this level of the interconnection hierarchy aims at relaxing the bandwidth limitations between these electronic processing modules primarily imposed by fundamental electrical signal propagation issues and the limited number of electrical chip pin-outs. With the debut of 25 Gb/s board-level interconnects, optical interconnects have demonstrated their ability to provide communications infrastructure for next-generation computing [2, 3]. In the domain of very-high-bandwidth short-range communications, light-based waveguides have consistently demonstrated higher placement density, more packaging flexibility, and superior alignment reliability than their electrical counterparts [4, 5].

A kind of two-dimensional monolayer optical interconnects providing interconnections between chips on conventional PCB are proposed in this paper. Detailed theoretical analysis along with the experimental measurements of the interconnection circuit performance is also presented.

2. VERTICAL COUPLING

Most prior designs of optical interconnections usually call for a high-precision Vertical Cavity Surface Emitting Laser (VCSEL)/Photodiode (PD) alignment, often with an alignment-error requirement of less than a few micrometers; this exhibits an immediate difficulty in the assembly of electro-optical PCBs. In order to increase the tolerance of the interconnection waveguide to alignment errors, we have designed coupling structure with a 45° TIR, a beam duct, and a polymer waveguide as in Figure 2(a) in order to provide high-speed optical communications within a board; the driving electrical pulses modulate the VCSEL, and the light received at the photodiode through the waveguide demodulates back as electric signals on the surface of the PCB. We utilized Zemax\textsuperscript{\textregistered} to simulate the efficiency of the beam duct by varying the length of duct section while
output light in the waveguide was monitored, and portion of simulation is displayed in Figure 2(b). The coupling efficiency peaked at around 6 mm for TIR reflector’s triangular prism structure at the proposed $0.5 \times 0.5 \text{mm}$ with waveguide cross section of $0.3 \times 0.3 \text{mm}$.

![Figure 1: Interconnect distance.](image1)

3. CROSSING AND BRANCHING OF LIGHT GUIDES IN IN-PLANE INTERCONNECTS

However, as optical interconnects will inevitably cross in-plane when used heavily within circuits and PCBs, cross-over or branching nodes are necessary for signal crossing, splitting, or isolation, and the performance of these nodes in the circuit becomes critical in determining the overall quality of optical signal transmission.

3.1. Crossing Node

For the cross-over node, as shown in Figure 3(a), crosstalk is usually required to be as low as 20–30 dB for a reliable data communications. Considering the multimode nature of the waveguides for on-board optical interconnections, we utilized both wide-angle BPM and ZEMAX® to simulate the efficiency of polymer rectangular waveguide by varying cross angle, while the output from the waveguide was monitored.

The results are shown in Figure 4(a) and (b) for both strong-confinement and weak-confinement core/clad assemblies, respectively. As shown in Figure 4, crosstalk as a function of cross angle was calculated and compared to experimental measurement for four selected cross sections of $50 \times 50 \mu\text{m}^2$, $100 \times 100 \mu\text{m}^2$, $200 \times 200 \mu\text{m}^2$, and $300 \times 300 \mu\text{m}^2$, with a cross angle ranging from $10^\circ$ to $55^\circ$ for strong-confinement assembly (core 1.50, cladding 1.00) and $5^\circ \sim 12.5^\circ$ for weak-confinement (core 1.50, cladding 1.48). For weak confinement, it is found that the crosstalk decreases linearly with crossing angle from $5^\circ$ to $9^\circ$, and then exhibits a faster-than-exponential attenuation when cross angle increases from $9^\circ$ to $12^\circ$; when above $12^\circ$, a crosstalk of less than $-30 \text{dB}$ is obtained. For strong confinement, however, a greater crossing angle of about $52^\circ$ is needed to achieve a $-30 \text{dB}$ crosstalk. It is also noted in Figure 4 that the $-20 \text{dB}$ cross angle, as denoted with dotted blue lines,
increases slightly with waveguide cross-section for both strong and weak confinement conditions. It is understood that as cross-section increases, the size of the crossing joint also increases, and so does the window of leakage to adjoining waveguide, therefore it takes a greater cross angle to achieve the same crosstalk.

Figure 3: (a) Schematic of a cross-over interconnect pair, (b) schematic of a branching interconnect pair;

Figure 4: Dotted blue line shows that crossing angle changes with cross-section at $-20$ dB crosstalk. Open symbols and blue fitted curves stand for experimental measurements. Refractive indices of core/cladding were at (a) 1.50/1.00 and (b) 1.50/1.48.

3.2. Branching Node
Highly multimode Y-branching deserves special attention for its possible applications in polymer interconnects, particularly due to the special phenomenon of beam center shift in post-branching waveguides, which significantly affects their crossing characteristics. We took the case of weak-confinement assemblies and calculated power leakage in BPM simulation for both $50 \times 50 \mu m^2$ and $100 \times 100 \mu m^2$ cross-sections as a function of branching angles at the Y-junction, as shown in
Figure 5(left), for a branching angle varying from 1° to 18°. By using BPM simulation we found that until a branching angle of 7° is reached, the leakage for 50 × 50 µm² light guides is negligible. In the range of 7° ~ 12°, the leakage suffers a linear increase from 0 to 100%, and remains at a constant for angles beyond 12°. The phenomenon is partly explained by Figure 5(right), which shows part of leaking waves in Y-branching at 3°, 8°, and 15°.

3.3. Mode Scrambling Dependence
Moreover, multimode waveguides exhibit many special transmission properties over short-range (mm to cm) applications [6, 7], such as mode scrambling and shifting of the center of beam intensity. Thus the single-mode beam from VCSEL should be transformed into multimode within a short distance before its further propagation in the optical layer. In our practical layout designs, it was found that a non-uniform mode distribution would influence follow-up circuit output by a great deal and makes it nearly impossible to predict output power from final terminals. A mode scrambler is thus a necessity in order to make beam output as planned. In case of board-level interconnection, however, instead of a particularly designed structure or a coil of fibers, a short segment of polymer rectangular waveguide with a suitable length can serve as the scrambler.

To obtain a good estimation of the shortest propagation length needed to scramble a VCSEL beam, we conducted an analysis of beam mode scrambling in terms of intensity profile as well as distribution of ray directionality. We define VCSEL beam filling factor as the fraction of FWHM (full width at half maximum) of intensity profile over waveguide width. For two typical cross-
sections of waveguides used in interconnects, 50 × 50 µm² and 100 × 100 µm², the beam filling factor was calculated as a function of propagation distance using Monte Carlo simulation and result is shown in Figure 6(left), it follows that minimum lengths of 1.3 mm and 2.5 mm are needed, respectively, for the beam to uniformly fill up the 50 × 50 or 100 × 100 µm² waveguides in terms of intensity regardless of incident direction. Four profiles of VCSEL beam filling factor of 10%, 25%, 40%, and 80% are shown in the insets of Figure 6(left). However, it actually takes a much longer propagation distance for ray direction to become completely scrambled. To demonstrate the effect, we calculated crosstalk at a 9° cross angle as a function of straight distance between a single mode VCSEL and crossing point and the result is displayed in Figure 6(right), in which a peak in crosstalk from below −11 dB to −9 dB was shown at 1.05 mm and 2.38 mm for 50 × 50 and 100 × 100 µm² light guide respectively, followed with three satellite peaks spanning to 15 mm of propagation distance.

4. CONCLUSIONS
Our analysis from the fabricated prototypes, demonstrate that this proposed integrated architecture of a polymeric optical interconnection for conventional PCB implementation is advantageous in the aspects of misalignment tolerance. The 2 × 2 cross-over circuit, as detailed in this paper, can achieve acceptable crosstalk at a cross angle of greater than 12° in weak confinement. We have also obtained suitable branching angle of a 1 × 2 branching node for the purpose of reducing leakage in the Y-junction. We have finally found proper lengths of propagation in a branching arm for the consideration of distribution uniformity of light rays. The results have a high degree of applicability to future optics-integrated PCBs featuring soft-lithography-fabricated interconnect structures.

ACKNOWLEDGMENT
This research is supported by the China National Science Foundation under grants No. 6047719.

REFERENCES