Development of an electro-optical MCM to produce a multi-channel transceiver using VCSEL arrays

Pierre Avner Badihi, Sylvie Rockman, Hanan Yinnon, Yaniv Rotem, David Sachs
XLoom Communications, Inc., 11 Derech Hashalom, Tel-Aviv 67892, Israel

Abstract

This article describes the implementation of VCSELs as light sources for a chip-scale, highly dense multi-channel transmitter and receiver. The VCSELs are implemented using flip chip technology, as part of a hybrid process for the fabrication of an integrated photonic chip, using standard semi-conductor processes. The results as published indicate that integrated photonic chips may be applicable for various high speed datacom applications where copper use is restricted.

Keywords: Interconnect, optical, copper, transmitter, receiver, wafer, chip, scale, multi-channel

1. INTRODUCTION

Optical links are replacing electrical interconnects, where the required distance/bandwidth factor makes the electrical solution too complex or costly to implement.

While fiber optic links have dominated network and data communications for long distances for over two decades, in shorter distances copper prevails as the interconnect of choice due to its low cost, high reliability and ease of manufacturability.

As data rates increase, copper interconnects are reaching their physical limits and optical links now rein in distances higher than 100m. The barrier for the penetration of optical links is still mostly related to high cost. A photonic manufacturing technology that uses standard semi-conductor processes may alter the optical interconnect landscape altogether providing for small size, low powered devices, at a low cost which is competitive with copper interconnect solutions.

Just as telecommunication bandwidth was increased by utilizing optical transmission, the designers of high performance clustered computing and data management systems are aiming to drive as much bandwidth as possible close to the processor. Already, fiber optics interconnect computer systems across distances of several hundred meters, and backplane setups are in the works that will speed up data transport from one board to another within a system chassis.

Farther down the road are architectures for increasing the bandwidth between two microprocessors, or among stacks of chips for massively clustered computing.

We describe in this paper the development of a cost competitive, integrated photonic chip, providing multi-channel optical interconnect designed to perform well enough to replace copper counterparts. The chip scale transmitter and receiver is manufactured at wafer level using standard semi-conductor processes. The process brings the economies of scale of semiconductor chip fabrication to a chip-scale VCSEL/photodiode based transceiver reducing both size and assembly costs.

The photonic chip integrates VCSELs (vertical-cavity surface-emitting laser) as its source of transmission. In the last years the VCSEL has emerged as a primary light source in very short range optical communication. This device offers many advantages over edge-emitting laser diodes, including high bandwidth, low current threshold, small physical size, circular output beams, and the capability of being produced and operated in arrays[1-3].

The typical VCSEL has the general device structure illustrated in Fig. 1. An optical cavity is formed along the device growth direction, i.e., perpendicular to the plane of the wafer on which the VCSEL is grown. Distributed Bragg reflectors (DBR) form the cavity mirrors. The optical power output is emitted either from the top or from the bottom of the device.

Finally, because of their small volume, VCSELs have relatively high modulation bandwidths and allow the production of extremely small form transmitting devices [4].

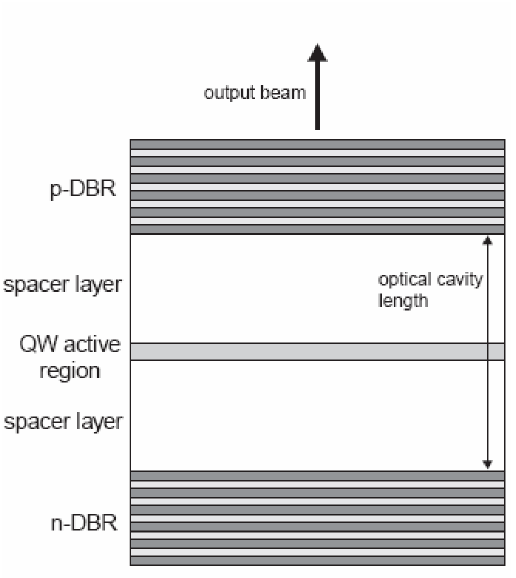
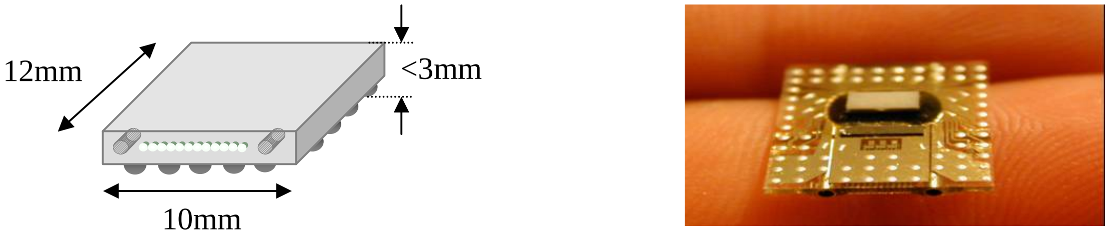


Figure 1: A schematic of a Vertical Cavity Surface Emitting Laser

2. THE MICRO-TRANSMITTER/RECEIVER MODULES

Die-size micro-transmitter/receiver modules have been developed . The modules are shown in Figure 2.



(a) Schematic outline

(b) Picture of the micro-transceiver

Figure 2: A schematic (a) and a photograph (b) of the micro-transmitter/receiver.

The transmitter and receiver size are extremely small - less than 10mm x 12mm in length and width and less than 3mm in height. These devices incorporate a 12-channel VCSEL array or a 12-channel photodiode array, and VCSEL driving circuitry, or amplifiers that amplify the photodiodes signal. The modules are designed for assembly on a printed circuit board using standard SMT assembly processes. Light coupling into and out of the modules is achieved by incorporating a mechanical alignment assembly into the module body.

By using high bandwidth VCSELs and photodiodes as well as fast drivers and amplifier circuitry the modules are capable of reaching very high data rates. The small size enhances the module bandwidth even further. Data rates of up to 3.2 Gbps have already been demonstrated and measured.

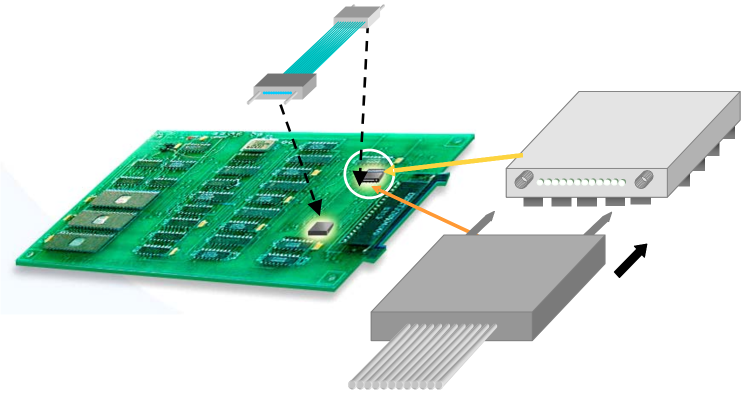
3. COMPATIBILITY WITH TODAY’S PCB TECHNOLOGY

The micro-transmitter/receiver modules extend well-known fiber-optic technology to board level interconnections. The modules are easily assembled onto the printed circuit board using standard SMT equipment and simply interconnected by optical MT fiber jumper. This allows for a simple interconnection from chip to chip, board to board, rack to rack scaling to a complete system-based interconnection.

The optical interconnect technology offered by these modules removes high frequency design hurdles from the printed circuit board and backplane, replacing high frequency copper signal lines, with VCSEL driven optical fiber links. PCB manufacturing remains simple, using standard laminate materials.

4. PCB ASSEMBLY AND CONNECTION

The assembled micro-transmitter/receiver module incorporates a micro-connector manufactured at the wafer level. The micro-connector is designed to mate with the industry-standard MT ferrule. Guides within the module and a locking mechanism allow the use of standard optical fiber ribbon jumper as shown in figure 3.



(a) The micro-transceiver module is assembled by SMT soldering to the PCB

(b) The micro transceivers connect to the fiber ribbon through a standard 12-fibers MT connector.

Figure 3: Micro-Transmitter/Receiver Assembly & Interconnection on the board.

5. TRANSMISSION REQUIREMENTS

The micro-transmitter and micro-receiver modules are designed for high bit rate operation over 12 multiple channels. Still, the small size imposes restrictions on the RF design of the module. However, lithography processes enable the

RF engineer to use design rules and take advantage of tight tolerances not available on standard printed circuit board. The micro-transmitter/receiver modules have initially been designed for operation at 2.5 Gbps per channel – 30 Gbps per link. This bit rate is required in Infiniband[5]. Slightly higher bit rates, such as 3.125 Gbps per channel (IEEE 802.3ae 10 Gigabit Ethernet[6]) and 3.187 Gbps (Fibre Channel[7]) can also be achieved with the present design. High bit rate performance per standard has already been measured proving the electronic and electro-optic design concept.

6. MANUFACTURABILITY

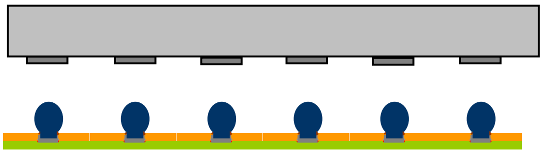
The micro-transmitter/receiver modules are manufactured using standard electronic and semiconductor assembly and mounting processes. The devices are manufactured entirely at the wafer-level.

The hybrid integration process uses "best-of-breed" optical and electronic devices attached on a common wafer substrate, to produce a highly dense optical transmitter/receiver photonic chip. The challenge is, among others, to achieve within the integration process, low loss coupling between VCSELs and fibers as well as between fibers and photodiodes. This is done by implementing lithographically defined structures to passively align various optical components, eliminating a costly closed loop procedure for optical component alignment.

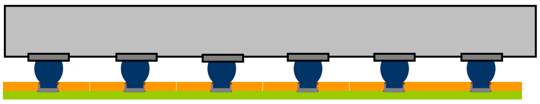
The substrate carrying the micro devices is processed from both sides; one side is used to define the electronic structures on which the Electronic and optoelectronic devices are assembled. The other side is processed to form mechanical structures by photolithography such as deep etching. These structures are accurately aligned to the electronic side. Miniature optics folds the light beam emanating from the VCSEL into the outgoing fiber or directs light from the incoming fiber into the photodiode.

Since VCSELs having solder bumps are not common, an alternative methodology is used. The solder bumps are grown on the module substrate, and VCSEL arrays having solderable pads are soldered on these grown solder bumps. The bumps, made of either pure Tin or eutectic Tin-Lead, are grown using an electrochemical growth process carried out at the wafer level, followed by a wafer level reflow of the grown bumps in a reducing H2 enviroment at 250°C.

(a) Solder bumps grown on substrate, after reflow (wafer level)



(b) Flip Chip Alignment of the VCSEL array, relative to the solder bumps on the substrate



(c) Flip Chip soldering

Figure 4: Flip-chip schematics: (a) bump growth and reflow, (b,c) flip chip assembly.

Figure 4 shows the different wafer level processes. The Under Bump Material layer is made of 3µm Nickel with a Gold flash coat of 300 Angstrom. The advantages of this Under Bump Material are low cost, good solderability and wettability with Sn/PbSn and finally a good adhesion to the copper conductive layer. The Bump height is 30+/- 5µm defining the chip distance to the substrate.

Following the bump formation, the VCSEL and Photodiode arrays are flip chip attached onto the substrate using a Suss microtec FC150 flip chip machine (see Figure 5). The solder is reflowed at a bonding temperature of 220°C and at an upper chuck force of 120 gr. The resulting placement accuracy is better than 1µm, while acheiving a very low electrical resistance of the formed bond.

Figure 5: Suss FC150

7. TECHNICAL RESULTS

7.1. Measurements

The insertion loss of the module optics has been measured on a large number of devices. Typical insertion loss values of 1 to 2 dB were measured when using 62.5/125 µm multi-mode fibers.

High optical cross talk in a closely spaced optical channel configuration may be very difficult to overcome. However, cross-talk measurements in the micro transmitter/receiver modules have proven that the optical design yields an optical cross-talk attenuation of better than 30 dB between nearest neighboring channels. The cross talk between the channels was measured on an optical assembly on which a 12-channel photodiode array was mounted using our flip-chip technique. Power from an 850-nm VCSEL was launched into one of the optical channels.

The current was measured on the illuminated photodiode as well as on the adjacent diodes. All the diodes in the array were biased. The results are given in Figure 6.

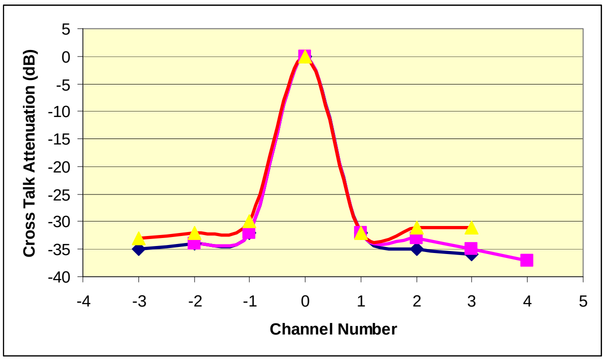
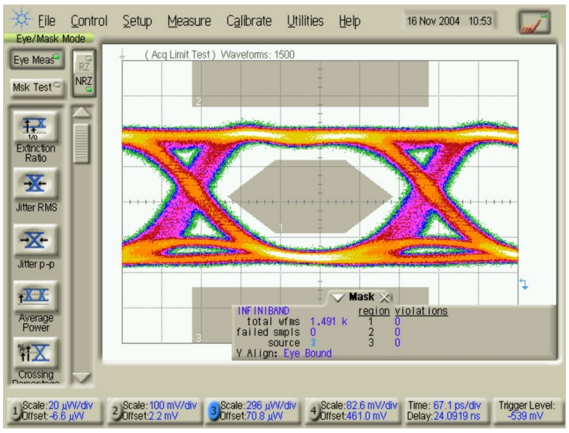


Figure 6: Optical cross talk attenuation between adjacent channels

7.2. Transmission Results

Extensive testing was conducted of the transmission properties of the micro transmitter and receiver pair. The full details of the measurement results will be reported elsewhere. Only some representative results are given here.

A typical eye pattern of the transmitter module is given in Figure 7. The transmitter was driven at 2.5 Gbps with a pseudo-random bit-stream (prbs) of 2^{23}-1. The mask in this Figure is the Infiniband mask. No mask violations were observed.



```
16 Nov 2004   10:53
( Acq Limit Test )  Waveforms: 1500

INFINIBAND                       region  violations
  total wfms   1.491 k             1      0
failed smpls   0                   2      0
      source   3                   3      0
Y Align: Eye Bound

Scale:20 µW/div     Scale:100 mV/div   Scale:296 µW/div    Scale:82.6 mV/div   Time: 67.1 ps/div    Trigger Level:
Offset:-6.6 µW      Offset:2.2 mV      Offset:70.8 µW      Offset:461.0 mV     Delay:24.0919 ns     -539 mV
```

Figure 7: Transmitter Eye pattern at 2.5 Gbps

Transmitter and receiver rise and fall times of 115 ps were measured in a wide range of drive current range and input power at 2.5 Gbps.

8. SUMMARY

The innovative merging of technologies presented in this paper is poised to change forever the shape of ultra-short reach communication. Copper conduits that dominated this communication domain are going to be replaced by fiber optics, just as was the case with longer communication spans.

The key for this change of guard is a combination of microelectronic wafer-level manufacturing technologies, highly accurate chip placement technology, innovative optical design and VCSEL technology. This combination leads to a manufacturing technology that combine advanced packaging capable of producing very high bit rate photonic chips at a competitive price to copper.

REFERENCES

1. K. Iga, F. Koyama, and S. Kinoshita, “Surface emitting semiconductor lasers,” *IEEE Journal of Quantum Electronics*, vol. 24, no. 9, pp. 1845-1855, 1988.
2. W. W. Chow, K. D. Choquette, M. H. Crawford, K. L. Lear, and G. R. Hadley, “Design, fabrication, and performance of infrared and visible vertical-cavity surface-emitting lasers,” *IEEE Journal of Quantum Electronics*, vol. 33, no. 10, pp. 1810-1824, 1997.
3. R. S. Geels, S. W. Corzine, and L. A. Coldren, “InGaAs vertical-cavity surface-emitting lasers,” *IEEE Journal of Quantum Electronics*, vol. 27, no. 6, pp. 1359-1367, 1991.
4. L. A. Coldren, E. Hegblom, E. Strzelecka, J. Ko, Y. Akulova, and B. Thibeault, “Recent advances and important issues in vertical-cavity lasers,” in *Proceedings of SPIE*, vol. 3003, 1997, pp. 2-13.
5. Infiniband Architecture Specifications Vol. 2, The Infiniband Trade Association
6. IEEE 802.3ae: “Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications”, IEEE.
7. “Fibre Channel 10 Gbps (10GFC)”, INCITS draft proposal