Development of Electro-Optical PCBs with Polymer Waveguides for High-Speed on-Board Optical Interconnects

M.Immonen [1], J.Wu [2], P.Chen [2], M.Ma [3], J.X.Xu [3], T.Rapala-Virtanen [4]
TTM Technologies Inc.
[1] Vilhonkatu 8, 02300 Salo, Finland
[2] No. 685 Lian Yang Road Songjiang, 201600, Shanghai, P.R.China
[3] No. 200 Jiangtian Rd. East, Songjiang 201600, Shanghai, P.R.China
[4] No. 1, Xinle Road, 510663, Guangdong Province, P. R.China
Corresponding author: Marika.Immonen@meadvillegroup.com

Abstract

We have developed technologies to embedded high-speed polymer optical interconnects on printed circuit boards for 850 nm applications. In this paper, we show results of fabricating optical-PCBs on a production scale panels in a modern HDI-PCB (high-density interconnect-PCB) process environment. Impacts on board design and manufacturing were studied with the developed optical technology verifiers. One verifier is an optical-PCB with 3-D optical routings realized with embedded waveguides, integrated i/o couplers and optical vias. Another one is a system level optical board assembly with 12.5 Gb/s Tx/Rx devices on surface mounted ball grid array (BGA) modules implemented for optical link analysis. Results show that optical waveguides were successfully embedded in conventional PCBs. Optical layer sustained undamaged during pressing used for multilayer PCB fabrication. Process was found capable of producing versatile multimode waveguides 25-50 µm microns square with step index structures with low-loss and tight bending radius. This paper describes design and fabrication of OE-PCB boards and waveguide termination by out-of-plane optical coupling structures. Fabricated boards are characterized of their functionality, physical characteristics and optical alignment throughout the critical optical path. Based on the results, capabilities of a modern production infrastructure to fabricate optical-PCBs and board assemblies are discussed.

Keywords: Optical interconnects, optical backplanes, optical PCB, optical waveguides, polymer waveguides

1 Introduction

The rapid spread of cloud computing services, smart phones, and bandwidth hungry applications such as real-time video processing are expected to strain data center networking infrastructure. Today, applications and datacenters are moving from 1 Gbps to 10 Gbps. It is anticipated that by 2017 market for 40 GbE ports will leverage off the existing 10G serial technology followed by wider use of 100 GbE [1]. Although 100 GbE initial deployments in the market utilize 10 G serial technology, narrower interfaces are needed to respond density requirements, to provide smaller package sizes, lower pin count components, connectors and optical modules, to lower power dissipation and clockless interfaces. [2]. For that, OIF CEI-25 project electrical specifications will define 28 Gbps signaling for chip-to-chip/module applications and 25 Gbps signaling for backplane applications. As data rates increase so does the challenges related long copper traces to maintaining signal and power integrity. Issues such as noise, jitter, inter-symbol interference and crosstalk will cause various design and fabrication challenges [3]. Optical interconnects have been suggested as a potential enabler for short-reach applications in future high performance computing (HPC) systems. Optics enables massive data transmission rates, however, the data center presents a different set of challenges. Low cost, low power dissipation, low latency, small physical size, and the ability to integrate with mainstream silicon electronics are more important than the ability to transmit signals over long distances, as is the traditional telecoms focus. Recent industry development efforts indicate of emerging need and interest to employ optical links in computer systems [4, 5, 6]. However, commercial implementation of optical links for data centers and in general for short computer network links, is prohibited by relatively high cost and high power consumption. The highest bandwidth-distance requirements (Tbpbs of data transmission over dozens of meters from one module are encountered in the hub/switch chips used for large-scale clusters and supercomputers – which are where the earliest requirements for densely-integrated optical interconnects are found [5]. An example of optical intra-system interconnect link in blade-server system is illustrated in Fig. 1.

Our work is motivated by the continually increasing bandwidth need in inter- and intra-board interconnects, which are demanding optical solutions that maximize bandwidth per unit area and minimize power consumption and cost. In this paper, we show results on developed OE-PCBs with polymer waveguide layers for high-speed optical signal routing. Impacts on board design and manufacturing are investigated with technology verifiers fabricated on production scale panels. Results on optical module assembly, optical connector assemblies and link level characterization are reported in the conference.

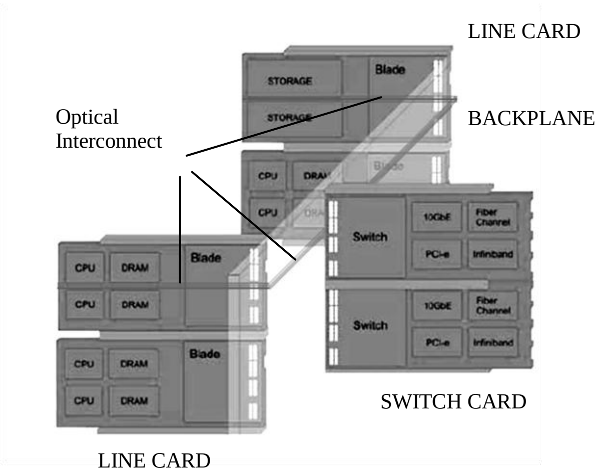


Figure 1. Optical Backplane Interconnect System [7]

2 EXPERIMENTAL

We have designed multiple generic optical test beds to verify design parameters and connectivity options for practical optical backplane system operating at 850 nm. The Test Vehicle (TV) reported in this paper is illustrated in Fig. 2. TV was designed to characterize polymer waveguide fabrication and performance on conventional MLB (multilayer) boards, to characterize optical via holes and high precision alignment structures for optical coupling, and to characterize waveguide coupling with fiber-ended connectors. TV is also used as a chip-to-chip waveguide interconnect data link demonstrator, as illustrated in Fig. 3. To allow use of high-precision tooling, TV size was restricted to 5”x5”, limiting straight waveguide links to 4”. Optical backplane with straight 8” and 12” waveguide channels, and 39” spiral is in evaluation and will be reported in the follow-on papers. TV was varied in board construction and layer count (2+W and 2+W+2, w=waveguide). Also, optical layout was varied to provide multiple design features – straight, cross-overs, bent waveguides – to meet practical application needs. Waveguides are terminated with 45° out-of-coupling micro-mirrors and with vertical edge. High-Tg FR-4 was selected as base material. Optical layer was fabricated on the laminate base. The waveguides are multi modal type with numerical aperture (N.A.) of 0.37. WGs were designed with square step index profile in multiple core sizes (WxH) of 25x50μm^2, 50x50μm^2, 70x50μm^2. Optical layers were fabricated in our production site as reported in [8].

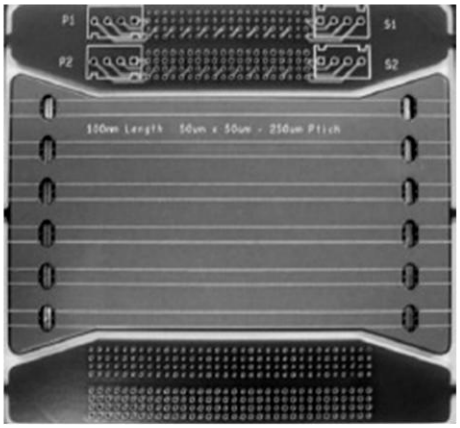


FIGURE 2. TEST VEHICLE BOARD WITH EMBEDDED WAVEGUIDES.

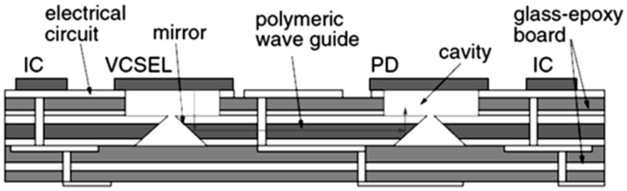


FIGURE 3. STRUCTURE OF OPTOELECTRONIC-PCB TEST VEHICLE FOR CHIP-TO-CHIP OPTICAL DATA LINK DEMONSTRATION.

For practical optical interconnect the maximum channel insertion loss is less than 10-12 dB. The channel insertion loss includes waveguide losses, coupling device losses, connector and splicing losses, and waveguide routing losses i.e. transition losses in bent waveguides due to modal mismatch between bent waveguide segments, and losses incurring at the crossing junctions in the waveguides. Currently, practical backplane link implementations are prohibited by immaturity of optical connectors, lack of low-cost low-power optical engines operating beyond 25 Gbps, and high waveguide loss, typically 100x compared with optical fibers. Each link component needs to be characterized individually and as a complete board-level link. This paper focuses on waveguide link; other parts are covered in the follow-on papers.

The reference optical link design is illustrated in Fig. 4. It describes end-to-end link parts in the target backplane-card system with 4 optical connectors. Optical engines are located close to host IC to avoid long high-speed traces on PCB. Engines are provided with MT/MTP termination.

High alignment accuracy is of paramount importance to achieve low optical coupling loss in the mating optical interfaces. Coupling loss is reduced further by matching the mode field and aperture of the optical link parts. At the waveguide input interface optical interfaces were designed with progressively larger aperture size and N.A. Aperture design in the link is VCSEL Ø ~10 µm to 50 GI MMF to 50 µm waveguide to 62.5 GI MMF to Photodiode Ø ~70 µm. Optical aperture design is VCSEL N.A.~0.2 to waveguide N.A. ~ 0.2-0.28 to 62.5 GI MMF N.A. 0.28 to detector.

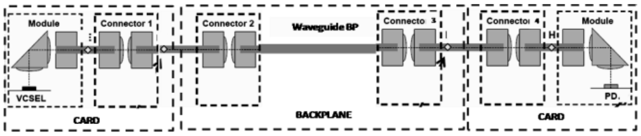


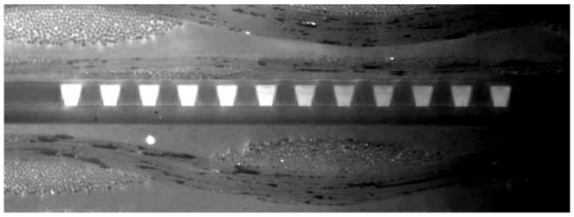
FIGURE 4. OPTICAL LINK DESIGN

Optical waveguide transmission loss, mirror coupling efficiency, and optical alignment tolerance are measured using insertion loss measurement at 850 nm. The physical characteristics (e.g. dimensions, surface roughness, and alignments) of the fabricated optical structures in PCBs are qualified using optical microscopy, confocal laser scanning microscopy (CLSM) and scanning electron microscopy (SEM).

3 RESULTS

3.1 *Optical Waveguides and Out-of-Plane Couplers*

First, the optical waveguides were evaluated of their physical characteristics – dimensional accuracy, alignment accuracy, core and clad optical surface quality, and process induced errors. Optical cladding layer surface roughness (micro roughness) was found very low, less than Ra=0.020 µm, even though built on an inherently rough base of Ra=0.670 µm. Core process needed optimization to achieve high L/S definition and low roughness in vertical walls. Micrographs of the core channels and cross-section of embedded waveguides are shown in Fig. 5. Also, materials mechanical toughness to withstand pressing conditions was evaluated of physical cross-section samples, and by comparing the measured loss before and after pressing. Optical layer sustained undamaged during the pressing conditions (total time 185min, T_{Peak}=195°C, P_{max}=2,4 MPa). Increase in IL was < 0.035 dB/cm.

a)


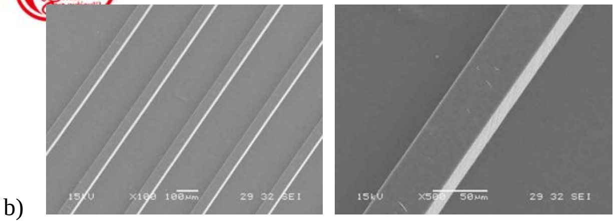


Figure 5. a) Cross-section of fabricated 50 µm waveguides embedded in OE-PCB. L/S 50/50 µm, Pitch 100 µm b) Fabricated waveguides L/S 50/200 µm, Pitch 250 µm.

Micro-mirrors fabricated as out-of-plane beam couplers are shown in Fig. 6. Critical mirror parameters – angle, flatness, surface roughness and positional accuracy were characterized. The measured mirror angle was 45° ± 1°. The average surface roughness was Ra= 75 nm. Yet, the peak-to-valley of the roughness Rz was in a range of hundreds of nanometers. Subsequently, the measured loss exceeded the specified value IL < 1 dB. The results indicate that the process is capability of fabricating uniform flat planes usable for micro-optical couplers, but further optimization is needed to reduce Rz and loss.

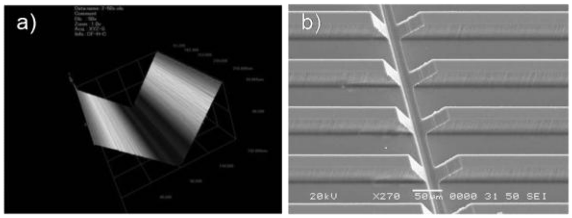


Figure 6. a) 3D profile of a mirror facet, b) Turning mirrors in 50 µm waveguides.

3.2 Insertion Loss Measurements

The insertion loss (IL) on the waveguides was measured using LSPM (Light Source Power Meter) method according to IEC 62496-2-1. Different launching/receiving conditions were used to of separate loss factors in the measured insertion loss. Earlier we used the cut-back method; here the measurements were conducted without destructive analysis. CW (continues wave) light was launched into the waveguide through a 1.5-meter-long multimode optical fiber with a 50 µm core (50 GI MMF) and N.A. fiber = 0.2 connected to an 850 nm VCSEL source on one end. The other end of the fiber was aligned and butt-coupled to the waveguide core with a larger N.A. waveguide = 0.37. A long input fiber was used to provide sufficient inter-mode coupling to ensure a uniform modal distribution pattern at the launch point into the waveguide. Initial measurement without DUT (device under test) was made to determine the reference power with the LSPM and fiber cables. In the first measurement case, light was collected with a large area silicon photodetector aligned to the waveguide. In the second arrangement light launching conditions were unchanged, but at the output side light was captured by 62.5µm cored fiber (62.5 GI MMF) with N.A. fiber =0.28 coupled to the detector. The coupling loss (CL) at the output side was derivated by comparing area detector and fiber measurements. Polymer material loss was characterized using low mode fill launched with single mode fiber (SMF) at input.

Fig. 7 shows results of the insertion loss measurements for 12 waveguides in 4” sample. The results show that the average loss of 3.7 dB was observed for most channels. Coupling loss of 0.5-1 dB is approximated for 50 GI MMF to WG coupling, and 2.5-3 dB when coupling from the waveguide to 62.5 GI MMF fiber. Using the approximated CL values, waveguide loss is about 0.3 dB/cm. This is higher than obtained previously by the cut-back 0.1-0.15 dB/cm [8].

Third measurement was done by using an index matching fluid (n = 1.47 at 850 nm) at both waveguide interfaces i.e. fiber-waveguide and waveguide-fiber. Fluid was used to reduce surface scattering and Fresnel back-reflections. Insertion loss measurements on the waveguides both with and without index matching fluid indicated of the strong dependence of loss on end facet roughness confirmed also by the reciprocity measurements.

O-PCB characterization with out-of-plane mirrors is shown in Fig. 8. For the measurement, O-PCB is placed perpendicular to the launching/receiving fiber directions. The input and output ports of the O-PCB are connected to the 45° angled mirrors in optical direction.

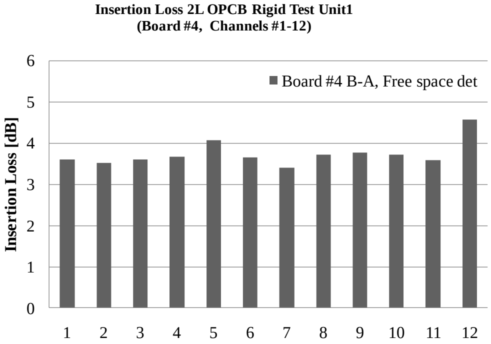


Figure 7. Insertion loss of 12 waveguide channels. Air filled coupling gap.

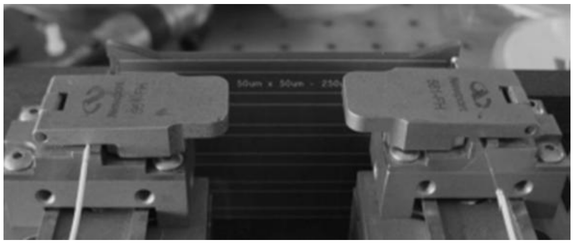


Figure 8. Insertion loss measurement of waveguide link with mirror terminations at both ends.

3.3 Coupling Sensitivity

Optical coupling dependence on the lateral (in-plane) off-set tolerance was measured in the alignment station by shifting the measurement fiber (50 GI MMF) laterally (X,Z) in respect to the waveguide input. With large waveguides (WxH 100x100µm^2), data in Fig. 9. shows that offset up to ± 50 µm provide efficient optical coupling with less than 1 dB loss penalty compared with ideal alignment, if the air gap (WG-to-fiber) is less than 40 µm. In-plane offset tolerance is ± 30 µm if air gap is larger, i.e. between 40-120 µm (WG-to-fiber). These measurements were carried out without collimating lenses. With the lens terminated fiber, the transversal off-set tolerance for 1 dB loss was similar ± 40…60 µm for smaller core WGs (WxH 50x50µm^2 and 50x70µm^2). Significant improvement was obtained however, when the fiber was moved along the waveguide optical axes (Y): The increase in loss was less than 1 dB even with 1 mm air gap, which indicated well collimated beam between lens and waveguide. This alignment accuracy is achievable with modern chip packaging and surface mount assembly units.

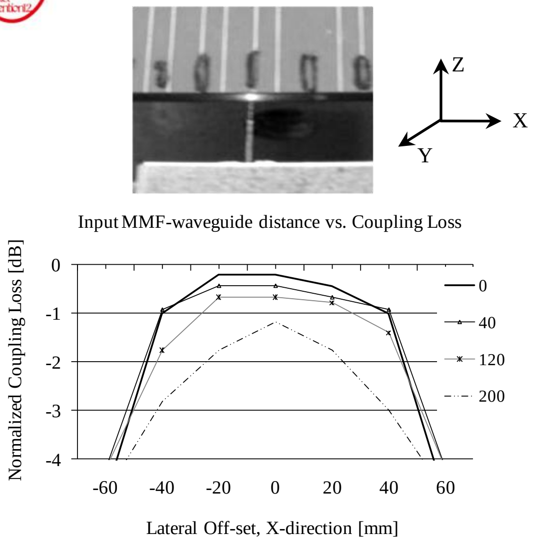


Fig. 9. Measured coupling profiles of the VCSEL coupled MMF fiber-to-waveguide interface as a function of input fiber's distance from the waveguide facet. Waveguide core size 100x100μm^2, MMF 62.5/125μm. Interface: Air gap, no lenses.

3.4 High Speed Data Transmission Measurement

The waveguides were characterized of their high speed data transmission performance. The eye diagram measured at 10.3125 Gb/s is shown in Fig. 10. Symmetrical and open eye was detected.

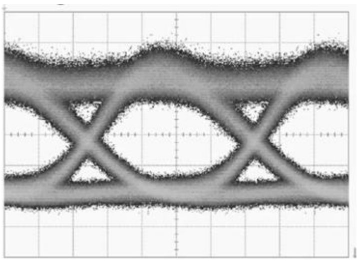


Figure 10. Eye-diagram at 10.3125-Gb/s.

Next step is to assemble optical engines on OE-PCBs to demonstrate full optical board-level end-to-end transmission link between chips on low-cost base material. For this purpose we use optical engines with direct optical interface to board embedded waveguides. In our earlier work with Aalto University and VTT Finland [9], we demonstrated 4-channel 10 Gbit/s (40 Gbit/s) utilizing such OE-BGA modules (Fig. 11). Now we aim to utilize 12-channel transceivers (12+12) for bidirectional data links based on 12.5 Gbps and up VCSEL and photodiode arrays and CMOS ICs.

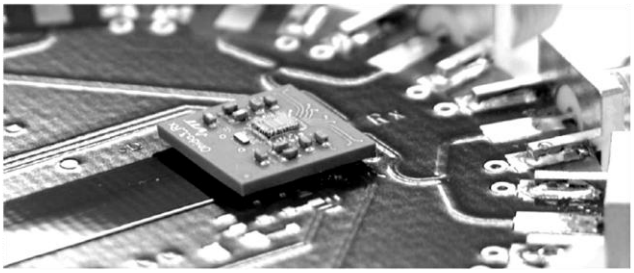


Figure 11. Optoelecronic BGA module assembled on O-PCB. Double lens array and turning mirror chips are located under module [8].

SUMMARY

We have developed and demonstrated scalable polymer fabrication process. Optical waveguides were successfully embedded in conventional PCB boards (OE-PCB). Optical layer sustained undamaged under pressing conditions used for multilayer OE-PCB fabrication. Process was proven robust and capable of producing versatile multimode waveguides 25-50 µm microns square with step index structures with low-loss and tight bending radius. The results in the paper show that manufacturing of optical interconnects on PCBs in a production scale is feasible, yet highly challenging. High positional and dimensional accuracy and surface quality requirements, low defect tolerance, and sensitivity to thermo-mechanical loads, chemical treatments during process and handling need attention and specific infrastructural modifications. Furthermore, system integration realized with passive alignment procedures requires unique alignment structures on optical-PCBs. However, as the materials, designs and fabrication processes reported herein are compatible or implemental in modern facilities, we conclude that this approach has great potential to realize next-generation high-density and high-capacity chip-to-chip and board-to-board optical interconnections projected for high-performance servers and routers.

ACKNOWLEDGEMENTS

We acknowledge Dr. Tingyun Wang and his Research Group at Shanghai University for conducting the waveguide loss measurements and optical simulations.

REFERENCES

[1] IEEE P802.3ba 40Gb/s and 100Gb/s Ethernet Task Force
[2] OIF - Optical Internetworking Forum
[3] Anritsu, "*Signal Integrity Analysis of 28 Gbit/s High-Speed Signals*", Application Note, May 2011
[4] B. E. Lemoff et al., "*MAUI: Enabling Fiber-to-the-Processor With Parallel Multiwavelength Optical Interconnects*" IEEE J. of Lightwave Technology, Vol. 22, No. 9 (2004), pp. 2043–2054.
[5] A. F. Benner et al., "*Exploitation of Optical Interconnects in Future Server Architectures*" IBM J. Res. & Dev., Vol. 49, No. 4/5 July/Sept. 2005, pp. 755 –775.
[6] A.V. Krisnamoorthy et al., "*Computer Systems Based on Silicon Photonic Interconnects*", Proc. of the IEEE. Vol. 97, No. 7, Jul 2009. pp. 1337–1361.
[7] T. Bierhoff et al., "*All optical pluggable board-backplane interconnection system based on an MPXTM-FlexTail connector solution*", IEEE Photonics Winter Topical 2010.
[8] M. Immonen, et al., "*Active Optical Flex Module for Ultra-Short Distance Data Applications*", Proc. IEEE Conference on ESTC, Berlin, Germany, 2010.
[9] M. Karppinen, et al., "*Parallel Optical Interconnect Between Surface-Mounted Devices On FR-4 Printed Wiring Board Using Embedded Waveguides And Passive Optical Alignments*". Proc. of SPIE Photonics Europe, Strasbourg, France, 2006.