Bi-Directional Optical Communication at 10 Gb/s on FR4 PCB
Using Reflow Solderable SMT Transceiver

Pamidighantam V Ramana, Haridas Kuruveettil, Bryan Lee Sik Pong, Kenji Suzuki (1), Tsuyoshi Shioda (1),
Tan Chee Wei, Jayakrishnan Chandrappan, Lim Teck Guan, Calvin Teo Wei Liang
Chai Yi Yoon, Yap Guan Jie, Cheryl Sharma, John H Lau
Institute Of Microelectronics,
11, Science Park Road, Singapore 117685
(1) Mitsui Chemicals Inc.,
Nagaura, Sodegaura, Chiba, Japan 299-0265
pvramana@ime.a-star.edu.sg

Abstract
We report the development of 10 Gbps bi-directional optical data communications on FR4 PCB to realize Opto-Electronic Circuit Board (OECB). The work includes the design, fabrication and high-speed performance of a 10 Gbps surface mount optical transceiver module that can be reflow soldered, developing efficient optical coupling methods using precise injection molded lenses and studying their attachment methods to the optical source and receiver, realizing efficient optical coupling between transmitter and receiver subsystems for a multi mode epoxy waveguide on the PCB and developing a test vehicle. The compact and highly integrated SMT optical transceiver module in multilayer LTCC substrate consists of optical devices like VCSEL and PIN Photo Diode and the electrical circuits like VCSEL driver, Trans Impedance Amplifier (TiA) and Limiting Amplifier (LA). The module contains a cavity, in which the electrical, optical devices and passives are mounted using passive attachment methods, a recess to house a lens and locator holes to align the lens with the VCSEL and PIN. The lens is an injection molded epoxy lens with biconvex elements for both transmitter and receiver integrated as a single element to improve the coupling between the source and the waveguide on the PCB. The module is designed to relax the assembly tolerances of optical elements so that normal conventional electronic assembly process can be used. Solder bumps are formed on the bottom layer of the LTCC to convert the module into a cavity down SMT package. The waveguides are made of high temperature epoxy material and are attached to the PCB using adhesive material. The 45° mirrors are formed through laser ablation process. The module is reflow soldered using conventional reflow oven. The Opto-Electronic Circuit Board (OECB) is performance evaluated and performance results are presented.

1. Introduction
The performance of electrical interconnects is limited by factors like bandwidth limitation due to line impedance, increased power consumption with increase in frequency, effects of crosstalk and electromagnetic interference due to inductance and capacitance, effect of interconnect density on performance, restrictions due to signal path termination and planar constraints. A bandwidth bottleneck is predicted within the next few years for the electrical interconnections linking Integrated Circuits (ICs) in a PCB due to the requirements of increased processing power.

One solution is to use optical interconnects for both the intra-board and inter-board communications. The advantages of optical interconnects include parallelism, low input/output driving energy, capability to withstand electromagnetic interference and low dispersion. Optical interconnects also allow longer interconnect length. Polymer waveguides are the popular choice for intra-board optical interconnects due to low cost, suitability for mass production, low optical loss and compatibility with PCB materials. The waveguide losses, depending on the fabrication process, materials and cross sectional area, range from 0.6dB/cm to 0.05dB/cm. Intra-board optical interconnects are being pursued by various groups, for example, Doany et al., at IBM demonstrated 16 channels of 10 Gbps between two processors [1], Karpinne et al., developed 4x10 Gbps using a SMT module on FR4 PCB [2], Matsubara et al demonstrated three-d optical Interconnects on Organic PCB [3], Shishikura et al., presented multi layer PWB with optical interconnects [4], Ishii presented optical I/O packaging technology for chip level interconnects [5]. We reported earlier on the development of high frequency data link using optical waveguides [6].

There are many challenges for the optical interconnects to be implemented widely. The optical devices should be integrated with the electrical driving circuits. The channel should be bi-directional to be integrated with digital systems. The assembly of optical devices should be done by the normal reflow process for which the devices need to be suitably packaged and aligned optimally. The amount of received optical power determines the maximum allowable speed. The received power is dependent on source optical power, coupling losses, and channel attenuation and receiver characteristics. The received power can be improved by adding lenses or other coupling elements. In this paper, a low cost, simple design and easier to fabricate optical interconnect is presented as shown in Figure 1. The design of this optical interconnects uses only commercial available components and it is fabricated using standard industry fabrication and assembly technologies.

2. Optical Interconnect system design
Figure 1 describes the concept of bidirectional optical communication using optical waveguides. The PCB is fabricated using normal FR4 fabrication process. The waveguides are attached to the top layer of the PCB creating an Opto-Electronic Circuit Board (OECB). The optical waveguide has core dimensions of 100µm x 100µm which provides sufficient assembly tolerances. The optical devices are integrated in a Surface mount LTCC common module with integral lens. The module is assembled to the OECB with SMT soldering process while controlling the placement. The
LTCC optical module is placed at 180 degrees orientation at the other end of the waveguide so that the transmitting and receiving channels are reversed to enable bidirectional communication. The following sections describe the summary of electrical and optical designs.

2.1 Design of LTCC SMT Transceiver module

The opto-electronic module is a LTCC Surface Mount Package containing an 850 nm VCSEL, PIN PD and driver electronics at 10 Gbps with provision for a coupling lens as shown in figure 2 below. Figure 3 shows the electrical design of LTCC substrate. The module uses four separate power planes to reduce the cross talk. The high speed signal lines are routed as differential micro strip transmission lines. The module size is 15 mm x 15mm, the recess has dimensions of 12mmx12mm and the cavity has a dimension of 11mmx11mm. The module has a total of 52 solder bumps of 600um dia with 12 signal I/Os and remaining as ground connections. Additional EMI filters and passive components are accommodated on the board. The VCSEL and PIN are from Emcore Corporation while the electrical ICs are from Maxim Integrated Products. The LTCC module is manufactured by Kyocera Corporation (GL-771 material).
The PCB itself is a FR-4 board with four electrical layers (two signal layers and two power planes) with a thickness of 1 mm. The individual metal layers have a thickness of 37µm. The coupled micro-strip lines on the PCB have a width of 300µm and spacing of 250µm.

2.2 Optical Design

The modeling of the optical component of an OECB consists of waveguide and lens designs. The schematic of transmitter and receiver optics is depicted in Fig.4. The transmitter section consists of a collimating lens attached to improve the coupling to waveguide. The refractive index of core is 1.56 while that of the clad is 1.51. The materials are proprietary to Mitsui Chemicals Co., Japan. The upper and lower cladding layers have a thickness of 10 µm. The larger area of waveguide core is aimed to increase the input coupling efficiency at the transmitter end and relax the placement tolerances. However, the 10 Gbps PIN PD has an optical aperture of 45 um only. Hence, a focusing lens is designed for the receiver. The transmitter and receiver lenses are two lenses with different sizes and radii of curvature to achieve the coupling efficiency and better total coupling tolerance. The collimated input beam diameter matches with the waveguide core dimensions. The collimating lens for the transmitter and focusing lens for the receiver are formed together as a single element using injection molding process. A stopper within the lens avoids optical crosstalk between the transmitter and the receiver within the same module. The lenses are assembled to the OE module using finely fabricated pillar structures that are glued to the assembly.

The optical link is simulated using ray tracing method to analyze the coupling losses and tolerances. Various alignments placement offset and components tolerances are also simulated. The optical link is simulated using ray tracing method with the VCSEL modeled as an incoherent source having a maximum full width beam divergence of 32° and emitting diameter of 40 µm. The photo detector has a sensitive area diameter of 45 µm. The height of the VCSEL and photo detector is 1.84 mm within the module and the distance between lens and waveguide is 0.47 mm. The alignment tolerance analysis is performed based on the displacement of VCSEL and photo detector. The waveguides are 10 cm long with a 45 degree mirror polished end faces. Fig.5 shows the schematic lenses for both transmitter and receiver modules.

The misalignment of VCSEL and photo detector in X-and Y-axes is very critical compared to the Z axis. The assembly tolerances are assumed to be a maximum of ± 20 µm and the extra loss is estimated at 2.5 dB for VCSEL offset and 1.6 dB for photo detector offset. The VCSEL displacement has highest deviation because the collimated light will be shifted. The modules are placed on the top of the waveguide by applying solder balls. However, the diameter of solder ball can be different from each other as the results the modules are tilted. The tilting of the transmitter (Tx) lens can cause higher optical link losses. The figure shows that within the range of ± degree, the loss is slightly constant from ideal conditions. These problems are also detected when the modules are tilted.

3.0 Assembly Process Flow

The assembly sequence starts with the measurement of mirror location of the assembled waveguide on the PCB. The mirror location is measured from the four corner bump pads. The SMT components except the OE module are pre-soldered on the board using standard SMT reflow process. The VCSEL and PIN location within the LTCC module is determined from the mirror center position with respect from the module bump pads on the PCB. The optical devices are attached using conductive epoxy Epotek H20E and cured for one hour. The VCSEL and PIN location is verified by visual and X-Ray inspection and the device wire bonding is completed. The electrical components within the module are attached using Sn63/Pb37 low temperature solder. The module is powered up and the VCSEL emission pattern and power measured. The lens is located coarsely by the four posts and finely by the location of VCSEL and aligned using the die attach machine and attached using Microchem SU8 epoxy. The module solder pads are filled with the Sn63/Pb37 low temperature solder. The Tx module is aligned with the mirror center location and reflow soldered. The module placement and VCSEL location are verified through X-Ray inspection. The VCSEL is powered up and the power output at the receiver location and beam spot diameter are analyzed. The receiver module is aligned and attached.
Assembly Process

Location of mirror on OECB

Location of VCSEL/PIN on Surface

X-Ray Image of VCSEL/PIN

Study of beam spot at Surface

Fully Assembled

Fig. 6: Assembled LTCC Module

Figure 7: Assembly process description

Fig. 8. Eye pattern at 6Gb and 10 Gb
4.0 Performance Characterization

The waveguides are initially characterized to estimate the optical losses using an external 850nm laser and wide area detector and mirror position offset. Optical losses include the losses of two mirrors and coupling at the input – output interfaces. The values obtained are averaged for both the directions. The LTCC module is characterized electrically for high speed response and optically for output beam profile shape, transmitted optical power and receiver response. The losses due to mirror core centre deviation in X and Y directions are also calculated. The VCSEL is attached in the LTCC module with the procedure described before and is analyzed for output power and beam divergence. The near field image of the VCSEL is collected using a beam analyzer at 3 different distances and the divergence of the VCSEL is calculated. The measurement is repeated with the lens module attached to study the effect of lens. The source divergence is found to be less than 5 degrees after the lens attachment. The properly aligned modules are then flipped, aligned to the waveguide on the PCB using vision system and soldered to the board while holding the module with a pick up tool. The transmitter module is powered up and the waveguide output profile is observed under microscope attached with an IR camera and the VCSEL to waveguide alignment is studied using X-Ray inspection tool. The proper alignment between the transmitter module and waveguide leads to a bright circular or square output spot at the waveguide edge. The proper lens alignment to VCSEL is indicated by a symmetric spot with a reduced spot size. The Mod_Set and Bias_Set controls are varied to optimize the output eye pattern. The receiver is characterized by launching light through single mode fiber (SMF) into the waveguide and measuring the Received Signal strength. The transceiver module is attached at the other end of the waveguide for high frequency analysis. It was observed that the waveguide and mirror losses together are about 2dB while the VCSEL to the waveguide input coupling is about 3.7 dB (including the material losses and Fresnel reflection losses from the lens). The losses at the receiver side could not be estimated due to the architecture. The test vehicle was evaluated upto 10 Gbps using high frequency fiber optic receiver and the results are shown in figure 8. Further evaluation of the system is in progress.

5.0. Conclusions

A simple and low cost OECB with a transmission rate of 10Gb/s is demonstrated on FR4 PCB. Its simple design allows the OECB to be fabricated and assembled with current industrial technology. Some important results are summarized in the following.

1. Designed and Developed a 10 Gbps surface mount optical transceiver module using a multi layer LTCC substrate with insertion loss of 0.1 dB from the module pad on the PCB to the VCSEL Driver/LA IC through 500 um solder bumps.
2. Designed and fabricated optical coupling elements between VCSEL/PD to waveguide using precision injection molding with dimensional accuracies of less than 10um.
3. Studied the attachment of lens with the module using different materials like optical grade epoxy and photo-resist and evaluated their performance during reflow up to temperature of 200 ℃. Photo-resist gave a better performance.
4. Reduced the VCSEL divergence from ~ 30° to 4° using injection molded lens
5. Achieved optical coupling loss of 2.5 dB with the lens between transmitter/receiver to a multi mode epoxy waveguide of 70x70um
6. Validated that the epoxy waveguide on OECB can withstand normal SMD reflow process (LTCC module was attached late)
7. Assembly of optical ICs in LTCC module with 10um accuracy using passive assembly with normal semiconductor assembly equipment.
8. Attached LTCC module to OECB using low temperature solder bumps on LTCC module at 180°C.
10. It is observed that the major issue at high data rate is the mis-alignment between waveguide and the receiver photodiode due to the small dimensions of 10 Gbps photodiode while the transmitter section has a good coupling. One method of reducing the mis-alignment could be to reduce the height of the module from the present 1.65 mm to <500 um.
11. The second issue that needs to be resolved is the drift of LTCC module during solder reflow process. This was addressed by firmly holding the module with a vacuum pick up tool during the reflow process in the present work. However, a more universal solution need to be implemented.

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7.0 References

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