Invited Paper

Polymer-based Optical Interconnect Technology -
A Route to Low-cost Optoelectronic Packaging and Interconnect

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ABSTRACT

Recent advances in optical devices, polymeric materials, and in the electronic MCM packaging and interconnect technologies could bring the cost of optical interconnect to a level affordable for module, board, and backplane level interconnect applications. Specifically, we discuss how the development in (a) vertical-cavity surface-emitting-laser devices, (b) multichip module packaging technologies, (c) optical polymers, and (d) adaptive interconnect can be applied to benefit optoelectronic packaging and interconnect. We show how these advancements will allow widely used planar processes and the already developed packaging technology in electronics to be applicable to optoelectronic packaging to reduce both recurring and nonrecurring engineering costs for this new technology insertion into computers and advanced electronic systems.

INTRODUCTION

The successful deployment of optical interconnect in telecommunication since the 70’s has led to the greatly reduced cost of the high quality phone calls enjoyed by tens of millions today. The technologies critical to this development were (a) the low-loss optical fiber as the optical interconnect medium, and (b) the reliable and long-life edge-emitting laser as the emitter source. The costs of interconnect devices, components, and media were not the most sensitive elements because of the nature of the telecommunication industry during the period of the technical development.

The advantages of using optical interconnect have been well recognized including increased I/O density, reduced crosstalk, ease of impedance control, insensitive to EMI, and a much higher bandwidth for data transfer with significant reduction in weight and size of cabling. The penetration of optical interconnect into computers for data communication on module, board, and backplane applications—both military and commercial—has been slow in the market place. The requirements of optical interconnect for computers are different from those for telecommunication and are summarized in Table 1. Among them, the costs of optical interconnect devices, components, and media are of paramount importance. Since the computer industry has made significant investment in materials, components, processes and packaging, as well as in capital equipment development, its infrastructure base is enormous and well developed. The challenge of introducing optical interconnect to the computer industry is demonstrating how to take advantage of technologies and infrastructure already in place such that both recurring and nonrecurring costs can be kept at an affordable level.

Several recent advances in optical devices, optical polymers, and electronic packaging technologies could bring the cost of optical interconnect to a reasonable level competitive to electronic interconnect on a cost/performance basis. Specifically, these developments are (a) vertical-cavity surface-emitting-lasers, (b) multichip module technologies as a packaging platform for optoelectronic devices, and (c) low-loss optical polymers as a board-level interconnect media. These developments are discussed as follows.
Vertical Cavity Surface Emitting Lasers (VCSELs)

The edge-emitting laser device that has been used successfully since the 70's is a discreet device suitable for single channel point-to-point interconnect in telecommunication. The development of VCSEL devices represents a significant advancement of optoelectronic devices for optical interconnect in board and module level applications—similar to the MOS technology that has impacted on the IC industry. VCSELs are compatible with IC planar fabrication and can be tested on a wafer-level and packaged as electronic die is presently packaged—two critical elements that allow electronic components to be mass-produced at very low costs. More important, VCSELs make parallel optical link technically feasible, also economically viable. Significant progresses has been made in recent years in reducing VCSEL array device threshold current, improving device efficiency, temperature capability, yield, and reliability. 32-channel VCSELs have been developed under ARPA’s OETC program and tested at 500 Mbps per channel with a total aggregate data transfer rate at 16 Gbps. Packaging of VCSEL devices continues to be a challenging problem, and the thin-film MCM provides a promising solution to the VCSEL packaging, which is discussed below.

Multichip Module (MCM) as a Packaging Platform for Optoelectronic Devices

Packaging cost contributes to a major proportion of the total cost in an assembled optoelectronic system. MCM technologies provide an ideal packaging platform common for both electronic and optoelectronic devices. MCMs can handle mixed types of devices on a common substrate. Unlike edge-emitting devices, VCSELs can be readily pre-tested on the wafer-level prior to dicing, thus only known-good-die (KGD) will be packaged.

The thin film embedded-chip MCM technology, originally developed at GE for high-speed digital and analog applications, is most suitable for optoelectronic device packaging and has been applied for packaging VCSELs devices in this study. In this MCM process, the VCSEL die and other electronic devices such as the driver are placed inside a chip well and are attached directly on top of an alumina substrate. The power dissipation can be further improved using substrate materials with higher thermal conductivity. After die attachment, a thin Kapton film is laminated over the entire module substrate resulting in a relatively planar surface. The die positions are identified by the alignment fiducial marks so that the exact location of the bond pads on the die are registered and stored. A laser system is used to drill microvias adaptively, and electrical interconnects are fabricated using planar thin-film metallization processes such as photo-patterning, sputtering, and electrode plating of Cu/Ti. After completion of electrical interconnects, the module surface remains planar, and the Kapton film is transparent at 0.8 um to laser emission. The VCSELs were tested before and after this MCM fabrication process and have shown no degradation in performance. Fig. 1 shows a packaged 32-channel VCSEL module based on an OETC-designed device using this MCM process. All electrical interconnect lines are impedance-controffed to 50-Ω. This MCM technology allows for packaging of electronic and optoelectronic devices on a common substrate with a nominally planar surface after completion of electrical interconnects. The next step is fabrication of the optical interconnect channels which is described below.

Several previous workers have also fabricated silica and polyimide optical waveguides on silicon or polyimide substrates to optically interconnect different devices using MCM packaging. Self-aligned techniques such as flip-chip and solder-bumps were employed for placement and packaging of optical devices. In these chip-last MCM technologies, thermal dissipation of active high power devices such as VCSELs can be a packaging issue.

Low-Loss Optical Polymers—Flexible Media for Board Level Interconnect

The polymeric materials are widely used in IC processing and are increasingly employed in electronic packaging. The optical, mechanical and physical properties of polymeric materials can be tailor-made for module, board and board-to-backplane optical interconnect applications. In addition, polymers are flexible and easy to incorporate into other semiconductor processes.

Significant progresses has been made in optical polymers in recent years. Optical losses less than 0.2 dB/cm have been demonstrated in certain polymers. Table 2 summarizes some of the reported optical polymers and their respective
properties. Among these materials, Polyguide®, developed by DuPont and licensed to AMP, has shown excellent layer quality and thickness control. These properties, combined with simple photolithography and lamination processing techniques, are attractive as a low-cost optical medium for board-level optical interconnect. Another class of acrylate-based polymers, developed at AlliedSignal, has shown optical loss less than 0.1 dB/cm at 0.8 μm. Waveguide structures, both single mode and multimode, with excellent sidewalls have been fabricated by photo patterning. This material can be placed on a variety of substrates and used to interface waveguides to micro-optical elements and fiber-to-waveguide interconnect structures.

The waveguide structure employed in our system uses polyetherimide (Ultem®) as the core and benzocyclobutene (BCB) as the cladding material. Ultem is an engineering thermoplastic with excellent temperature and mechanical stability, and a good optical transmission in near IR. Both Ultem and BCB materials exhibit low optical losses at 0.8 μm and are compatible with the module fabrication processes. Optical waveguides were fabricated using RIE and laser ablation methods. Optical losses of 0.2 dB/cm have also been measured. Fig. 2 shows a multimode waveguide using the BCB/Ultem/BCB structure with 45-degree end face fabricated on top of a MCM module. Using this structure, waveguide ribbons have been fabricated on a flexible Kapton substrate with no increase of optical losses. This structure can be used as an interface between the board and MCMs.

Adaptive Interconnect and Process Integration

Alignment between optical interconnect channels (e.g., waveguides) and active devices (e.g., lasers, detectors) is a key problem in optoelectronic packaging and contributes much to the packaging cost in subassembled optoelectronic systems. Active and passive alignments require precision-machined components and involve serial assembly procedures and discreetly handled parts. All of these factors contribute to the final assembly cost. In addition, optical interconnect for computer applications will require parallel optical links and any packaging technology developed has to be scalable for handling multiple channel array-type devices.

In our approach, the device-to-waveguide alignment is accomplished by using an adaptive alignment method. In this process, the actual chip location is determined by the fiducial marks, and an adaptive laser system is used to pattern the interconnect channel adaptively. This alignment process is much like that used in the electrical interconnect for identification of electronic die location. Fig. 3 illustrates the adaptive alignment between an active device (e.g., an VCSEL array and optical waveguides). The top left figure shows the design position in which the devices are aligned properly to the waveguides, while the bottom left figure shows the actual device location in which the laser array is positioned slightly downward. In this case, the device fiducial marks are registered and the laser tool is directed to pattern the waveguide channel adaptively, as shown in the right figure. The coupling loss introduced by the adaptive interconnect was calculated using a 2-D waveguide model under various conditions. The results have shown the minimal loss can be achieved under the condition that the bending angle is smaller than the critical angle defined by the indices of core and cladding materials.

Figure 4 shows integration of the processes described above to package optical and electronic devices using planar fabrication, thin film MCM packaging and the adaptive interconnect process. Our current effort is to integrate the VCSEL into the thin film MCM and to couple the light output into polymer waveguides using 45-degree end reflectors. Multimode waveguides are used to relax alignment tolerances to a level compatible to electrical systems, typically of microns.

SUMMARY

In this paper, we described a polymer-based optoelectronic packaging for optical interconnect on module and board level applications. Recent developments in (a) vertical-cavity surface-emitting-lasers as a low-cost emitter, (b) multichip module technologies as a packaging platform for optoelectronic devices, and (c) low-loss optical polymers as an interconnect medium will allow planar fabrication processes to be employed for optoelectronic packaging to take the full advantage of packaging and fabrication technologies and infrastructure already available in IC processes and manufacturing.

® Polyguide is a registered trademark of the E.I. du Pont de Nemours & Co. Inc.
® Ultem is a registered trademark of the General Electric Company
ACKNOWLEDGMENTS

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REFERENCES


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Table 1. Summary of Requirements of Optical Interconnect for Computers and for Telecommunication Applications.

Optical Interconnect Technology

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<tr>
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<tbody>
<tr>
<td></td>
<td>Telecommunications</td>
<td>Data communication</td>
</tr>
<tr>
<td></td>
<td>Telephone systems</td>
<td>LAN, Data Bus</td>
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<tr>
<td>Sources:</td>
<td>Edge Emitting Lasers</td>
<td>Computers backplane boards</td>
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<td>Media:</td>
<td>Optical Fibers</td>
<td>Control/Sensors</td>
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<td>Requirements:</td>
<td>Long haul (~Km)</td>
<td>Surface Emitting Lasers</td>
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<td></td>
<td>Point-to-point Interconnect</td>
<td>Optical Polymers</td>
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<tr>
<td></td>
<td>Fiber-loss limit</td>
<td></td>
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<td>Performance-driven</td>
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<td>Cost is not a driver</td>
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<td></td>
<td>Reliability is key issue</td>
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<td></td>
<td>Short haul (~meter)</td>
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<td>Array Multi-channel</td>
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<td>Interface-loss limit</td>
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<td>Design tradeoff</td>
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<tr>
<td></td>
<td>Cost is a driver</td>
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<td>Packaging is key issue</td>
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Table 2. A Summary of Some of the Reported Optical Polymers and Their Respective Properties.

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>INDEX</th>
<th>TRANSMISSION LOSS (dB/cm)</th>
<th>REF.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polycarbonate</td>
<td>1.59</td>
<td>0.19 (0.83 μm)</td>
<td>(1)</td>
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<td>Polymethyl Methacrylate (PMMA)</td>
<td>1.49</td>
<td>&lt; 0.1 (0.63 μm)</td>
<td>(2)</td>
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<tr>
<td>Photopolymerizable Acrylate (Polyguide)</td>
<td>1.46 - 1.52</td>
<td>0.3 (0.83 μm)</td>
<td>(3)</td>
</tr>
<tr>
<td>Fluorinated Acrylic</td>
<td>1.32 - 1.56</td>
<td>&lt; 0.1 (0.80 μm)</td>
<td>(4)</td>
</tr>
<tr>
<td>Preimidized Polyimide</td>
<td>1.62</td>
<td>0.3 (0.83 μm)</td>
<td>(5)</td>
</tr>
<tr>
<td>Fluorinated Polyimide</td>
<td>1.55</td>
<td>&lt; 0.5 (0.63 μm)</td>
<td>(6)</td>
</tr>
<tr>
<td>Photosensitive Fluorinated Polyimides</td>
<td>1.55 - 1.60</td>
<td>0.4 (0.80 μm)</td>
<td>(7)</td>
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<tr>
<td>Fluorinated Polyimide Copolymers</td>
<td>1.52 - 1.62</td>
<td>&lt; 0.5 (0.83 μm)</td>
<td>(8)</td>
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<tr>
<td>Benzocyclobutene (BCB)</td>
<td>1.50 - 1.55</td>
<td>0.1 (0.8 - 1.3 μm)</td>
<td>(9)</td>
</tr>
<tr>
<td>Polyetherimide</td>
<td>1.61 - 1.65</td>
<td>0.23 (0.83 μm)</td>
<td>(10)</td>
</tr>
</tbody>
</table>

(8) Hitachi Chemical, S. Nara, Private Communications, (1993)
Polymer Waveguides with 45°-Reflector

Alignment Pedestal

Via for Electrical Interconnect

I/O Pads

Cu Lines
Kapton Overlay

Adhesive

VCSEL Array

Chip Well

Substrate

Fig. 1. A packaged 32-channel VCSELs of an OETC-design device using the embedded-chip thin film MCM process.

Fig. 2. A multimode waveguide using the BCB/Ultim/BCB structure with 45-degree end face fabricated on top of a MCM module.
Fig. 3. The adaptive alignment between an active device (e.g., an VCSEL array and optical waveguides).
An Integrated Electrical and Optical Interconnect Approach

Key Features:
- Hybrid MCM Packaging (GE HDI Process)
- Adaptive Interconnect (AI)
- Planar Fabrication Process

Fig. 4. Integration of the processes to package optical and electronic devices using planar fabrication, thin film MCM packaging and the adaptive interconnect process.