Invited Paper

Recent Advances on Chip-to-Chip Optical Interconnect

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ABSTRACT

Copper (Cu) interconnect has been used for communication systems at shorter length scales for both latency and bandwidth sensitive applications. However, as the computational bandwidth of the integrated circuits increases dramatically, Cu interconnect at short distances especially in bandwidth sensitive applications is struggling to keep up. This presents a good opportunity for optical interconnect to penetrate the short distance world.

This paper reviews the latest advances of optical interconnect for off-chip high bandwidth communications. The focus will be on the materials and processing aspects for realizing optical interconnects through low cost and manufacturable approaches, especially on various novel schemes to achieve passive optical alignment between optical device and waveguide, and on novel package architectures to achieve high bandwidth using the optical interconnects.

Keywords: optical interconnect, chip to chip, passive optical alignment

1. INTRODUCTION

The demand for higher bandwidth interconnects continues to grow for all levels of interconnection within high performance computing and switch/router systems. Advances in processor speeds, multicore processors, parallel systems with a large number of processors, and wider data buses present steadily increasing aggregate bandwidth, channel data rate, and density requirements that are progressively more difficult to meet using electrical interconnect technology [1].

Optical interconnects with low signal attenuation and crosstalk could potentially be very useful in short distance, bandwidth sensitive applications. As a matter of fact, optical interconnects have been increasingly used to replace copper interconnects since they provide significant advantages for applications with longer links as well as supporting higher data rates, increased bandwidth density, and more compact cables and connectors. By the late 1990s, multi-Gb/s serial fiber optic links were increasingly used for data communications in local and storage area networks to interconnect systems located hundreds of meters apart. During the last few years, rack-to-rack interconnects over tens of meters have become more commonplace using parallel fiber optic modules, forming the communications link between compute nodes and storage systems in high performance cluster computers. The optical links used in these systems are typically 8- or 12-channel commercial parallel optical modules operating at data rates up to 5 Gb/s/ch over multimode fiber (MMF) ribbons [2, 3]. As bandwidth requirements of computer systems continue to increase to new levels, the communications bottlenecks are moving toward shorter and shorter distance scales close to the processor. One of the major system bottlenecks today is at the inter-chip (or off-chip) communications. The off-chip electrical interconnects, typically provided through ball grid arrays (BGA) or land grid arrays (LGA), are limited primarily by the I/O density (off-chip) and also by the package-to-package electrical link density [4]. Next-generation parallel optical data buses will require higher data rates, lower power consumption, lower cost and, most significantly, a greater level of integration.

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2. RECENT ADVANCES ON OPTICAL INTERCONNECTION SCHEMES

The costly assembly and packaging process is one of the major road-blocks on the success of inter-chip optical interconnects. More specifically, the alignment of the optical components to each other is of critical importance. This assembly step for achieving optical alignment greatly impacts the overall system cost, performance, manufacturability, yield, and reliability. Traditional active optical alignment is time-consuming and costly. Passive optical alignment is a much preferred method due to its simplicity and lower processing cost. Recently, much research has been conducted to explore various passive alignment approaches to achieve low cost optical alignment.

2.1 Utilizing Self Alignment of Solder and Polymeric Liquid

Molten solder joints have high surface tension and thus will change their shape to minimize the surface energy (called solder self aligning). Solder alignment concept has been utilized widely in forming various solder interconnections in electronic industry. Due to the self alignment capability of solder joints, a slightly misplaced component can be automatically aligned more accurately to its designed position during solder melting (i.e. reflowing) process. The alignment accuracy provided by solder self alignment highly depends on the solder bump size, number of bumps, and bump layout on the components [5]. Tsunetsugu et al. [5] studied the alignment accuracy by 20- to 30 -μm diameter micro solder bumps. It was found that the alignment accuracy increased as the number of bumps increased. An average misalignment of less than 0.2 μm was obtained for more than 20 bumps with a diameter of 26 μm.

To address the needs for low cost, high yield manufacturability, compactness and versatility, Intexys Photonics with CEA/Leti have developed a highly integrated optical sub-assembly based on the Multi Chip Module (MCM) approach [6]. The basic concept is to integrate in a miniature package a VCSEL laser chip together with its driver IC, both chips being assembled on a silicon substrate using flip-chip technology, e.g. indium (In) micro-bumping or gold stud-bumping technique. The size and the position of In bumps were carefully controlled by vapor deposition of In. It was found that, for all bump sizes, the alignment accuracy increased as the In bump and Au-stud bump overlapping ratio increased. The chip positioning is repeatable with misalignment value below 0.2μm for overlapping ratio exceeding 4%. It was also found that this packaging technique was quite reliable: no misalignment was observed when samples were exposed to severe environmental conditions such as 500 hrs at 85°C/85%RH, or temperature cycling (500 cycles from –40°C to 85°C). The light is coupled in an optical fiber inserted and guided into a hole precisely etched through the silicon substrate (Fig. 1). DRIE etching was used to fabricate this hole, whose shape was designed to allow the insertion of a 125μm cladding diameter fiber with minimum tolerances.

Fig. 1. SEM photo of the Indium bumps for VCSEL hybridization and hole etched for fiber placement [6]

Oppermann et al. [7] demonstrated a passive alignment approach using the flip chip self alignment mechanism in combination with micro-mechanical stops and spacers which were fabricated precisely on a

Si chip. Stops were used to control the lateral positions while spacers were used to control vertical position (Fig. 2). It was shown that it is possible to use the self-alignment mechanism in combination with mechanical stops and spacers to achieve high accuracy alignment. The chip moves until it is stopped through the stops, i.e., the final position of the chip in regard to the substrate is determined solely by the stops.

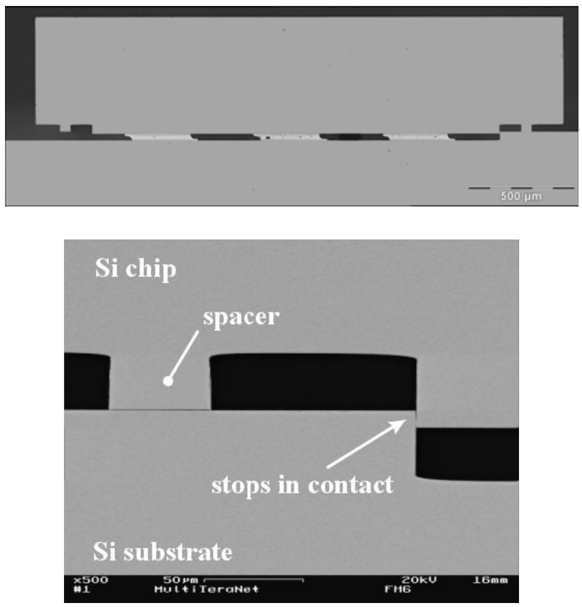


Fig. 2. Cross-sectional images to show how spacers and stops determine the final positions of the chip [7]

Ishii et al. from NTT [8] have proposed a new concept of chip-to-chip optical interconnection, which used surface-mountable packages and a polymer optical waveguide (Fig. 3). The main feature is to use a short-distance free-space optical coupling between LSI packages by means of microlenses. Optoelectronic semiconductor dies (VCSEL/PD) were embedded inside the interposer and the PCB contains a polymer optical waveguide with 45° mirror as an interlayer (called "OptoBump"). The optoelectronic packages which contain a VCSEL/PD array chip inside their cavity of an interposer were assembled on PCBs through solder joints, and the alignment between the VCSEL/PD and optical waveguide in the PCB was achieved through self-alignment of the solder joints. Such full compatibility with surface-mount technology (SMT) reduces the cost of assembly, and is essential for the introduction of optical interconnections into the on-PCB interconnections. It was demonstrated the optical loss between optoelectronic package and polymer waveguide with 45º mirrors to be 4 dB/m, and 1.25 Gb/s x 3 channel parallel optical interconnections over a 30-mm-long waveguide on the PCB to be functional. The key to making practical chip-to-chip optical interconnection is reducing the cost, especially the cost of assembly, to the same level as that of ordinary electronic products. This work demonstrated the great potential of this approach to provide low-cost, high performance optical interconnections on a printed circuit board.

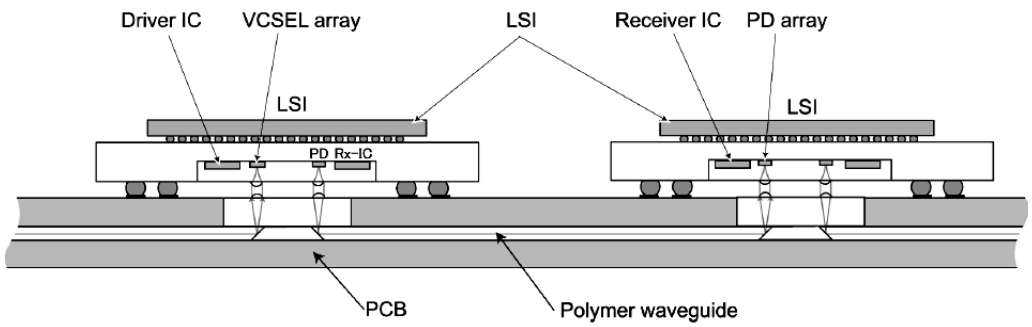


Fig. 3. Schematic of on-PCB optical interconnection based on the OptoBump interface [8]

IBM recently developed parallel optical interconnect technologies designed to support terabit/s-class chip-to-chip data transfer through polymer waveguides integrated in PCBs (Fig. 4) [9]. The board-level links were based on a parallel optical module, or Optomodule, with 16 transmitter and 16 receiver channels which were assembled and fully characterized, with transmitters operating at data rates up to 20 Gb/s. Receivers characterized as fiber-coupled 16-channel transmitter-to-receiver links operated error-free up to 15 Gb/s. The low-profile Optomodule is directly surface mounted to a PCB using convention ball grid array (BGA) solder process. Optical coupling to a dense array of polymer waveguides fabricated on the PCB was facilitated by turning mirrors and lens arrays integrated into the optical PCB. A complete optical link between two Optomodules interconnected through 32 polymer waveguides were demonstrated with each unidirectional link operating at 10 Gb/s achieving a 160 Gb/s bidirectional data rate. The full module-to-module link provides the fastest, widest, and most integrated multimode optical bus demonstrated to date.

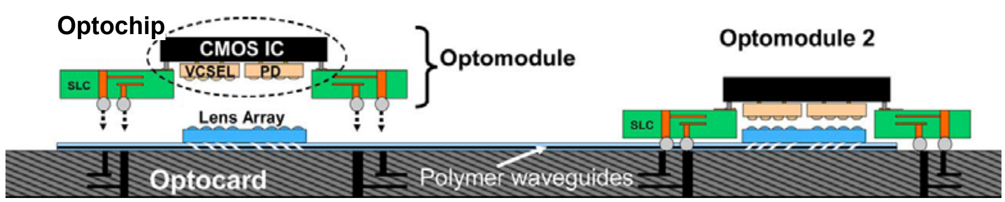


Fig. 4. Schematic of IBM Terabus package [9]

Lo et al. [10] demonstrated a passive alignment concept of align a fiber to an optical component utilizing the surface tension of a liquid epoxy. A low viscosity epoxy was dispensed in a “reservoir” and then flows into the V-groove on a Si substrate. Subsequently the epoxy flow runs through the gap between the optical fiber and the V-groove walls. The flow of epoxy aligned the optical fiber by the surface tension. Once the optical fiber was aligned and the epoxy was cured, more epoxy was applied in a glob-top manner to mechanical enhancement.

Suzuki et al. [11, 12] demonstrated a self-alignment approach to align optical devices with multimode optical fibers by avoiding the use of mechanical parts. A VCSEL was automatically aligned with a fiber by the action of surface tension of a liquid adhesive (Fig. 5). An ultraviolet (UV)-cure adhesive was used to attach the VCSEL to the fiber after the self-alignment was complete. Alignment accuracy of average 13 μm was achieved and coupling efficiency of the self-aligned VCSEL to the optical fiber was maximum 35%. 1-Gb/s optical signal transmission using the optical sub-assembly was also demonstrated. This self-alignment technology and the fabricated optical sub-assembly are effective in achieving low-cost optical modules for optical interconnect systems from commodities to high-end applications.

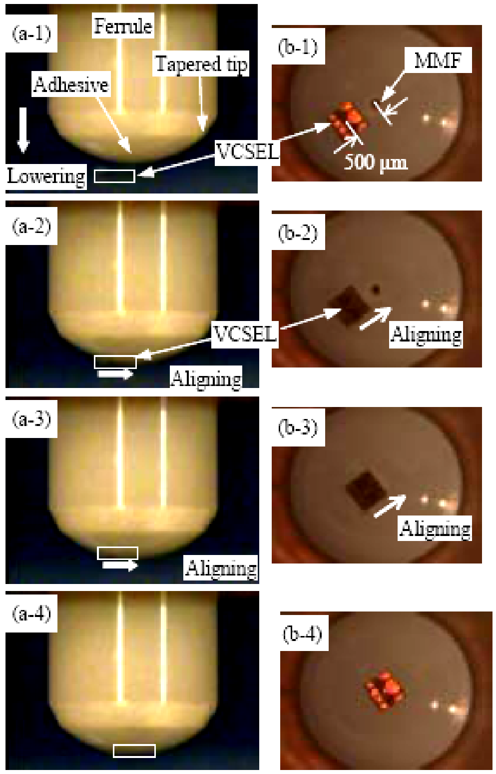


Fig.5. Process of self-aligning VCSEL to MMF: Photos a-1 to a-4 show the side views with the adhesive and VCSEL while b-1 to b-4 show the bottom view [12]

2.2 Self writing waveguide

Utilizing self-written waveguide to achieve easy, convenient and accurate optical coupling between optical components has also been investigated [13]. Self-written waveguides (or light-induced / self-organized waveguides) [14-20] can be easily formed using photosensitive medium like UV sensitive resin as a waveguide material as firstly reported by Frisken [14]. The mechanism is based on very fundamental principle under the condition that the refractive index increases after exposing the medium by light. When light is introduced from an optical fiber edge in the medium, the light is guided in the exposed area due to the refractive index change. Thus, an optical waveguide are induced along light propagating axis and grow with exposure time; the misalignment of the waveguide and the optical fiber waveguides using this method (call "one-side exposure") have been reported using UV curable resin [14, 15, 17-19], holographic material [20] and GeO_2 doped SiO_2 [16] as waveguide materials; Application of an optical transceiver module has also been suggested [18,19]. Exposing light from two faced optical fiber edges (call "both-side exposure") would result in efficient coupling even if significant gap and misalignment exist between the fibers. If such a phenomenon actually occurs, self-written waveguides would act as "optical solder" between fibers and would relax conventional tight control restriction of optical fiber/device alignment process. Based on a concept of optical component coupling using self-written waveguides reported by Yoshimura et al [20], the methods are experimentally demonstrated using MMFs coupling with various gaps. The systematic study shows that this method is effective. Fig. 6 shows coupling behavior for MMFs gapped with approximately 1100 µm. At initial state, the gapped MMFs have large coupling loss, > 10 dB. The poor coupling efficiency is clearly seen when visible laser is radiated from the fiber edge (Fig. 6A). Figures 6B to 6E show light guiding behavior during both-side exposure of step #1 to step #4 and Figs. 6B' to 6E' are the corresponding microscope view. Self-written waveguides grow from both sides of the fiber edges with step by step, and the radiation angle of UV light somewhat becomes narrow at step #3 in Fig. 6D. After step#4 (Fig. 6E), two MMFs look optically coupled by a self-written waveguide. Visible laser is also successfully guided in the formed waveguide as shown in Fig. 6F and uncured resin are also plotted in the figure. With increasing exposure steps, the coupling loss significantly decreases within step #2 to step #4, depending on the gap values. The loss values tend to be almost constant afterwards.

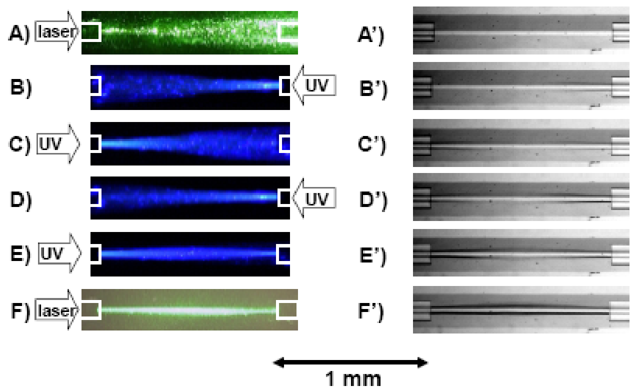
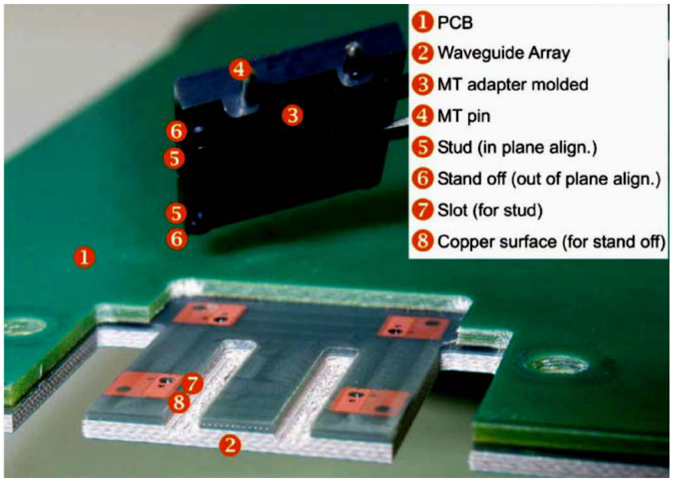


Fig. 6. Optical coupling of gapped MMFs using self-written waveguides (both-side exposure). The left is light guiding behavior. The light input directions are marked on each. The right is corresponding actual waveguides view. A: Green laser irradiation at initial state (the gap is filled with uncured resin). B, C, D, E: Step#1 - #4 of both-side exposure with UV intensity: 0.7 mW/cm2. F: Green laser irradiation after step#10

2.3. Passive Alignment through High Precision Guiding Structures

A successful implementation of optics into PCBs (printed circuit boards) requires a precise passive alignment of optical elements relative to the optical waveguides in the board. Lamprecht et al [21] tackled this challenge with a novel concept that allows the passive alignment onto a PCB of any optical or optoelectronic building block with a precision of a few micrometers. Markers, fabricated into a copper layer during PCB manufacturing, were used as a position reference for the polymer waveguide fabrication and for the formation of mechanical alignment features in the PCB (Fig. 7). To form the latter, laser drilling, a standard process for via formation in PCBs, was used. An opening in the copper marker can then be used to define an accurately positioned alignment slot, independently of the low positioning accuracy of the drilling laser. The authors demonstrated repeated insertions of adapter elements into these alignment slots with a standard deviation of 3 µm for in-plane displacements. Afterwards, optical modules were mounted onto the adapters, using a standard MT interface provided by the adapter. A standard deviation of the order of 5 µm for the in-plane and out-of-plane misalignments of the module with respect to the optical waveguides was achieved. This passive alignment concept enables accurate and simple plug-in of optical and optoelectronic elements, into a PCB. The concept is based on established PCB manufacturing processes, which is crucial for the development towards a low-cost optical interconnect technology.



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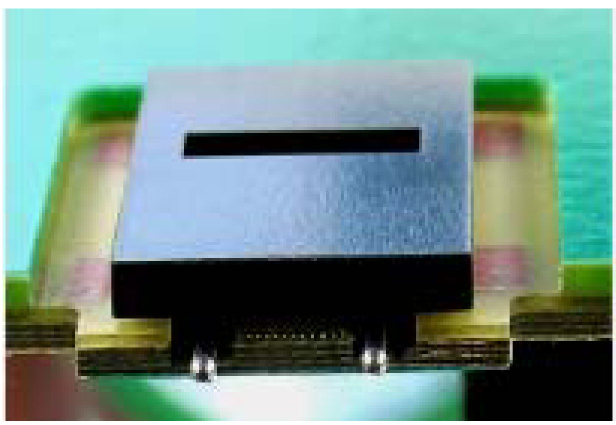

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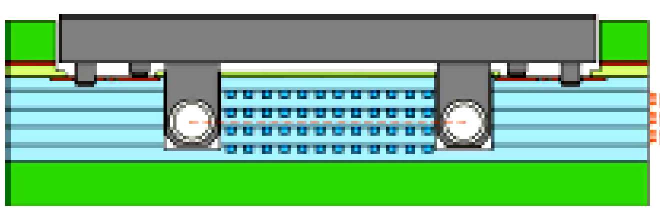


(c)

Fig. 7 (a) MT adapter and its mating site in the optical PCB; (b) MT adapter passively aligned onto the optical PCB (the waveguide were illuminated from the back with white light); (c) Schematic of MT adapter passively to a 2-D waveguide array – enabling the alignment of optical components relative to the waveguide in the PCB [21]

Based on these building blocks, a 12 channel card-to-card optical interconnect link have been built and successfully tested with data transmission rate up to 10 Gb/s. The integrated polymer waveguide technology allows to use large-area, low-cost fabrication through simple deposition techniques and low propagation losses (dB cm) [22]. Each element of the optical module is integrated on a highly resistive silicon motherboard. A module consists of a 10-Gb/s 850-nm VCSEL (or photodiode) array, a driver (or TIA IC), an MT-fiber ferrule interface with protruding fibers, some passive components, and an LCP flex-cable for signal transmission and commands. The MT interface was chosen to leverage the development costs and be compatible with established standards. The optical interface is, therefore, based on the following principle: the light is coupled into an MT-fiber ferrule, in which optical fibers have been inserted and guided through a hole etched through the silicon substrate. DRIE etching is used to process this hole, whose shape is designed such that a 125-m cladding diameter fiber can be inserted with minimum tolerances. Fig. 8 describes the optical interface concepts, where the MT adapter is passively aligned onto the waveguides and serves as connector for the optical module. The light is directly injected into the waveguides by butt coupling.

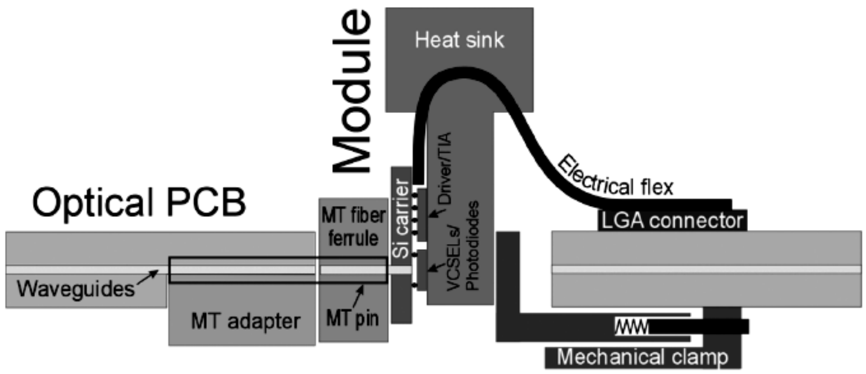
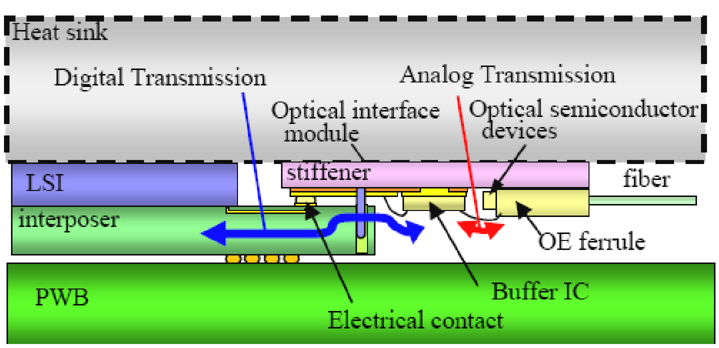


Fig. 8. Schematic of the optical module passively aligned onto the embedded waveguides [22]

Toshiba developed an optical package (called post-reflow optical-interface stacking technique - POST) which enables high speed operation at more than 10Gbps/ch on the standard FR-4 PCB [23]. The POST package includes an interposer and an optical interface module (Fig. 9 (a)). A slightly modified interposer is used where electrical contacts for high speed signals are added on the top surface. After the reflow process of the interposer, the optical interface module was connected to the interposer through the electrical contacts. The POST LSI package enables the use of the standard FR-4 solder reflow process for the optoelectronic LSI packaging, and realizes a cost-effective package with a bandwidth of over 1Tbps. To realize a cost effective and small optical interface module, the authors developed the injection molded optoelectronic ferrule shown in Fig. 9(b). This ferrule has 3D wiring electrodes fabricated on the optical coupling surface which extends to the electrical bonding surface, and guiding holes for optical fibers. The VCSEL or PD was flip chip mounted on the optical coupling surface, and a graded index multi-mode optical fiber array was set into the guiding holes and fixed by a transparent adhesive which also served as the underfill resin of the optical semiconductor devices. The optical coupling between optical semiconductor devices and optical fibers with passive alignment was used for this OE ferrule. Thus, a cost effective and small optical interface module by using the OE ferrule can be realized.



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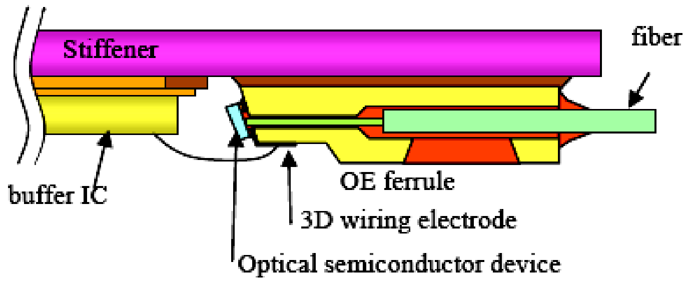


Fig. 8. Cross-sectional view of POST LSI package (a) and Cross-sectional view of optical module [23]

Kim et al. [24] designed and demonstrated a novel fabrication process using a hot embossing technique for micromechanical passive alignment of polymer planar lightwave circuit (PLC) devices. With only one step of embossing, single-mode waveguide straight channels and micro-pedestals for passive aligning were simultaneously defined on a polymer thin film with an accuracy of 0.5 μm (Fig. 9). The hot embossed devices were automatically aligned on a silicon optical bench (SiOB) with v-grooves for fibers and pyramidal pits for the passive alignment. This process reduces the steps for fabricating alignment structures. A fabricated polymer PLC chip and fibers were combined on a v-grooved silicon optical bench (SiOB) in a flip-chip manner. The process provided a coupling loss as low as 0.67 dB per coupling face and a cost-effective packaging solution for various polymer PLC devices. The propagation loss of a fabricated single-mode polymer PLC was 0.83 dB/cm at a wavelength of 1550 nm, and a passively aligned polymer PLC device with accurate SiOB had an average coupling loss of 0.67 dB. In conclusion, the hot embossing technique is a novel means of fabricating polymer PLC devices; it is cost-effective and produces accurate passive alignment.

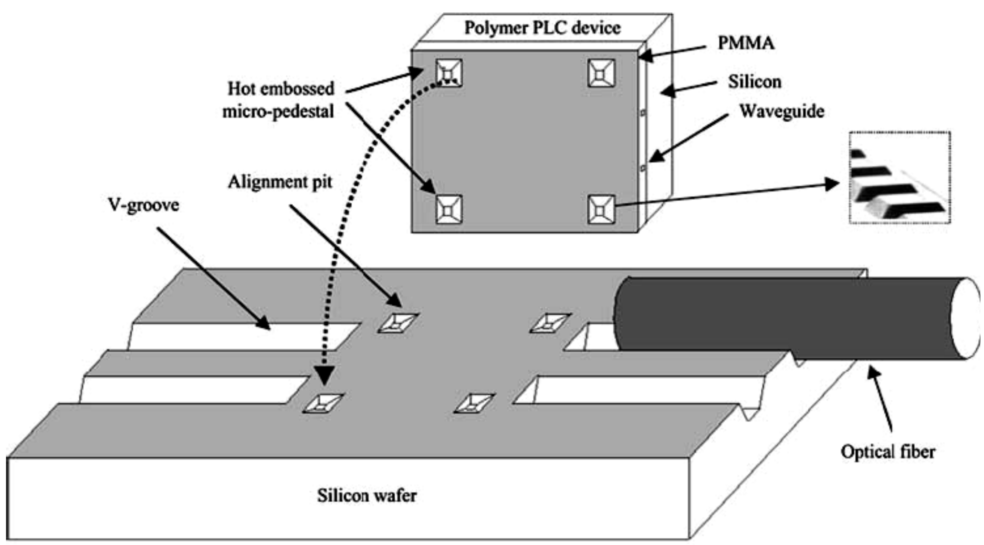


Fig. 9. Principles of the passive alignment of a hot embossed polymer PLC device [24]

2.4 Utilizing MEMS for Optical Alignment

Ishikawa et al. [25] reported a new micro-optical system for laser-to-fiber alignment. An integrated microsystem platform, which has a thermally-actuated micromirror, a silicon etched v-groove and flip-chip bonding pads, was successfully fabricated and actuated for beam adjustment from a VCSEL to a fiber (Fig. 10). The micro-mirror has 4.0 degree maximum beam steering angle with the resolution of 0.08 degree/mA.

With the steering angle reaching 2.5 degrees, the coupling efficiency improves to 80 YO from 9% initial efficiency.

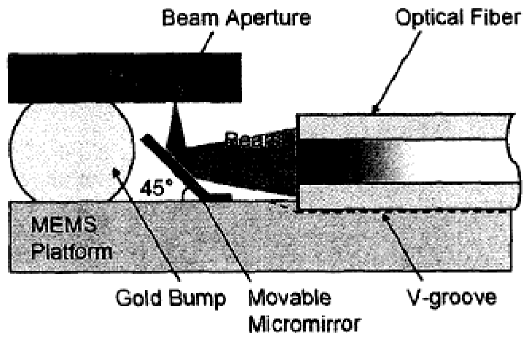
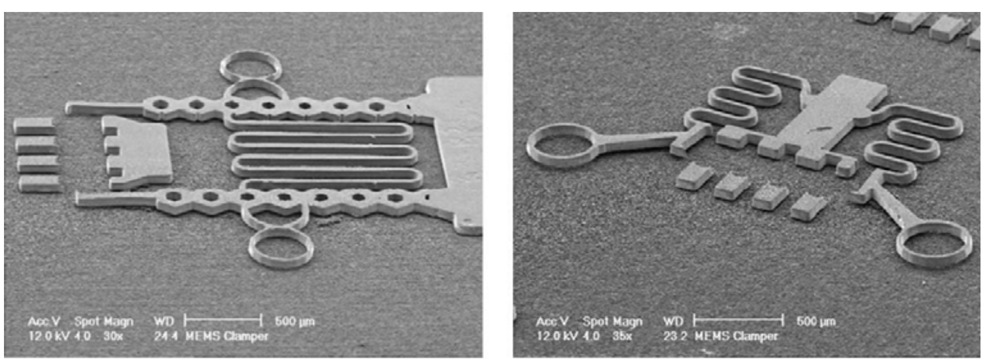


Fig. 10. A cross-sectional schematic view of laser to fiber coupling concept [25]

There is an interest to have the VCSEL beam emitting parallel to the substrate so that the coupled elements can either be fabricated or assembled on the same chip or substrate. Nallani et al. [26] reported research work on using MEMS micro-clampers and ink-jet printed reflowed solder techniques for reliable and precise positioning of VCSEL die parallel to the substrate and low parasitic electrical interconnections. Figs. 11 (a) and (b) shows SEM images of the fabricated two types of micro clampers on an alumina substrate. The mounting of the VCSEL onto the micro clamper was done manually using a probe station. Probes were inserted into the rings attached to the clamper arms and stretched to hold the arms open while the VCSEL array was placed between them. Fig. 12 shows a 4 × 1 VCSEL array with an integrated microoptic element clamped by a micro clamper. To obtain an electrical interconnect to the VCSEL die, a Microfab Technologies Solderjet station was used to dispense solder onto the contact pads and followed by a reflowing.



(a) (b)

Fig. 11. SEM pictures: (a) Type-1 micro clamper structure. (b) Type-2 micro clamper structure

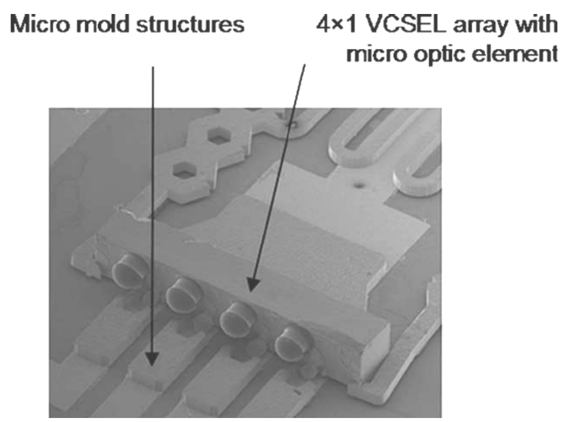
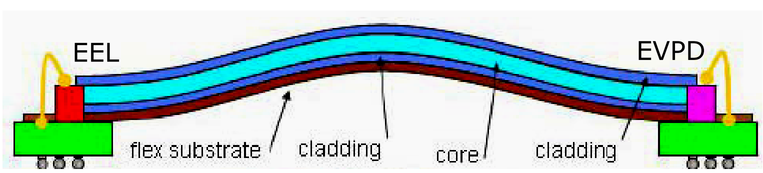


Fig. 12. A 4 × 1 VCSEL array held in position by a type-1 micro clamper

2.5 Embedding OE Devices in Waveguide

Chang et al. from Georgia Tech demonstrated the concept of lithographically aligning edge emitting lasers (EELs) and edge viewing photodetectors (EVPDs) with the embedded polymer waveguide during the waveguide definition, and also assessed the preliminary performance of this novel integration scheme for coupling optically active devices to the lighwave circuit on printed circuit boards up to 10 Gb/s [27,28]. The basic concept of the Georgia Tech approach, as sketched in Fig. 13, is to butt-couple ELs and EVPDs to the waveguide wherein each forms an interface with the polymer waveguide. The integration process consists of forming a photo-definable polymer buffer layer followed by a lower ladding layer, core material layer, waveguide definition, and top cladding layer. EELs and EVPDs are lithographically aligned with the embedded lighwave circuit during the waveguide definition process. The advantages of this technique include scalability, ease of manufacturability, and elimination of mirrors or lenses. The authors have demonstrated the use of this integration process for the simple fabrication of flexible optical interconnects containing pre-aligned EELs and PDs.



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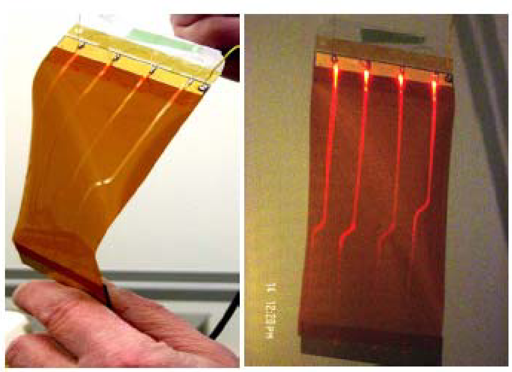

(b)

Fig. 13. (a) Schematic of Georgia Tech's optical interconnect; (b) Array of waveguide on a flexible substrate directly

coupled to EELs [27,28]

Thin-film optoelectronic active devices (on the order of microns thick) can be heterogeneously integrated directly onto the board or chip without significantly changing the topography, and embedded with the optical waveguides, eliminating the need for beam turning out of the plane of the system. For example, thin-film PDs are thin enough to embed in waveguides, and can evanescently or directly couple from the waveguide to the PD [29]. In addition, the use of thin-film devices creates integrated systems that are topographically flat enough to enable standard process techniques such as photolithography and metal deposition to be used. This results in mask-based waveguide alignment between devices, as well as waveguide and metal interconnections created utilizing standard fabrication techniques, mimicking silicon interconnection fabrication. Thus, optical systems may evolve in the same manner as electronic systems: from bulky, interconnected discrete devices to integrated circuits. Seo et al. [30] reported the first demonstration of independently grown and optimized thin-film InP-based edge emitting lasers (EELs) and PDs that are heterogeneously integrated onto a single Si substrate, with a polymer waveguide interconnection between the two active devices to form a complete point to point planar optical interconnection (Fig. 14). The thermal profile of the heterogeneous integration process is compatible with Si complementary metal–oxide–semiconductor (CMOS). The coupling efficiency from the laser to the waveguide is estimated to be 22.6%, and from the waveguide to the PD, 49.2%. Both of these coupling efficiencies can be increased with further design refinement.

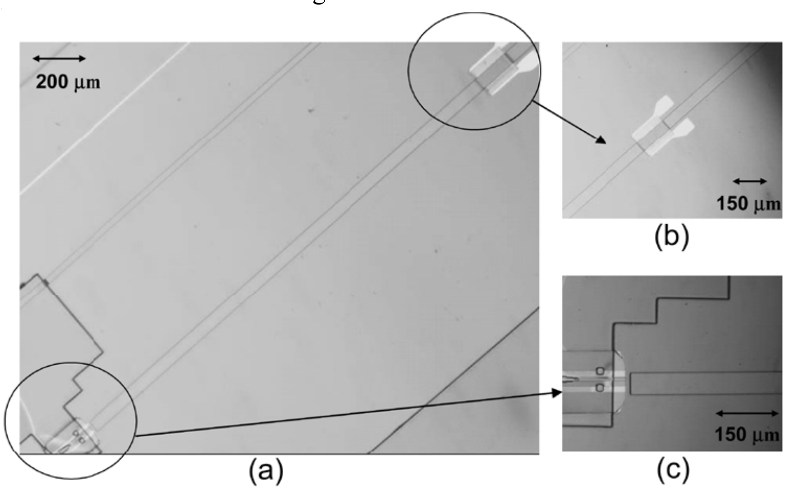

Fig. 14. Fabricated point to point optical interconnection system using a thin-film laser and a thin-film I-MSM PD [30]

2.6 Silicon Bench

Silicon is often selected as a substrate or interposer for optical interconnections because it is very flat and high precision features can be fabricated easily using lithography [6,22,24].

Yoneda et al. [31] assembled the transmitter and receiver by using automatic assembly equipment for several types of module using similar optical design. Fig. 15 shows the optical coupling scheme of optical transmitter. An optical sub-assembly consists of a 4-channel array laser diode (LD), a Si optical bench with V-groove and alignment marks for LD positioning, and a 4-parallel short fiber with mini-MT ferrule. The optical output from LDs is directly coupled to the MMF. The alignment marks are patterned on the LD bottom surface and on the Si optical bench using photolithography technique. A 4-channel LD was mechanically positioned by detecting alignment marks placed on both sides of LD array chip, and soldered with AuSn solder that is evaporated onto the electrodes by Au/Sn/Au multilayer plating. The LDs' anodes/cathodes are directly connected by the solder to the electrode lines on Si optical bench. As the result, the LDs can be operated at high speed modulation as described in last section. Through the assembly process, 4-channel LD array is precisely positioned within ±0.5 μm accuracy for each direction. The coupling loss was measured less than 4.5dB, including MT-RJ connector loss. Fig. 16 shows the optical coupling scheme of receiver module. The light from the flat ended optical fiber is reflected upward on the face metallized Si-V grooved ends and coupled to the detecting area of PD. The 4-channel PD array chip is precisely self-aligned on Si optical bench by means of AuSn solder bump flip-chip bonding. The micro punch and die technique was applied to deposit AuSn solder bumps on to Si substrate. After roughly placing the PD array chip on to Si substrate, the Si submount was then heated to the AuSn solder melting temperature in nitrogen atmosphere. Through these assembly process, PD array chip is precisely positioned within 0.5μm accuracy for each directions. At the wavelength of 1.3μm, the quantum efficiency was measured more than 70±5 %. Using the passive alignment technology described above, 4-channel transmitter and receiver can be assembled by automatic assembly equipment. As the result, assembly cost can be reduced drastically.

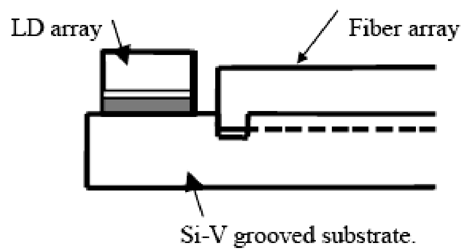

Fig. 15. Optical coupling scheme of transmitter [31]

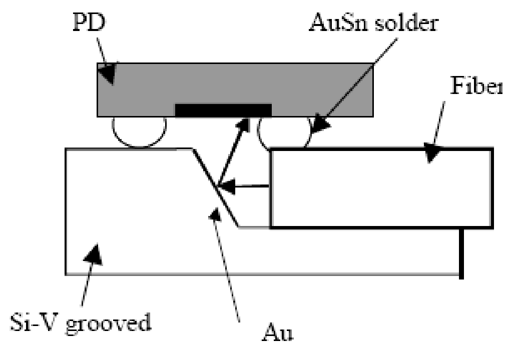

Fig. 16. Optical coupling scheme of receive [31]

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