Micropackaging for the Next Generation of Optical and Electrical Components

An OIDA Forum Report

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Table of Contents

Table of Figures

Tables

1 Introduction

In August 2006, the Optoelectronics Industry Development Association (OIDA) held a one day forum on micropackaging. OIDA held this Forum in conjunction with the 100 Gbit Ethernet Forum with the objective of focusing on the issues presented by next generation components for communication systems. Historically, the telecommunications sector invested heavily in new communications technology at the component and semiconductor level. Industry stratification over the last 10 to 15 years, however, changed the business model, research activity, and funding levels. At the same time, the requirement for higher data rates and smaller components that are more intelligent has evolved.

Optical components are ubiquitous. Applications that use them include DVD players, audio devices, cell phones, re-writable drives, projection displays, and communication devices. This report concentrates on the role of micropackaging for the communications industry. This topic is highly relevant to the 100 Gbit Ethernet Forum that took place in conjunction with this meeting.

The configuration and cost of optical component packages depends on the application. Packages can incorporate individual passive or active components, or be 'hybrids' that incorporate two or more components. This report focuses on packaging for optical components for systems that operate at high data rates. The next generation of optical communication products, such as the 100 Gbit Ethernet, will require such components.

The communications industry is constantly being pushed to deliver higher data rates and lower cost products. The movement is away from discrete components to functional modules, especially in the Ethernet and fiber channel markets. There are several competing approaches for miniaturizing and increasing the optical component functionality. The direction of component development will ultimately be linked to the evolution of networks and new applications. Standards are also important for the development of next generation products.

Participants in the forum addressed three main questions:

1. Which is the right approach: hybrid packaging or system on chip?

2. What are the technology roadblocks and how will integration play a role in the next generation of equipment development?

3. What issues are going to drive micro optic packaging: placement, thermal, electromagnetic interference (EMI) or signal integrity (optical and electrical)? How far down does the functionality need to reach?

First, this document provides background information on optical component packaging. It will evaluate the impact of communication business drivers and the issues on the future of technology development. Next, it incorporates the discussions and positions of several

U.S. companies. On the technology side, the report discusses the continuing need for more sophisticated components and the opportunities for photonic integration. It highlights concerns over cost structures and outsourcing. The document concludes with a discussion of the three parallel breakout sessions and a summary of the Forum's findings. Based on the presentations and the breakout sessions, the report provides several recommendations.

2 State of the communications industry

The bandwidth requirements of consumer and peer-to-peer applications, as well as mobile access to the internet are driving the evolution of the communications industry. Consumers demand greater storage capacity, more secure networks, and higher bandwidth. The industry on the other hand is competing to provide more content services, such as the "triple play." Higher data rates for the core/metropolitan area networks and the shift to the all internet protocol (IP) network are driving new applications such as voice over IP (VoIP), video on demand (VOD), mobile internet/video streaming (VCast), and internet TV (IPTV). Future consumers will likely require on-demand mobile access to the internet and perhaps a single black box for all media applications in their living space. Because of this market expansion, the optoelectronics industry is recovering from the effects of telecommunications bubble that burst in 2000. The volume of components shipped today is comparable to that in 1999.

All around the world, network upgrades are taking place. British Telecom is implementing a 21st century network, investing close to $19 billion USD. In the U.S., AT&T is upgrading its core network to OC-768. Cable and telecom operators are also upgrading their networks to provide additional consumer services. Several companies are deploying fiber-to-the-home/premise (FTTH/P) in an attempt to capture market share. The storage sector is deploying more and more fiber and copper links and offering newer network-attached storage services. Servers are incorporating fiber optic technology to speed up the transfer of data within the box and between servers. All these advances require better, faster, cheaper, and very reliable optoelectronics components.

The communications industry uses wired, wireless, and satellite communications. From the optoelectronic component perspective, the most interesting segment is the wireline industry. Currently, three different market segments use fiber optic components:

- Communications networks
- Storage area networks (SAN)
- Server communications

In these segments, fiber optics has always had to compete directly with copper connections.

The communications network consists of both enterprise and service providers. In the U.S., the service providers are the traditional telecom operators (carriers), and the cable operators (CATV). This industry is undergoing a transformation, with new services offered by both cable and telecom operators. The communications network partitions into the following distinct segments:

- Core network
- Metro
- Access
- Last mile/local area network (LAN)

The core network is the traditional space of the Carriers such as AT&T, BT, France Telecom, and Deutche Telecom, which provide fixed line and mobile wireless services. These operators have traditionally preferred switch-based networks, SDH/SONET, and MPLS. Now they are considering the IP Multimedia Subsystem (IMS) network structure, Ethernet, and the associated revenue stream.

The rollout of new services to the consumer and the technology used to provide them varies with geographical location. With the dominance of data on the backbone, the transport of the information is packet orientated. The dominance of data transport led the Telecommunications Industry Association (TIA) and International Telecommunications Union (ITU) to develop the generic framing protocol (GFP), which allows a more efficient use of switch-based networks. Today the backbone still transports more than 50% of Ethernet traffic using the SONET/SDH/MPLS network.

Different technologies compete in the data transport market. Both the enterprise and storage sectors compete in terms of fiber network requirements and the number of optical ports. Their reliance on optoelectronics increases as the data rate increases. In the U.S., the cable operators have been upgrading their networks and now compete directly with the telecom carriers for voice traffic. This movement to voice over IP (internet telephones) and internet based television is changing transport requirements. The implementation of high definition TV (HDTV) and the movement to streaming video directly to the home is increasing the burden on the carrier networks. In Japan and Korea, the deployment of fiber to the home has enabled such a convergence of services.

2.1 Investment in the optical components space

The optoelectronics component industry requires significant research and development (R&D) investment. In a vertically structured organization, the corporate laboratory develops the next generation components and transitions them into the internal manufacturing facilities. The financial structure of a horizontal business model, however, does not have a parent organization that can fund the R&D. Over the last 25 years, the telecommunications industry in Europe and the United States has moved away from the vertical business model of the 1970s and 1980s to a horizontal structure. In Asia, especially in Japan, however, the vertical model still dominates.

During the late 1980s and early 1990s, the telecommunications industry became even more stratified. The communications carriers, who had driven most of the new optoelectronics product development and research, sold or spun out their optoelectronics business units as separate entities. The venture capital (VC) community then became the source of cash for optoelectronics component research and development. The VC community fed large amounts of cash to the component industry, as shown in Figure 1. This level of investment led to projections that 40 Gbit optoelectronics components would be in widespread use by 2003. As we know today, this expectation proved to be unrealistic.

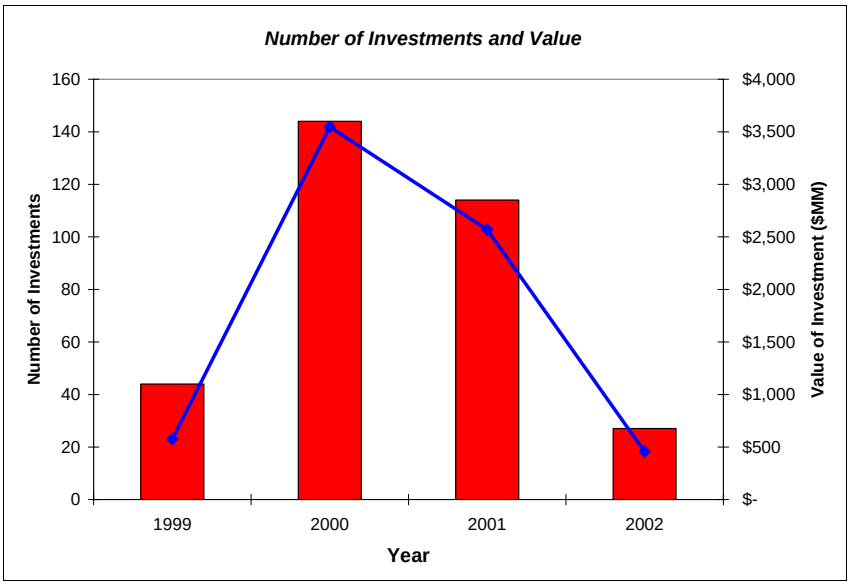

Figure 1: Number of investments during the bubble and cash investment

(Source: M. Lebby private communication)

The bursting of the bubble in 2000 led to product price erosion and optoelectronics component vendors sustained heavy losses. Until recently, most optoelectronics component companies have had a negative operating income. Industry consolidation has been slow and very few players merged or exited the business. This forced every company to review its fundamental operating structure and implement cost reduction strategies, such as outsourcing to low labor cost countries. On the other hand, several companies have taken advantage of the downturn to invest in a vertical manufacturing infrastructure and have gained access to new technology through acquisitions. Table 1 lists the current financial situation of several of these companies.

Communications: Datalink & Component Vendors	**Revenues (Millions)**	**Operating Income (Millions)**	**Financial Year reported**
Cyoptics	Private Company		
Mitsubishi	$ 31,917.80	$ 424.40	2005
Avago Technologies	$ 1,800.00	private	2005
JDSU	$ 712.20	$ (261.30)	2005
Finisar	$ 364.30	$ (24.90)	2006
MRV (LuminentOIC)	$ 283.70	$ (16.30)	2005
Bookham	$ 200.30	$ (248.00)	2005
AVANEX	$ 160.70	$ (108.40)	2005
EMCORE	$ 127.60	$ (13.10)	2005
Opnext	$ 100.00	private	2005
OCP	$ 56.00	$ 0.90	2005
Eudyna (Fujitsu)	$ -	-	
Excelight	$ -		
Sigma-Links	$ -		

Table 1: Optoelectronics component companies and their operating incomes

(Source: Company reports)

It is important to note that Japanese companies are subsidiaries of major corporations and are not truly independent. This relationship reduces the visibility of the actual losses or profits of these subsidiaries. Additionally, the Japanese companies working in the components space continue to practice long-term investment strategies and continue to invest in the next generation of optoelectronics components.

The outsourcing of manufacturing to South East Asia has enabled several U.S.-based companies to reduce their operating costs. The productivity and efficiencies have improved and the restructuring of the business has lead to a slimmed down approach to development and product engineering. Several companies have taken the next step and have eliminated or reduced product development in the U.S. by creating R&D centers in China. This transfer of intellectual property raises several concerns for the Department of Defense, future supply of the components, and the health of the electronics industry in the U.S.

Even though optoelectronics component companies have implemented the cost reduction strategies, most still report an operating loss. Industry consolidation or companies exiting the market have been slow. Companies no longer fund research and development. Some of the technology requirements for higher data rates, on the other hand, require significant investment in new modeling tools, test equipment, and device technology. One approach places more functionality on the optoelectronics chip, but requires further discussion and calls for a new approach. Another solution may be the development of the foundry model within the communications industry.

2.2 Markets and drivers for higher data rate devices in communications

The optoelectronics components market requires new products as the development of new applications and transport requirements continue to expand. Optical fiber links offer several advantages over copper links for communication at high data rates. Copper links, however, have continued to improve and have prevented optical fiber from becoming the dominant technology. The next section highlights some of the important market drivers.

2.2.1 Server applications

The massive amount of data processing by businesses has increased the demand for servers. The current server market is over $56 million. The cost of server technology has been decreasing and e-business applications have been increasing. More memory, increased processor speeds, and the movement to 64-bit processing mean more bits are being processed and transported within the servers. To support this increase in traffic, the server environment relies on more and more optics. Fiber optics addresses two critical issues: the cost per transmitted bit and I/O port congestion. A study has shown that in the future there will be a bottleneck with respect to processor technology and the number of I/O ports off the chip. New I/O technology, preferably relying on optical interconnect

technology, will need to be implemented. The second issue is the cost/transmitted bit. Figure 2 illustrates this relationship.

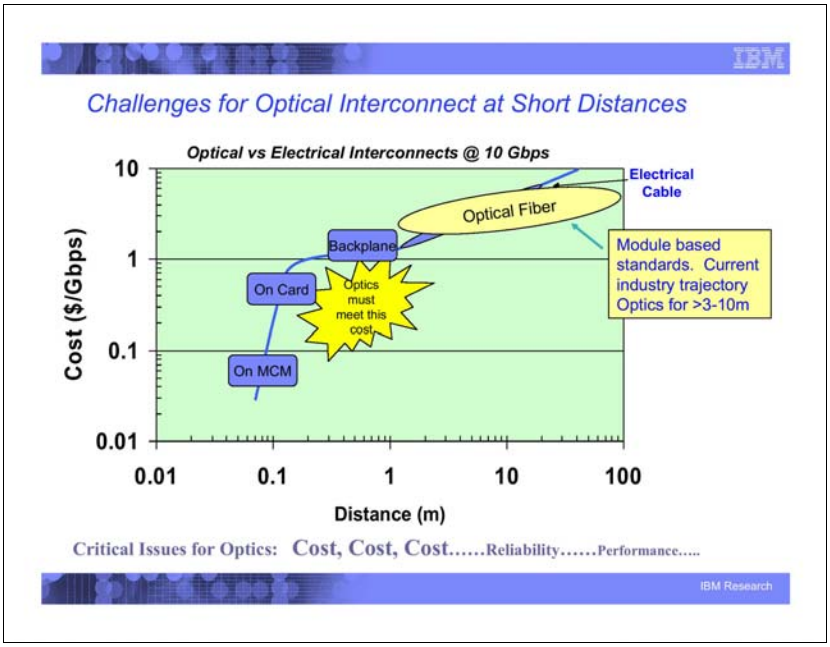

Figure 2: Cost per transmitted bit and the cost requirements for optoelectronics components

(Courtesy of IBM: P. Pepeljugoski)

Today, the demand for optoelectronics technology is for the modules or components to achieve a greater than 100 Gbit/s aggregate transport speed. Industry currently uses a parallel optic fiber approach. In the future, the aggregate transport speed will need to increase further.

2.2.2 Enterprise applications and carrier networks

The carriers are investing in Ethernet and the enterprise space continues to grow. The increase in content and more services to the consumer are driving increased bandwidth demand. In the 100 Gbit Ethernet Forum, participants highlighted several discussion points on the market drivers. Increased content and the change in type of traffic will increase demand for bandwidth in the metropolitan area network and subsequently on other areas of the network. Figure 3 highlights the forecasted change in traffic.

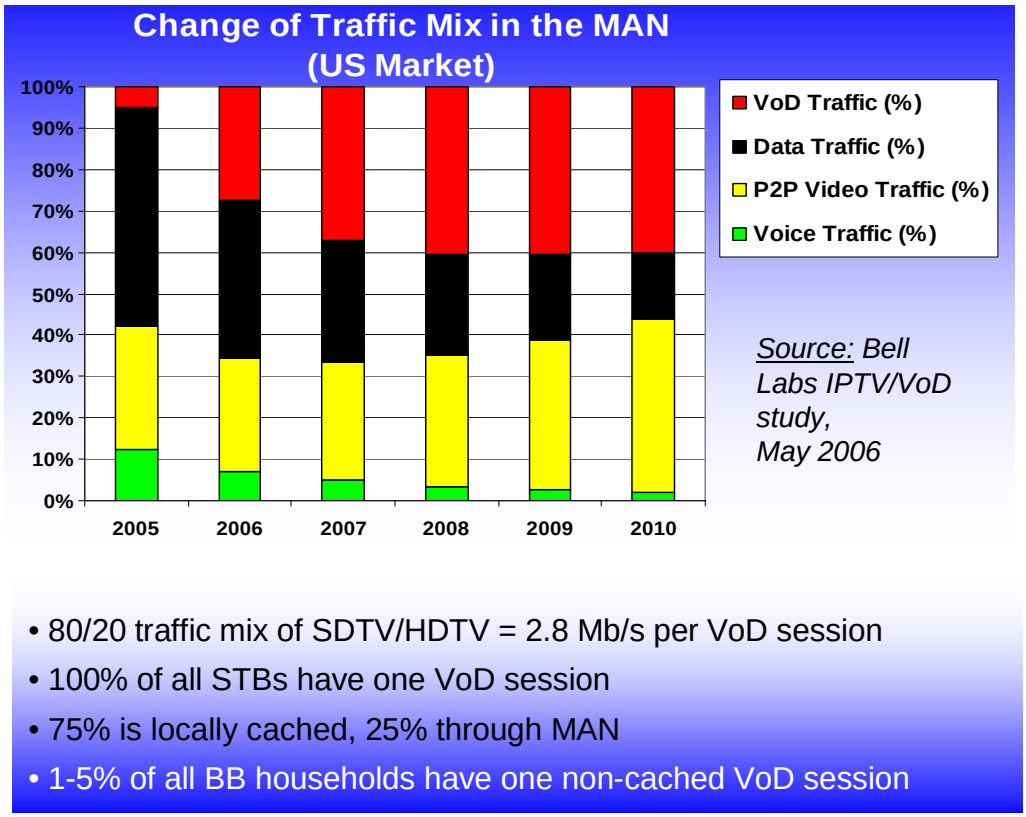

Figure 3: Forecasted change in traffic across the network from 2005 to 2010
(Courtesy of Lucent Technologies: M. Zirngibl)

The drivers for video content include the movement to HDTV and VOD services. The competitive drive is to gain share by providing more services to the consumer. The telecommunications carriers are developing IPTV services and are moving into the traditional space of the cable operators. The cable operators, on the other hand, offer both data and phone services in addition to their broadcast subscription services. As carriers and cable companies upgrade their networks, they are looking for the best and most reliable technology.

For the router and switch companies, the management of the data flow is going to be a problem. The issue of MAC look-up table explosion for E-line services has been addressed. The concerns over the layer 3 flow control are now pushing for a 'big fat pipe' solution. This means that the switch vendors are looking at 40 Gbit/s and 100 Gbit/s systems. With the high data throughput through a pipe, packet loss, congestion, and under-utilization of capacity are controllable. As a result, switch vendors are putting pressure on the optoelectronics component companies to offer 100 Gbit Ethernet capability.

2.2.3 Storage applications

The amount of data that is being stored and transmitted grows exponentially. The hardware for data storage comes in several formats today:

- Optical disc – DVD, CD, HD DVD
- Flash memory
- Magnetic hard drives

Server farms process companies' information and provide secure data storage. There are three different types of storage approaches:

- Network attached storage (NAS)
- Storage area network (SAN)
- Direct attached storage (DAS)

The storage area network utilizes optical fiber communication relying on the Fibre Channel Protocol (FCP). Low-cost vertical cavity surface emitting lasers (VCSEL) technology dominates this market with current emphasis on 8.5 Gbit/s. FCP requires backward compatibility at all data rates and the same module footprint. The market segments into host bus adaptors (HBA) and switches. Typically, the HBA market relies on fixed optoelectronic components–a transceiver soldered to the board. The switch segment uses pluggable modules that are easily replaced or reconfigured. The constantly growing demand for data storage is causing the data rate to keep doubling.

The next section looks at the device and packaging developments within the communications industry. Each of the different approaches presents different challenges and benefits.

3 Optical devices for high speed communications

The telecommunications companies developed the basic materials and component technology for optoelectronics devices, which have been in production for more than 20 years. In the field of optical communications, regulations and standards drive the performance requirements of the basic components. Although standards generally help the industry, they may at times be detrimental for new technology. Market acceptance can take several years before production volumes can ramp to large volumes and provide a return on investment (ROI). Embedded technologies protected by standards and regulations may serve as a barrier to a new technology, preventing it from achieving adequate ROI.

Since the optical bubble in 2000/2001, industry has been trying to achieve cost structures for new technology that are comparable to those of established technology. Switch and router companies have used the abundance of suppliers to force severe price erosion in the component market. As a result, lower tier suppliers are no longer profitable. The net result is a paradigm shift in the cost of optoelectronic vs. copper modules. An increase in volumes to substantiate such a cost structure, however, has not materialized.

The market for optoelectronic telecommunication devices is relatively small as compared to devices for consumer electronics. Light emitting diodes (LED) and CD/DVD lasers are mass produced, making it easier to amortize the investment. In the high definition (HD) DVD market, backward compatibility with different media causes significant cost increases. The transceiver market faces similar compatibility requirements. Figure 4 shows the number of optoelectronic telecom devices shipped from 1996 through 2005.

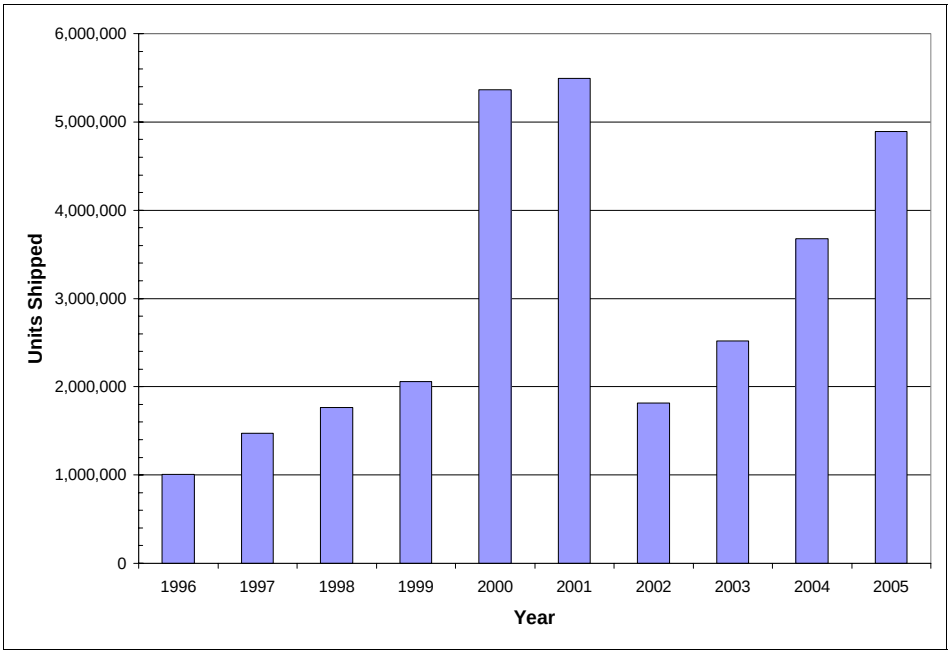

Figure 4: Volume of telecom optoelectronic devices shipped by year
(Source: Laser Focus World)

Price declines for optoelectronics components have averaged 20% to 35% per year, without substantial increases in unit volume. The low volume and average selling price (ASP) have broken the vertical supplier business model. The return on investment for component manufacturing does not justify entry into this market. The customer, on the other hand, demands high quality and reliability with field lifetimes on the level of 25 years. In contrast, consumer electronics products are usually obsolete within a few years and low price is more important than high reliability. Table 2 shows a good example of price declines for a low volume product.

Year	**Power**	**Sales Price**	**Source**
1993	90mW	$7000	Lasertron
2006	90mW	>$300	JDSU
2006	500mW	<$1000	JDSU
Note: 21% annual price reduction and 15% annual power increase			

Table 2: Example of price reduction seen in the telecom sector

(Courtesy of JDSU: Toby Strite – OIDA forum on high power lasers)

The next section discusses some of the building blocks for high-speed communications– the optoelectronic devices. First, it provides an overview of the device requirements, followed by a discussion of the different packaging technologies and photonic integration.

3.1 Building blocks

Local area networks (LAN) and storage area networks (SAN) use multi-mode fiber and copper cabling. Multi-mode 62.5 μm core fiber links dominate the horizontal and vertical fiber risers in a building infrastructure. Single mode fiber is preferred for inter-building and inter-city links.

Several different types of fiber are available for optical links. The optical fiber has different characteristics depending on whether it is multi-mode or single mode. Table 3 provides examples of fiber media.

Fiber	Wavelength	Core Diameter	Over Filled Launch Bandwidth
OM-1	850nm	62.5um	200
	1310nm		500
OM-2	850nm	50um	500
	1310nm		500
OM-3	850nm	50um	2000
	1310nm		
OM-3+	850nm	50um	4700
	1310nm		
SMF-28e	850nm	10um	NA
	1310nm		

Table 3: Types of fiber media deployed for communication links

Optoelectronic devices are fabricated from direct band gap III-V materials. An optical link requires both a transmitter and receiver. The characteristics of the transmitting medium, the optical fiber, directly affect the type of device employed. The optical transmitter needs to overcome the impairments of the optical fiber, such as chromatic and polarization mode dispersion. The receiver needs to have enough bandwidth and sensitivity to detect low-level signals and a wide dynamic range to prevent saturation. The link distance and data rate, therefore, depends on the device structure, electronics, connectors, and fiber characteristics.

For fiber transmission, the wavelength windows of interest are 850 nm, 1310 nm, and 1550 nm. Dense wavelength division multiplexed (DWDM) transmission systems use a grid of wavelengths on a narrow spacing of 100 GHz, 50 GHz, or 25 GHz centered at 1550 nm. Improved fiber characteristics enable wider operating windows. Fore example, low water content fiber allows DWDM and coarse wavelength division multiplexed (CWDM) systems to use more of the fiber wavelength window. Table 4 lists the transmitter types available today.

Device Type	Wavelength	Data Rate							
		155Mb/s to 1.25Gb/s	2.488Gb/s		10Gb/s			40Gb/s	100Gb/s
			<300meters	> 300meters	<300m	<2Km	>2Km		
Fabry Perot	850nm								
	1310nm							X	
	1550nm								
Direct Modulated DFB	850nm								
	1310nm								
	1550nm								
Integrated DFB EA	850nm								
	1310nm							X	
	1550nm							X	
Electro-Absorption Modulator	850nm								
	1310nm								
	1550nm								
Mach Zender Modulator	850nm								
(LiNbO3)	1310nm								
	1550nm								
VCSELs	850nm								
	1310nm								
	1550nm								
X: Demonstrated in the lab or field trial									

Table 4: List of devices, transmission distance, and bit rate as reported in the literature

Fundamentally, all laser devices are p-n diodes. There is no standard laser transmitter and the industry sets device requirements based on the application. Enhancements in material growth, understanding of the loss mechanisms, and the electron-photon interactions have enabled designers to achieve high bit rates. The problem is that most of the designs are proprietary and there is no standard toolbox for device design. Some software modeling tools are available but they do not come close to those provided by the CAD industry for application-specific integrated circuits (ASIC) or other electrical circuits. The following section highlights transmission component issues and how they relate to packaging requirements.

3.2 Device design concerns

The fundamental issues for a designer developing optoelectronic devices are:

- Is the operating voltage/current requirement low or high?
- Does the absorption or emission efficiency matter? Low or high?
- Is the device coupled to a fiber or other type of waveguide?
- What is the bandwidth requirement?
- What are the spectral requirements?
- What are the noise requirements?
- Is the structure a multi-electrode or single electrode device?
- What are the capacitive losses that need to be controlled?

The properties of the material, waveguide geometry, and device structure directly impacts the final characteristics and performance. The next section briefly highlights some of these topics to provide a background of the complex nature of the field.

3.2.1 III-V material systems used for communications

The direct band gap (Γ point) of the semiconductor determines the emission wavelength. The material utilized for the laser depends on the wavelength required for the transmission. Table 5 shows the properties of the binary compounds.

Compound	Type of Energy Gap	Lattice Constant (A)	Energy Gap at 300K (eV)	Wavelength (um)
AlP	Indirect	5.4510	2.450	0.507
AlAs	Indirect	5.6605	2.163	0.574
AlSb	Indirect	6.1355	1.580	0.786
GaP	Indirect	5.4512	2.261	0.549
GaAs	Direct	5.6533	1.424	0.872
GaSb	Direct	6.0959	0.726	1.711
InP	Direct	5.8688	1.351	0.919
InAs	Direct	6.0584	0.360	3.450
InSb	Direct	6.4794	0.172	7.221

Table 5: Binary compounds for devices fabricated on InSb, GaAs, and InP substrates

(Source: Published materials papers)

The actual emission wavelength can be tailored by the device structure, i.e. bulk layer, quantum well, or quantum wire/dot. Several loss mechanisms and defect issues affect the performance of semiconductors fabricated from III-V materials, which the designer must take into account. Table 6 provides examples of such mechanisms.

Material system	Defect
GaAs	Dark Line Defects
	Heterobarrier leakage
	Point Defects
InP	Intervalence Band Absorption
	Auger Recombination
	Heterobarrier leakage
InSb	Miscibility Gap
	Intervalence Band Absorption
	Auger Recombination
	Heterobarrier leakage

Table 6: Major loss mechanism and substrate material system

The properties of the material system and the loss mechanisms determine the ultimate switching speed and thermal characteristics of the device. Other factors such as crystal lattice matching, strain, and doping concentration will also affect device performance.

As the semiconductor band gap gets smaller, the effective mass of the carriers get smaller. This implies high transport speeds and higher frequencies. Several factors other than the direct band gap, such as the indirect minima and valence bands, also influence device performance.

3.2.2 The waveguide

The waveguide is an important structure for both passive and active optoelectronic devices. Waveguides are defined using etched features and layer control to ensure confined modes. These guided modes confine the light and define modal properties for the device. For example, the waveguide design impacts the threshold current and wavelength control in lasers and the wavelength selection in arrayed waveguide devices.

In both vertical and horizontal waveguide structures, control of the refractive index is critical. The effective single oscillator model defines the variation of the refractive index for direct band gap materials. This means that the refractive index below the band edge is proportional to the inverse of the photon energy.

3.2.3 Capacitance and bandwidth

The capacitance and bandwidth of a semiconductor device influence the maximum operating speed. There are several different capacitive effects including:

- Metal Ternary Semiconductor (MTS)
- Metal Insulator Semiconductor (MIS)
- P-N Junction capacitance
- Device Geometry and Structure (including doping levels)

These capacitive effects and the choice of the material system determine the modulation bandwidth. Electro-absorption modulation up to 40 Gbit/s for system links has been demonstrated using co-planar waveguides for the metallization. 40 Gbit/s directly modulated DFB lasers with high extinction ratios have been demonstrated. Continued research will push the bit rate to new levels.

3.2.4 Simple device geometries

Optical links employ several device geometries. The multi-functional devices, such as tunable lasers use the basic geometry and replicate sections of fabrication along the device length. The basic device structures include:

- Ridge waveguide
- Buried hetero-structure (BH)
- Electro-absorption modulators (EA)
- Distributed feedback
- Vertical cavity surface emitting lasers (VCSEL)
- Expanded mode devices

These basic structures can be integrated into multi-chip modules or integrated circuit configurations. Each of the device geometries has its advantages and disadvantages.

Some structures require re-growth, which increases complexity and reduces yield, while others do not. Figure 5 highlights several examples of these structures.

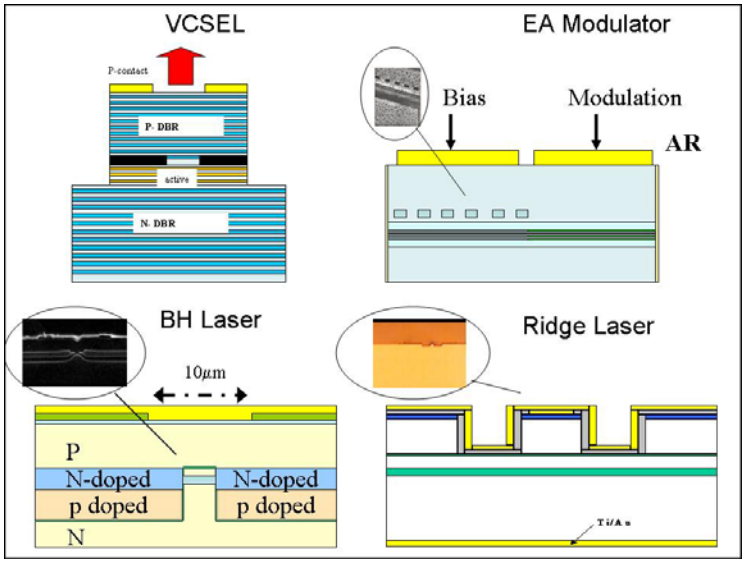

Figure 5: Several device geometries used today in communications

The device geometry, the metallization scheme, doping profiles, and waveguide geometry, all affect the device performance characteristics. Good design practices can yield high bandwidth and low drive voltages. For example during the 1990s, the p-n-p-n buried hetero-structure laser was believed to be 'too slow' to achieve a data rate of 2.5 Gbit/s. The development of better RF packages, device simulators, and understanding the capacitance contributions allowed 10 Gbit/s data rates to be achieved. Currently, most 10 Gbit/s lasers are either EA-based or directly modulated BH lasers. The change from InGaAsP to AlInGaAs material led to much lower threshold currents and superior bandwidth performance. Table 7 highlights several key properties of the different structures.

Device Structure	Ithr at RT	Ithr at 85mA	Modulation Capability	ESD threshold (1st change)	Size
VCSEL	<3mA	<6mA	10Gbit/s	>100V	250um x 250um
BH laser	<10mA	<30mA	10Gbit/s	>500V	250um x 350um
Ridge Laser	<20mA	<90mA	40Gbit/s		250um x 350um
Photodiode	-	-	40Gbit/s	100V	300um x 300um
EA Modulator	<20mA	-	40Gbit/s	>500V	250um x 1000um

Table 7: Key properties of the basic device structures

The electro static discharge (ESD) threshold level of a device directly affects the choice of manufacturing processes and device performance. Different device structures fail at different ESD levels, i.e., long devices, such as pump lasers, can withstand up to 50 KV discharge before failing. Properly designed InGaAsP BH lasers exhibit no change in current-voltage (I-

V) characteristics even if subjected to 500 V ESD. VCSEL-based products, on the other hand, are vulnerable to ESD voltages over 100 Volts and require protection to prevent high infant mortality. Thus, ESD can affect field lifetimes and the random failure rates of devices.

The next sections present an overview of packaging technology used for optoelectronic devices and will serve as the basis for a discussion of future trends.

4 Discrete packaging in communications

Optoelectronics component packaging is a complex discipline. Package requirements depend on the application and the properties of the device. There are several types of packaged components: discrete components, modules, and hybrids. The following sections provide an overview of packaging, including the complexities and the impact on next generation components. The issues associated with high data rate system packaging follow this overview.

Discrete optical components have been in use for more than 20 years. The primary package type has been the dual in line (DIL) butterfly package. DIL butterfly packages are made of metal, ceramic, or a combination of both. The manufacturing technology is mature and yields a reliable hermetic package. The optical connection is either through a fiber pigtail or through an optical lens system. The mini-DIL is the smaller version, and modules often incorporate these packages. Figure 6 shows some examples of butterfly-type packages.

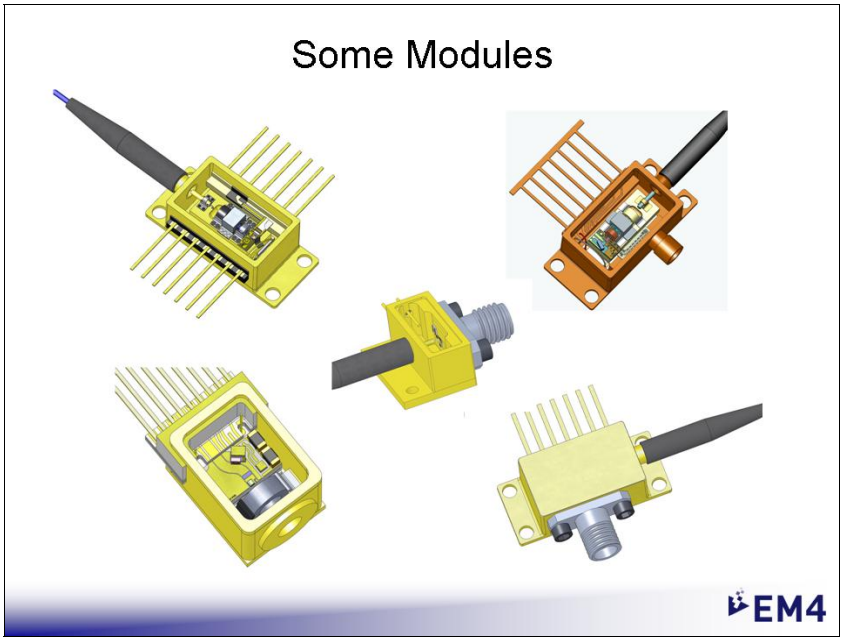

Figure 6: Various butterfly type packages used in commercial and military applications
(Courtesy of EM4: A. Rosiewicz)

Another common package is the TO-can. This package is a legacy from the discrete transistor era of 1950s and 1960s. It is the dominant package type of low-cost components. Figure 7 shows an example.

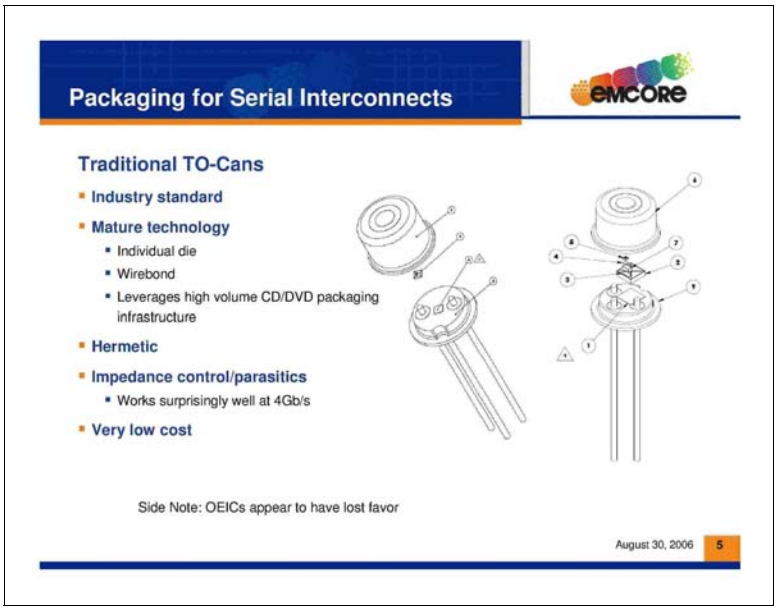

Figure 7: Traditional TO-can package used in commercial and military applications
(Courtesy of EMCORE: K. Jackson)

Transceiver modules and VCSEL devices rely on the TO-can package. It provides a hermetic environment and some level of ESD protection. Both the TO-5 and DIL butterfly packages have improved and evolved with the shift to higher data rates. The butterfly package is the workhorse of 40 Gbit devices, and the TO series dominates 2.5 Gbit applications. New package designs are in production for 10 Gbit optical transceivers. Alterative ceramic transmitter optical sub-assemblies (TOSA) and receiver optical sub-assemblies (ROSA) are in development and production for 10 Gbit/s applications. Figure 8 shows an example of a TO version.

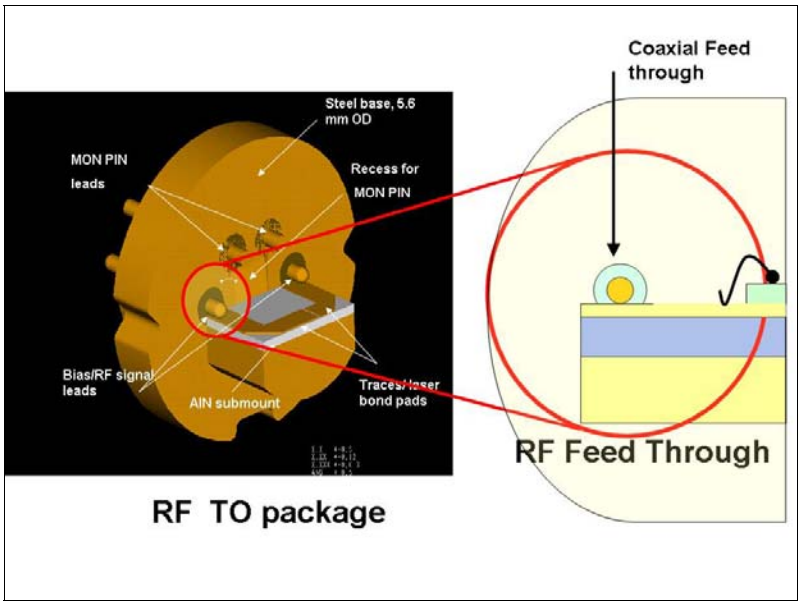

Figure 8: RF TO can with glass to metal feed through to RF AlN pad

Optoelectronics devices must couple light through the package. Most DIL butterfly packages use a pigtail–a fiber cable fitted with a connector. In TO can-type assemblies, the type of optical connection depends on the degree of alignment precision required by the device. Low tolerance applications can use a plastic active device mount (ADM) assembly. For high tolerance devices, on the other hand, a metal ceramic ADM is welded to the TO body. The electrical connection is typically from a printed circuit board (PCB) interface to the devices' electric leads.

For devices that interface with single-mode fiber, the alignment requirements are very precise. This level of placement accuracy requires either a two or three-axis high precision stage. For multi-mode fiber applications, the alignment requirements are more relaxed. Standard micrometers are sufficiently accurate for manual peaking or power adjustments. A certain level of automation is possible, but it must be competitive with low-cost labor in China and other countries.

At high data rates, the electrical connector is extremely important. In discrete butterfly packages, the radio frequency (RF) connector mounts directly on the package wall. Table 8 presents a summary of different types of RF connectors and the bandwidths they support.

	Connector Type	Cut-off Frequency	External Diameter
Threaded	SMA	18GHz	312 mil (7.92mm)
	3.5mm WSMA	34GHz	312 mil (7.92mm)
	2.92mm K-Connector	40GHz	312 mil (7.92mm)
	1.85mm V-Connector	65GHz	312 mil (7.92mm)
Push-on	GPO SMP	40GHz	164 mil (4.17mm)
	GPPO SSMP	65GHz	130 mil 3.3 mm

Table 8: RF connector and bandwidth

Since the RF connector sits directly on the package wall, the input feed structure determines signal integrity. The small dimensions inside the package simplify the design of the RF feed to the optoelectronics device and any necessary matching components. Figure 9 shows some examples of feedthroughs.

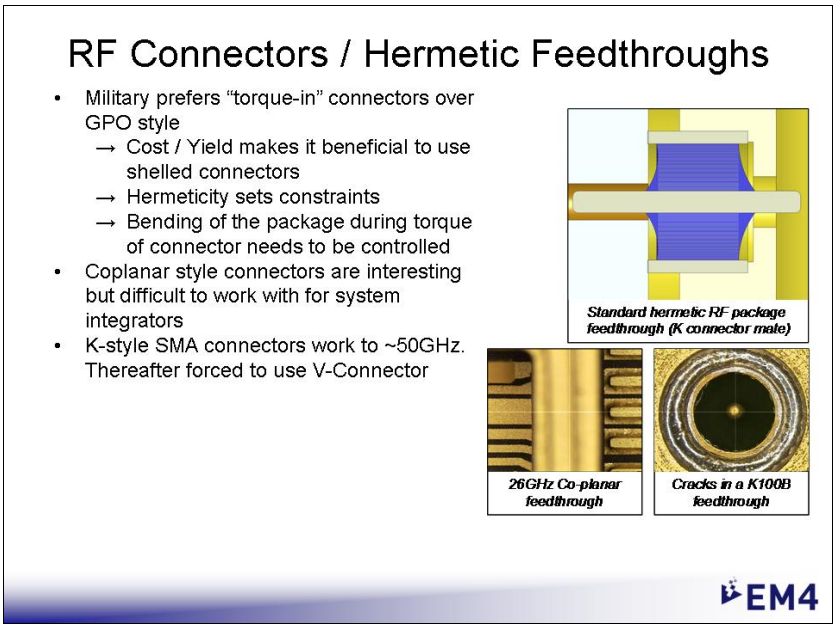

Figure 9: Different types of RF connectors used in the butterfly type packages
(Courtesy of EM4: A. Rosiewicz)

The lead frame package offers an alternative low cost and high bandwidth planar package. The LED industry is the main user of the lead frame package but it is moving into the CD/DVD market segments. Figure 10 illustrates a lead frame package used in the LED industry:

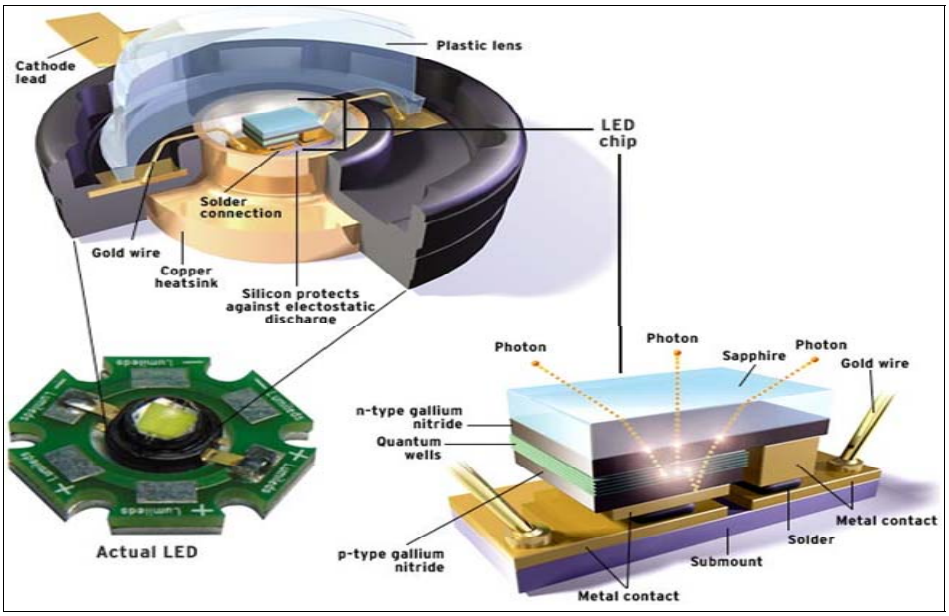

Figure 10: Luxeon lead frame package
(Courtesy of Philips-Lumileds: W. Goetz)

The lead frame package is widely used by the semiconductor industry. In the optoelectronics sector, however, the package introduces a non-hermetic environment for the device. The telecom market has always required long field lifetime guarantees and low failure rates. The communications device industry, therefore, is very concerned with meeting the reliability requirements imposed by system vendors. The cost of failure is very expensive. For example, a failure in a submarine fiber link can cost more than $1,000,000 per day in repair costs.

The TO can is the dominant package for VCSEL devices. This package is hermetically sealed and protects the device from moisture and other contaminants. Being GaAs based structures, VCSELs are prone to dark line defects (DLD), which the hermetic environment helps prevent. Likewise, the package and circuit board provide ESD protection. VCSELs are widely used in the storage and enterprise market segments; they dominate based on product shipment volume. These market segments have stringent reliability requirements similar to the telecom sector.

Low cost TO can-type packages use plastic optics for devices such as 1310 nm VCSEL, FP, and CD/DVD lasers. Existing injection molding technology has sufficient mechanical tolerance to provide good coupling to multi-mode fiber and potentially to single mode fiber ferrules. The plastic package interface provides two advantages: (1) lower manufacturing cost, and (2) reduced EMI radiation. Figure 11 shows an example:

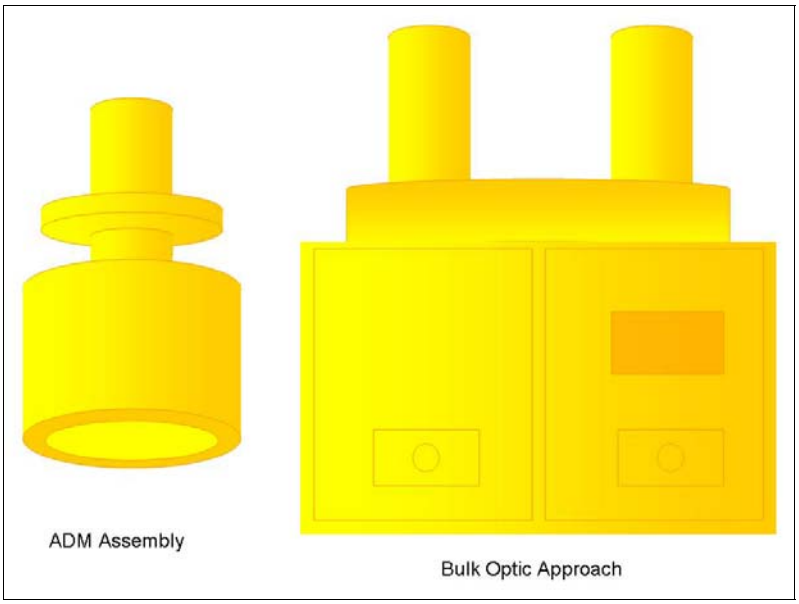

Figure 11: Plastic molded piece parts for coupling to multi-mode fiber

The plastic optics provides an alignment mechanism for the optical fiber. In single mode applications, the plastic in conjunction with TO cans or lead frame packages enables low-cost manufacturing processes. Figure 12 shows an example of a LX4 module:

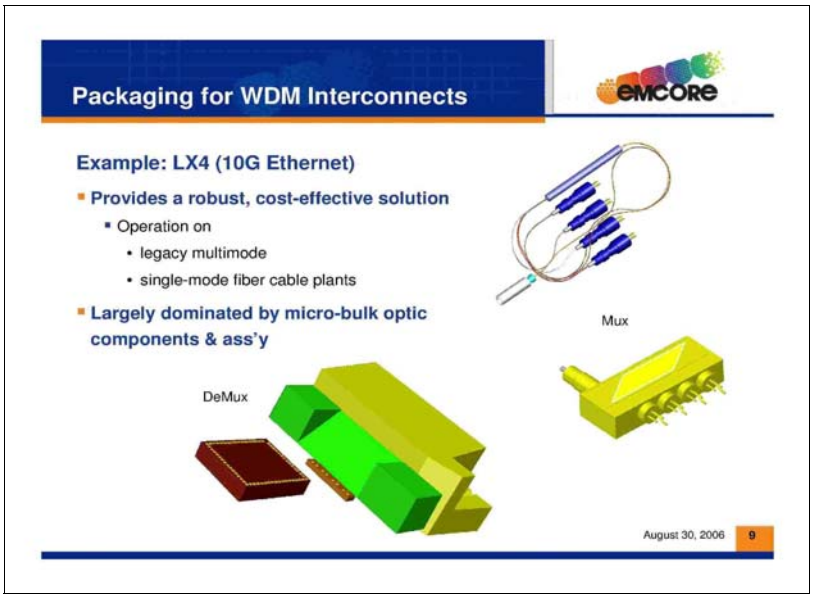

Figure 12: Plastic molded optics for coupling in single or multimode LX4 applications
(Courtesy of EMCORE: K. Jackson)

Single mode products can use plastic optics but they require tight tolerances to align with edge emitting devices. The MT-RJ transceiver for 100 Mbit applications used 'bulk' optics to guide LED light to multi-mode fiber ferrules. The proposed next generation Quad SFF/SFP transceiver for single mode multi-fiber uses four separate lasers to couple to a 12-fiber ribbon cable. The transmitter and receiver each use four of the fibers in the cable. Plastic optics can couple to either a single mode or multi-mode fiber. Figure 13 shows an example of a quad small form factor transceiver:

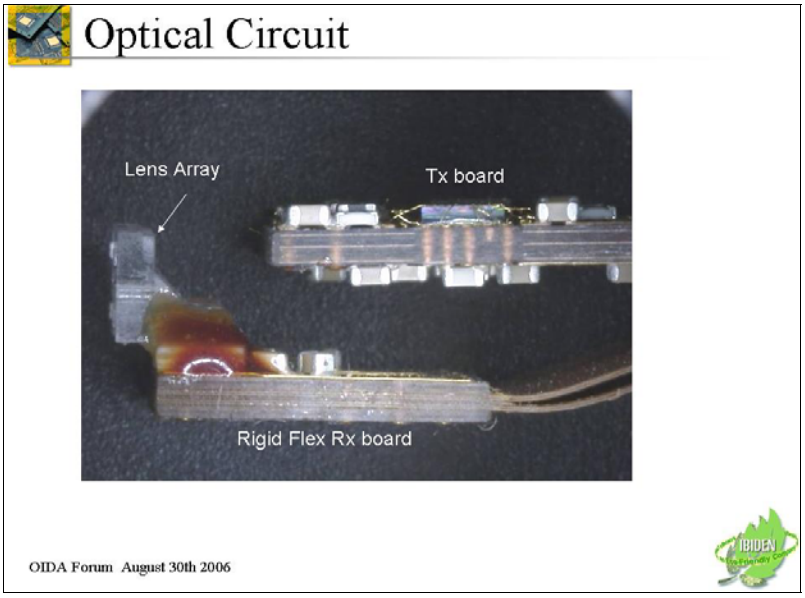

Figure 13: Lens Array for a QSFP transceiver with single mode 1310 nm lasers
(Courtesy of IBIDEN: K. Keller)

TO-can hermetic packaging cannot readily accommodate this configuration. The module has insufficient room for four separate TO cans housing Fabry-Perot (FP) or distributed-feedback (DFB) lasers. Since the silicon IC world rarely uses hermetic packages, there is no technology to readily leverage. The only alternative is non-hermetic packaging.

Non-hermetic packages are susceptible to moisture. Moisture in an optoelectronic device package can cause chemical corrosion and infant mortality. This is particularly true for VCSELs. They have a low ESD threshold and the GaAs material is sensitive to chemical corrosion. A silica gel overcoat, however, can protect the device from moisture. Although silica gels do not eliminate moisture from a package, they reduce the likelihood that moisture will affect the device by adsorbing water. Silica gels and additional semiconductor processing steps such as enhanced nitride coating result in a relatively long lifetime and low failure rates.

Wire bonding and eutectic die attach are used both in discrete and hybrid packages. In this area, the optoelectronic industry benefits from technology developments that can be transferred from silicon fabrication and other mass assembly processes. Advances in ceramic and printed circuit board technology by the wireless communications industry are likewise applicable to maintaining RF and signal integrity in optoelectronics devices. As industry moves to higher data rates, routing signals becomes more difficult and cumbersome in discrete packages. Figure 14 provides an example of this situation:

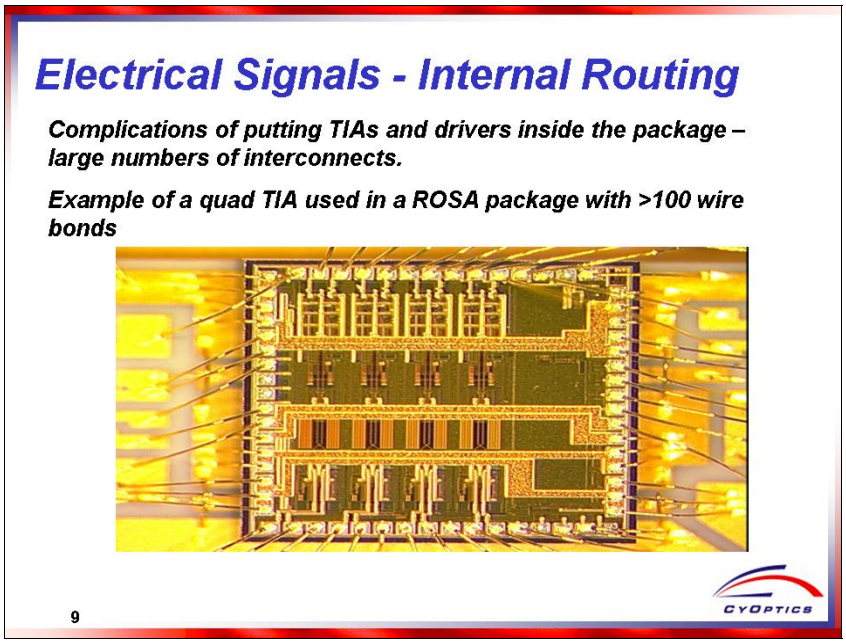

Figure 14: Wire bond complexity for discrete packaged components
(Courtesy of CyOptics: J. Dormer)

The next section reviews “hybrid” technology approaches. It focuses on the approach that has been the subject of research for more than 20 years now: the silicon optical bench.

5 Hybrid packaging

It is difficult to define hybrid packaging precisely, as there are often multiple components mounted and interconnected within a package. At what stage of complexity does an assembly become “hybrid?” Is a sub-mount with integrated RF components a hybrid package? Does a sub-assembly of standard discrete components qualify? This section discusses different packaging methods classified as hybrid. For the purposes of this report, hybrid packaging is a group of discrete optoelectronics devices that together form a more complex component. As an illustration, the report discusses silicon optical bench technology. As the level of on-chip integration increases, the discussion transitions into photonic integration.

5.1 Silicon optical bench

The silicon optical bench consists of a patterned and etched silicon substrate which serves as the assembly template for the integration of VCSELs, pin photodiodes, fibers, integrated electronics, and other components. The concept behind the silicon bench is to drive mass production on a wafer scale for photonic packaging to reduce product cost. Silicon benches classify into the following general areas:

- Silicon sub-mount technology
- Passive waveguide technology
- Passive alignment technology
- Wafer bonded integration

Several of these approaches have reached the market while others have remained laboratory curiosities. This report reviews both historical and current trends of silicon optical bench technologies to for optical communications applications.

5.2 Silicon sub-mount technology

The silicon sub-mount is a building block technology for photonic integrated circuits. Lucent Technologies developed silicon sub-mount technology for the mass production of laser modules. Essentially, the system allows the optics designer to align the fiber optically by moving the sub-mount within the package relative to the package wall. This is the famous Laser 2000^{TM} approach, which was widely published in the late 1990s. The technology is in production today and lends itself to integration on a hybrid platform.

The silicon bench is essentially a sub-mount technology for high-speed applications that uses pre-patterned solders and RF traces. It uses a ball or aspheric lens close to the diode laser facet to couple the laser to the fiber. Figure 15 shows a sub-mount in a discrete package module:

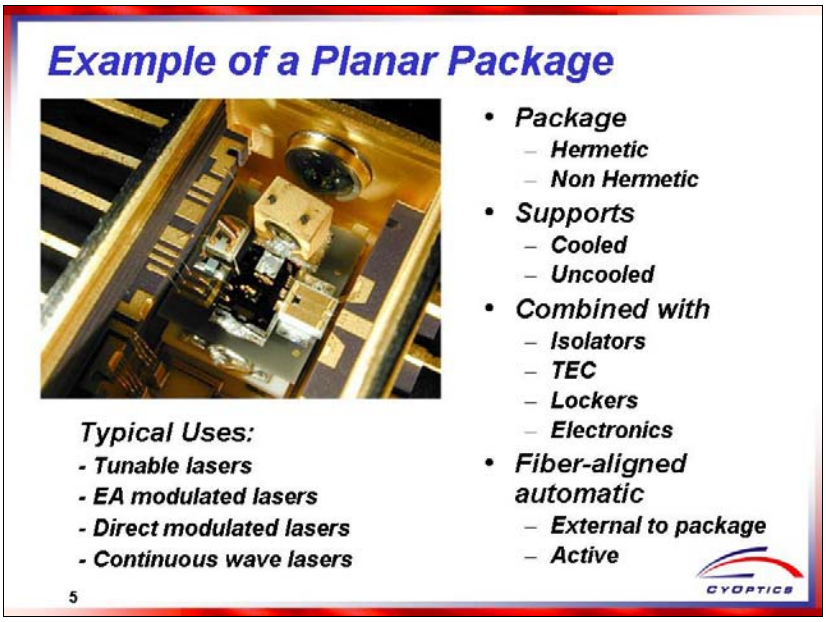

Figure 15: Integration of a silicon sub-mount in a discrete packaged module
(Courtesy of CyOptics: J. Dormer)

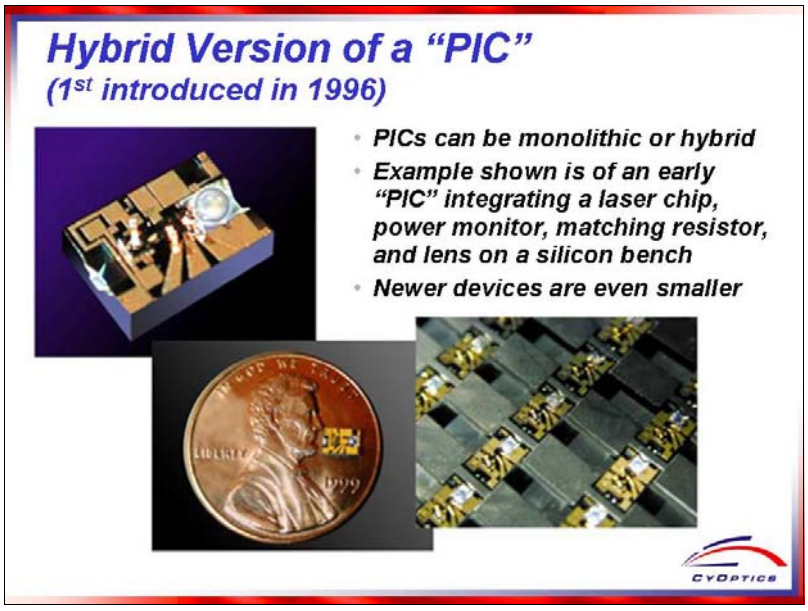

Figure 16: Integration of a silicon sub-mount in a discrete packaged module
(Courtesy of CyOptics: J. Dormer)

The next section shows that integrating optical waveguides onto the silicon bench can allow functions that are more complex.

5.3 Passive waveguide technology

The integration of waveguides on the silicon allows more functionality. There are several approaches for optical transmission on planar silicon substrates. These include polymer-based waveguides, silicon, and silica waveguides. Silica waveguide technology is the most mature and is now in commercial products. It is fabricated using the flame hydrolysis deposition (FHD) production process. The primary application of silica waveguide technology is to couple optical components. It also allows for wavelength routing, which is the basis for an arrayed waveguide grating (AWG). The AWG is an alternative to thin film interference filters for DWDM systems. Figure 17 illustrates an AWG:

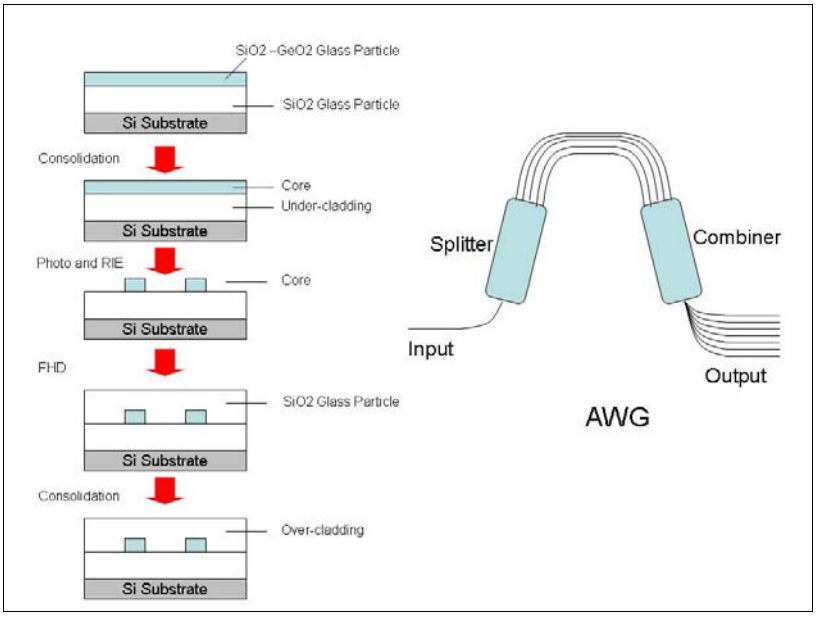

Figure 17: Arrayed waveguide grating (AWG) and fabrication process flow

An alternative to the silica waveguide is the Silicon-Silicon Dioxide-Silicon (Si-SiO_2-Si) waveguide. Silicon waveguides are not yet in production and are still in the laboratory. The advantage of silicon waveguides is that they would enable the direct integration of optical devices. Silicon waveguides, however, are still a hybrid approach since most active optical devices are fabricated from materials other than silicon. They must be attached with some type of wafer or die bond to the silicon substrate. Recently, however, modulators fabricated on silicon have demonstrated bit rates of greater than 1 Gbit/s. A silicon light source, however, is not yet available.

5.4 Passive alignment technology

The key to reducing device cost and improving reliability is to eliminate the need for the manual alignment of optical components. Two approaches, single emitter and array

hybrid packaging, simplify component alignment. The two approaches lead to the development of different modules: parallel optical and serial.

5.4.1 Single emitters

The objective of single emitter technology is to couple a single mode waveguide emitter to single mode fiber. The optical device can either retain the standard device geometry or utilize a converted spot size. British Telecom Research Laboratories spent several years developing spot size converter devices. Figure 18 shows several examples of different mode converter geometries:

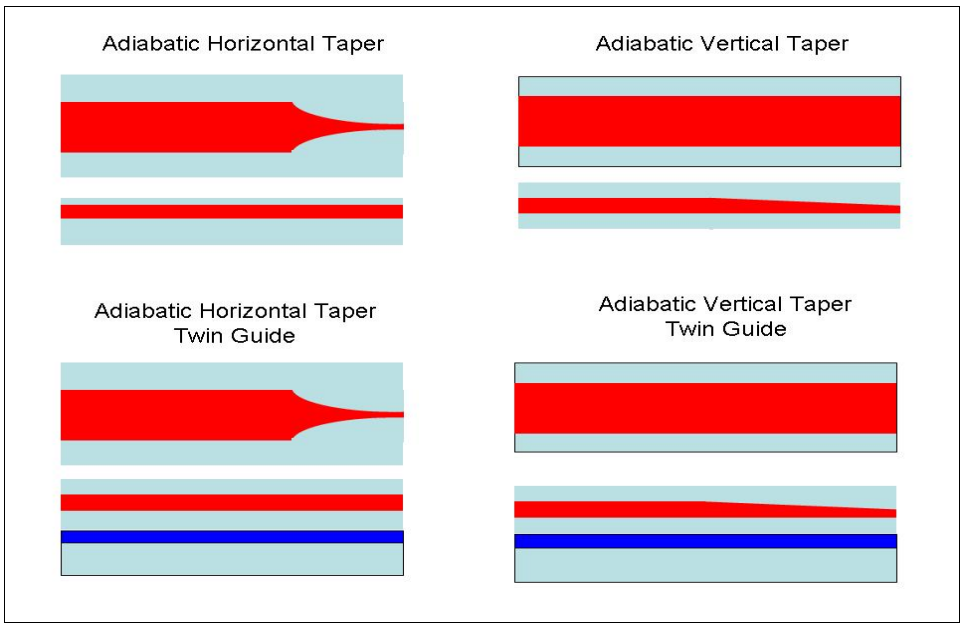

Figure 18: Four examples of adiabatic taper geometries for mode size converter devices

The advantage of a spot size converter is that by modifying the optical mode field, the coupling tolerances increase. Expanding the optical mode requires a mode transformation section in the package. A typical mode transformation section is an adiabatic taper. The adiabatic taper reduces losses and reflections that could adversely affect the optical gain of the laser. Semiconductor optical amplifiers and other devices use adiabatic tapers.

A spot size converter can suffer from gain ripple effects that can lead to modal instability. One source of instability is mode beating between a weak waveguide and a strong waveguide. Alternatively, if the adiabatic taper is not perfect, small reflections in the cavity between the two waveguides create a coupled cavity situation. The two cavities then interact causing gain beating.

Using single mode devices alleviates modal instability. A DFB, for example, produces a gain profile such that there is a large difference between the DFB mode and the FP gain

spectrum. This large difference dominates the device performance and suppresses or eliminates the beating.

A V-groove etched into the silicon platform is a way to provide a guide for the accurate placement of a fiber. The groove is fabricated using standard silicon wafer fabrication processes: stepper or contact aligner patterning, and dry or wet chemical etching. Wet chemical etching relies on the <110> silicon crystal plane for smooth vertical sidewalls. A test pattern etched in the corner of the wafer identifies the proper crystal orientation of the substrate. This test pattern also serves as an alignment feature for the stepper.

Dry etch processing, on the other hand, is essentially non-isotropic and is independent of the crystal plane. The BOSCH process is a standard dry etch silicon process and appropriate for optical bench assemblies.

In reality, the V-groove process moves the active alignment of the optics for discrete components further down the assembly chain to the die attach process. At that stage, the process uses precision optics and tolerances that are achievable on a wafer scale.

Precision solder pad re-flow technology is similar to solder ball process used in silicon IC packages. This process can achieve < 1 μm realignment from offsets of up to 20 μm, and lends itself well to passive alignment batch processing. The Heinrich Hertz Institute is developing this process for passive optical alignment.

The alignment tolerances for non-mode converted optical devices are critical and require extremely accurate die bonding equipment. Two companies provide R&D machines and production tools: Suss MicroTec and Toray Engineering. Their equipment is capable of placing bond heads with less than 0.5 microns variation. The cycle time is below one minute, and batch processing is available on the automated production machines. Figure 19 shows the degree of alignment precision required:

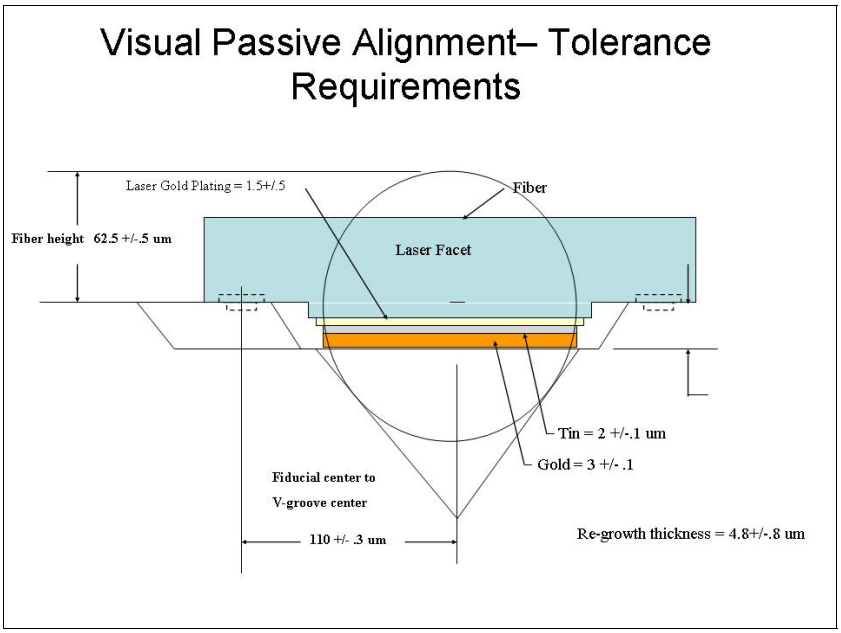

Figure 19: Silicon optical bench alignment tolerance issues for single emitter technology

A mode-expanded device eliminates the need for high accuracy die bonders and can use less accurate and lower cost assembly equipment. When coupled to a waveguide on the silicon bench, more complex functions and higher integrated package assemblies are possible.

Table 9 summarizes silicon bench approaches.

Attachment Process	Features	Processes
Mechanical Stops	2 Axis 3 Axis	Bosch LOCOS Wet Chemical RIE (CL and FL)
Fiducials	Etched Features Pattern metal Fiducials Precision Cleaved Edges Re-grown Fiducials	
Precision Solder	Etched Precision Solder Pads	

Table 9: Summary of silicon bench approaches

5.4.2 Silicon bench and planar waveguide technology

Incorporating a silica waveguide on the silicon bench enables higher levels of functionality. Multiple waveguides enable multi-port devices. An application area for this technology is the fiber-to-the-home market. Figure 20 shows an example:

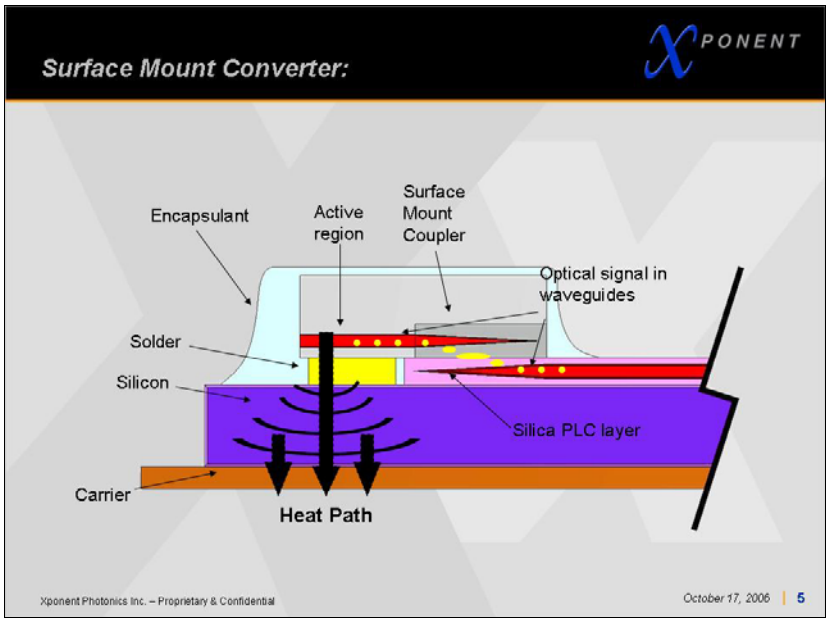

Figure 20: Surface mount converter for mode conversion to planar waveguide on silicon
(Courtesy of Xponent: J. Rittichier)

Incorporating the mode converter to the silica fabricates a complete waveguide integrated module. This approach enables DWDM 100 Gbit Ethernet sub-modules. Figure 21 shows an example of a module:

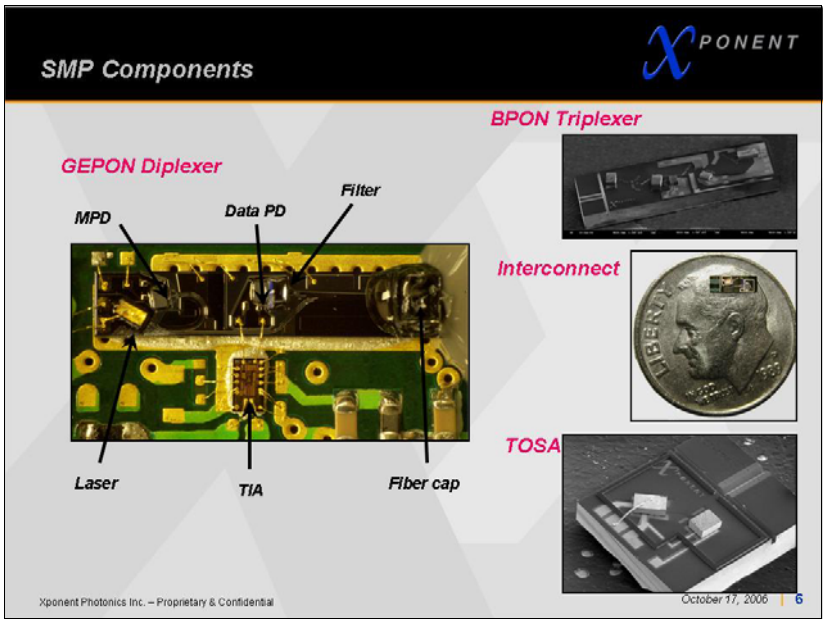

Figure 21: Surface mount converter for mode conversion to planar waveguide on silicon
(Courtesy of Xponent: J. Rittichier)

The hybrid approach requires attaching different optical devices to a common sub-mount. Epoxy or solder is the adhesive used to attach these devices. Laser devices primarily use

gold-tin solder since it provides the best heat transfer path to the sub-mount. Soldering several components to the same substrate is more complicated. It requires either a full wafer flow process, or placing and soldering with solders that melt at different temperatures. Different solders, however, can lead to the failure of the joints. Attaching with an epoxy allows the placement of multiple components followed by simultaneous curing. The difficulty with epoxy is maintaining the placement tolerance after re-flow.

5.4.3 RF signaling and silicon optical bench

An advantage of the silicon bench is the ability to mount silicon integrated circuits next to the optical devices and to route optical signals via waveguides. High data rates require specially fabricated signal routing traces. A nitride or silicon dioxide layer beneath the metal traces helps maintain signal integrity at high speeds. Another approach developed by MA/COM uses the silicon on glass process. Figure 22 shows an example of a device fabricated using this process. MA/COM is mass-producing wireless products and high power amplifiers with this technology. An alternative approach is to access a micro-strip line through a via in the silicon. Figure 23 shows an example.

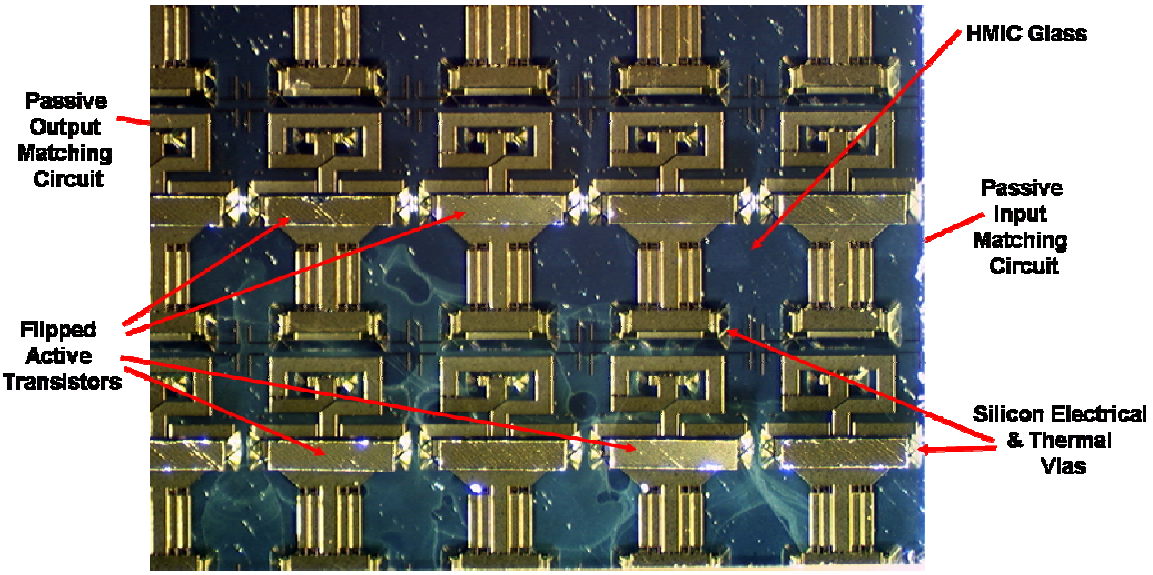

Figure 22: Glass on silicon process with high power surface microwave package
(Courtesy of Tyco Electronics: J. Goodrich)

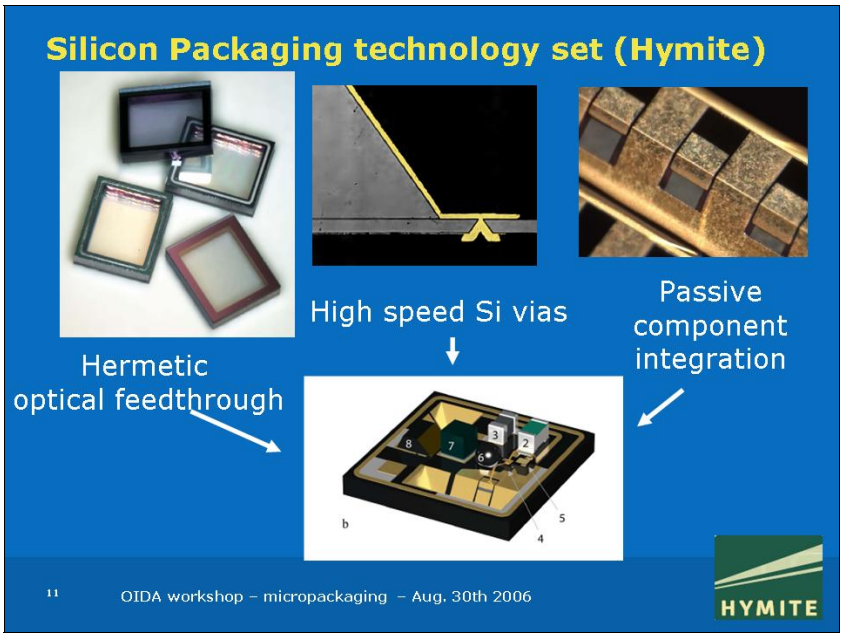

Figure 23: High speed signaling via in the silicon wafer package approach
(Courtesy of Intel: M. Finot)

The high speed via through the silicon is compatible with surface mount technology. It is planar and allows routing and integration of inductor/resistor and filter components directly in the wafer process. The bandwidth and reflection sensitivity have been measured up to 50 GHz. This technology provides a potential route to higher speed micro-optic packaging and may be applicable to wafer scale module production.

The high-speed signaling requirement for micro-packages and for next generation products, such as 100 Gbit Ethernet, will be a challenge. The degree of difficulty will depend on whether industry adopts a serial or parallel approach.

5.4.4 Multi-emitter technology – parallel optics

One of the advantages of silicon as a platform is that it allows the integration of the driving and receiving electronics with the optical components. Several companies have investigated integrating electronics and optics on the same silicon substrate. Honeywell produced a 2-D integrated VCSEL and electronic array in the 1990s. Xanoptix integrated a VCSEL and photodiode on top of the ASIC for multi-fiber array transceivers such as parallel optic modules. This allowed for a small fiber spacing found in multi-fiber push on (MPO) connectors and ribbon fibers. Avago Technologies also incorporated this method of production in their parallel optic modules. The main disadvantages with this hybrid integration approach are the thermal load on the active components and their need for a hermetic environment. Figure 24 shows an illustration of the parallel integration approach.

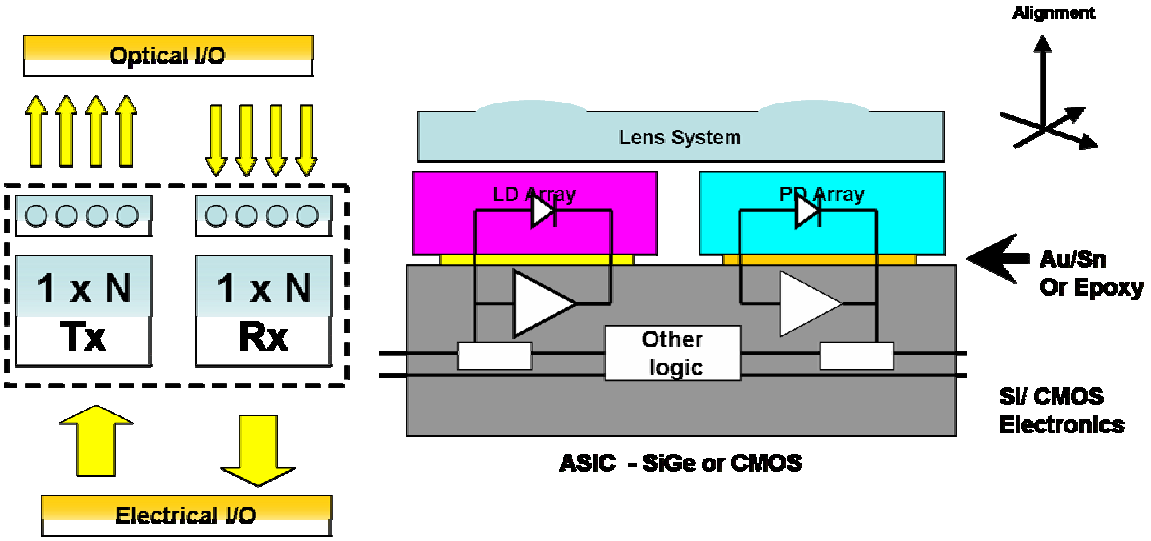

Figure 24: Integration of optical components and silicon for parallel optical module

Avago Technologies has been developing this technology for over a decade (first as HP, then as Agilent Technologies). At the R&D stage, they discovered that a rise in the junction temperature of a parallel array of VCSELs significantly affected their operating characteristics and the failure rate. Placing an ASIC circuit in close proximity to a VCSEL can cause the optical device temperature to rise by up to 50°C. Therefore, while the temperature of the package was 25°C, the diode array was actually at 70°C. Such modules would need extremely efficient heat extraction. Rather than focusing on heat extraction, Avago solved this problem by developing a 980 nm VCSEL. Adding indium into the active region inhibited dark line defect formation and thereby reduced the failure rate.

EMCORE Corporation is another supplier in the parallel module market, which acquired its technology from Alvista. Parallel modules can also utilize the glass-on-silicon process. Peregrine Semiconductor announced products fabricated with this approach in 2002 but they are not widely used.

Parallel VCSEL arrays can also serve as on-board optical interconnects. The silicon optical IC is flip chip bonded onto the circuit board and signals pass through embedded waveguides in the PCB. Several companies have been exploring this technology to increase the operating speed and to eliminate cross talk on the circuit board. Both polymer-type and embedded plastic waveguides are potential candidates. The cost of copper vs. optical technology and the required bit rate will drive the acceptance of this approach. Figure 25 shows an example of this concept.

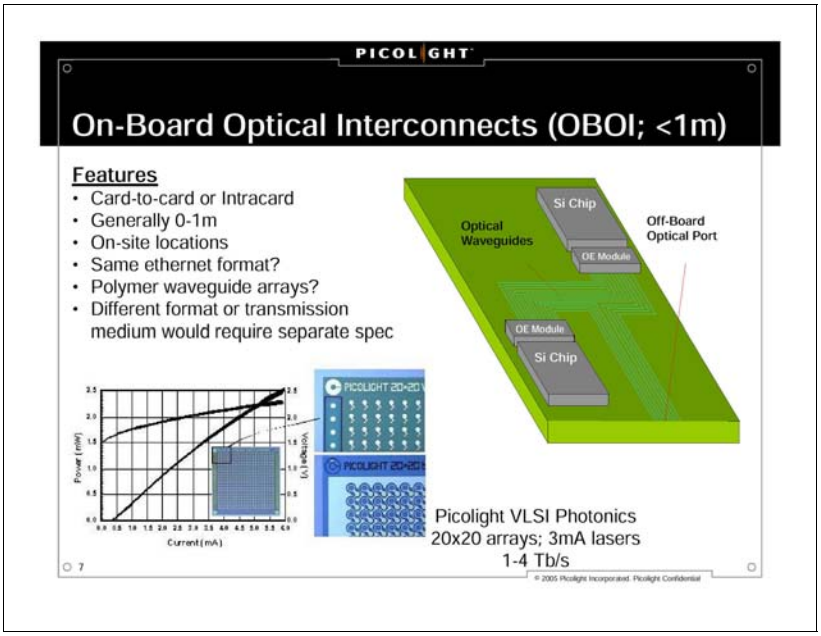

Figure 25: Silicon optical IC integration onto a PCB board for signaling
(Courtesy of Picolight: J. Jewell)

5.5 Wafer scale technology and processes

Utilizing silicon as the integration "bread board" offers the advantages of wafer scale production. This is essential if the product succeeds and the market requires high production volumes. Wafer scale technology essentially amortizes the production capital investment over the large number of units produced. Since wafer production in a silicon or GaAs fabrication facility is batch-orientated, it has a minimum amount of labor content. The capital and operational expenses and materials content become the primary components of the cost structure.

The micro electro-mechanical systems (MEMS) device used in many projection TV systems today is an example of optical wafer-scale technology. It consists of micro-mechanical assemblies with extremely accurate control. This technology should also be applicable to optical alignment or self-alignment of photonic devices.

One of the principle problems with single mode devices is that the optical mode field and the divergence angle of the optical fiber do not optically match to transmitter and receiver devices. Lenses and accurate positioning are necessary to focus the light. MEMS technology with non-mode expanded lasers can potentially provide a 'mini' laser welder for the production of transmitter or receiver optical sub-assemblies. The application of this technology is still in the early stages and the cost is not known. Figure 26 highlights the concept for this hybrid integration approach:

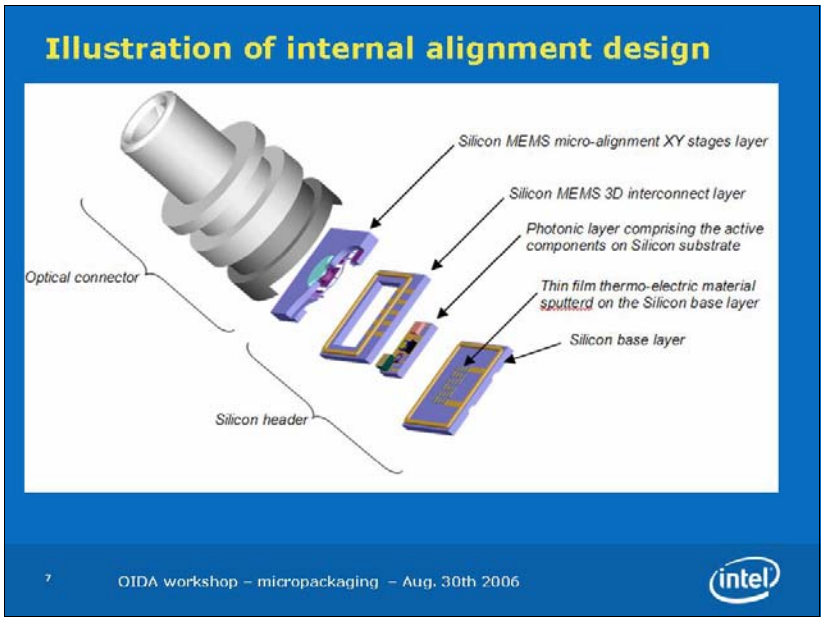

Figure 26: Concept of the integration of MEMS technology for optical alignment
(Courtesy of Intel: M. Finot)

The main challenges to the adoption of the hybrid silicon bench approach are the robustness of the process itself and the eventual singulation of the optical components into the final assembly. One of the advantages is the optical waveguide integration as highlighted in Figure 27.

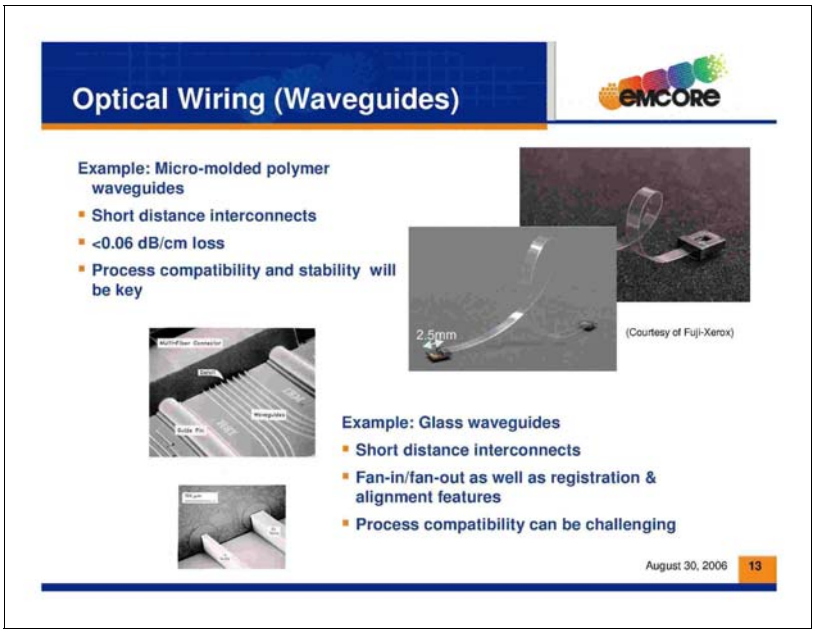

Figure 27: Concept of the optical wire for silicon hybrid packaging
(Courtesy of EMCORE: K. Jackson)

Hybrid silicon packaging is essential for the industry to move forward. It allows integration of functionality and provides compatibility for different material systems. The next step is photonic integration. Will photonic circuits be able to provide the cost and capability that they potentially promise?

The next section briefly discusses the first level of integration of the optical components, such as optical transceivers. These are the principle optical components sold in the storage and enterprise markets today.

5.6 Module technology – optical transceivers

The optical transceiver was one of the first hybrid packaged products. It is a principle optical component used in communications. The advantage of hybrid packaging is the integration of receive and transmit functions in a single package. The first transceivers were based on surface emitting LED technology for FDDI (100 Mbit) links. The transceiver has evolved over the last 15 years as requirements for smaller footprints and higher data rates grew. Figure 28 shows the general requirements for a transceiver:

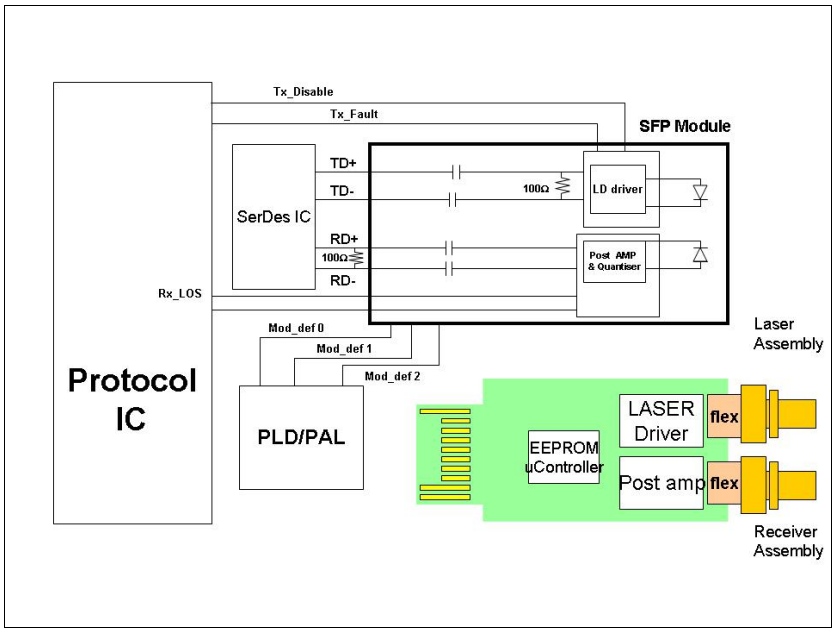

Figure 28: Optical transceiver interconnection and layout

In a transceiver, the two optical sub-assemblies, the TOSA and ROSA, connect to a printed circuit board. The circuit board contains the driver, post amp, and associated controllers and connects to the host card. In addition, most small form factor (SFF) and small form-factor pluggable (SFP) transceivers contain an electrically erasable programmable read-only memory (EEPROM). This memory chip integrates software functionality into the SFP for monitoring and storing of product information.

Currently, the highest data rate "transceiver" operates at 10 Gbit/s. There are multiple flavors and footprints with different interfaces to the host card. Generically, the interface is either running at four times 3.125 Gb/s or is a single serial unit operating at 10 Gb/s. The transition to a pluggable design allows plug and play or data rate agnostic functionality. As the data rate has increased, signaling issues and radiation issues have become more challenging. At high frequencies, the circuit board dielectric constant and signal trace layout are critical. This transition to 10 Gbit serial transceivers has proved challenging for designers. Cross talk and signal recovery have complicated design considerations. Additionally, as discussed previously, the design of the optical component plays a significant role. Figure 29 compares the different approaches to packaging and the associated physical footprints.

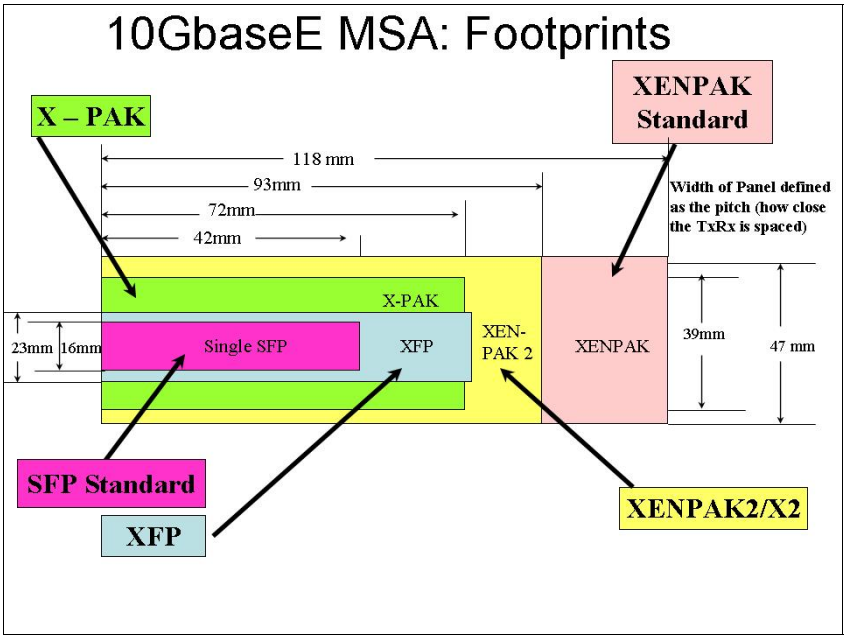

Figure 29: Transceiver footprint comparison to standard SFP for 10 Gbit/s MSA modules

The fiber connector used by these modules is either an SC (2.5 mm OD) or LC (1.25 mm OD) fiber ferrule connector. The choice of electrical connector for 10 Gbit/s transceivers is critical to maintaining signal integrity. The connector originally designed for the SFP module was adequate for 10 Gbit/s. The following sections discuss the evolution of this package and some of the challenges presented.

5.6.1 Electrical connectors and their limitations – speed is the key

Since their introduction in 1992, optical transceivers have evolved with increasing data transport requirements. As systems move to even higher data rates and greater complexity, however, interaction among components within a package can affect overall system performance. The telecom networks have begun their upgrade to 40 Gbit systems, and the next level will be either 160 Gbit or 100 Gbit systems. At these data rates, the physical

layout of components becomes more complex and new approaches to the optical transceiver will likely be required.

At high data rates the issue of signal integrity and EMI become critical. Existing surface mount connector technology will require investment in R&D to increase the data rate above 25 Gbit/s. Existing technology will be adequate in the backplane if multiplexing takes place inside the transceiver. Figure 30 shows several issues presented by copper connector technology.

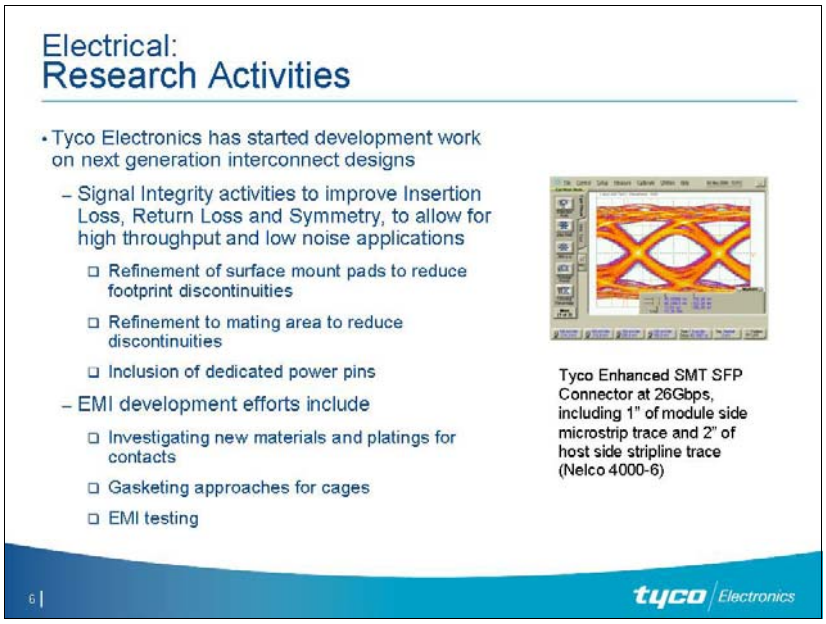

Figure 30: Signal integrity issues of the current SMT technology for electrical connectors
(Courtesy of Tyco Electronics: S. Dhamejani)

The industry today prefers the surface-mount technology (SMT) pluggable connector and the SFP footprint. The switch/router vendors would like to move to a smaller package than the XFP, for example the SFP+ 10 Gbit standard. This transition involves the removal of IC functions from the transceiver and raises several questions: Is this the right trend? Are transceiver vendors going to be asked to now make mainly optical transmitter and receiver pairs? The answer will depend on how much integration the transceiver incorporates by utilizing either hybrid or photonic integration technologies.

5.6.2 Meeting the ASIC challenge and compensation

Today the transceiver is either produced with application specific integrated circuits (ASIC) designed by the transceiver vendor or commercial houses specializing in the technology. As the data rate has increased, the complexity and “intelligence” of the circuitry inside the transceiver has increased. High data rate transceivers incorporate electrical signal and optical signal recovery chips sets. The reduction in footprint to the SFP+ will require changes to the specifications for 10 Gbit and higher transceivers. Unless

integration technologies for the circuit and optical components improve, the choice between compensating in the electronics or the optics will depend on the packaging approach. As the data rate and signaling speed increase, more attention will be required to the following areas:

- Impedance discontinuities
- Impedance losses
- Coupled lines
- Volume resonances

The 40 Gbit/s transceiver package is a transponder module. This reduces the electrical input complexity and hides the issues inside the module. If this trend continues, hybrid or photonic integration will be required as an alternative to the existing packaging approach. The chief concern is the signal integrity and the signals being transmitted to the module. Modeling and simulation of the signal is critical to understand the impact of the package and chip interactions. The obvious question that arises is whether the integration of the optical components provides a better solution.

Some basic aspects of integration and the benefits for optical component and system technology are discussed in the next chapter. In the silicon world, the system on chip (SOC) approach has become popular and the 3-D integration inside the package. In optics, the platforms are different and the level of sophistication is not at the same level. Photonic integration produces several new issues that need to be controlled, most importantly thermal management.

6 Photonic integration

The definition of photonic integration requires some clarification. The term photonic integration frequently refers to products that use the silicon optical bench as a “bread board.” In this report, however, the term photonic integration refers to devices that integrate multiple functions within a single wafer or die. Hybrid packaging is a form of photonic integration, but is not fabricated using wafer scale processes.

The next level of evolution for optical device fabrication is “pure” photonic integration. This is comparable to the evolution from the discrete packaged transistor to the integrated circuit. Figure 31 shows an example of a tunable laser photonic integrated device.

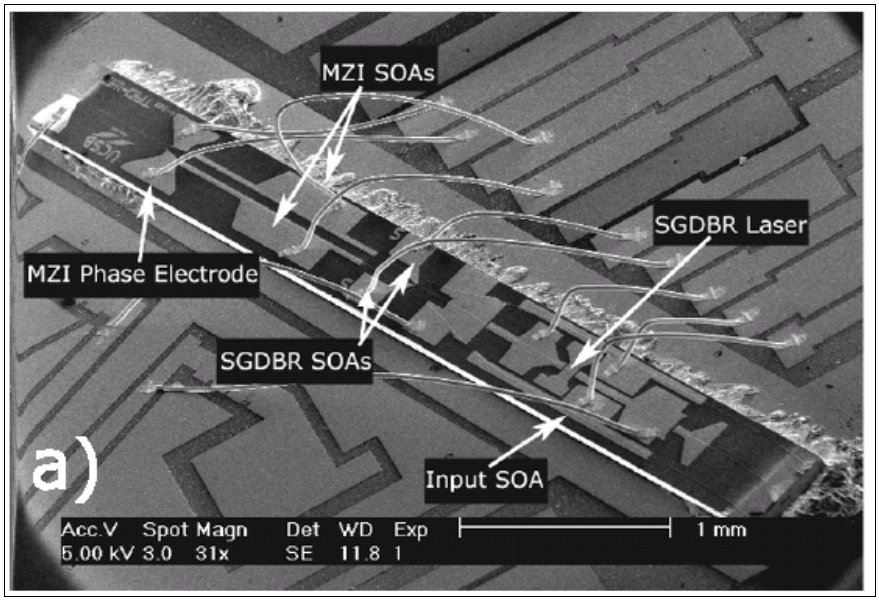

Figure 31: Tunable laser structure
(Courtesy of JDSU, formerly Agility Communications: N. Puetz)

The building blocks for photonic integration are basic optical device structures. Photonic integration involves fabricating multiple interconnected device structures on a common substrate. These electrically and/or optically interconnected building blocks form new device functions. Figure 32 shows an example of a photonic integrated DWDM system.

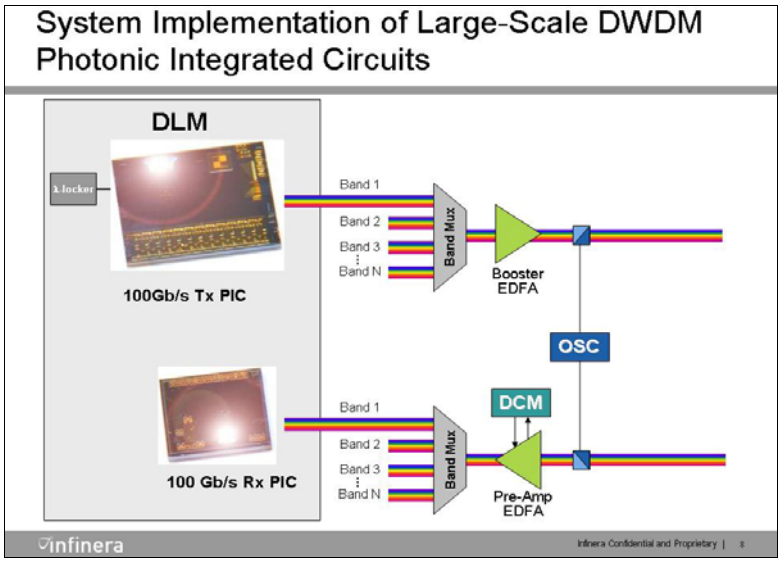

Figure 32: Example of a photonic integrated chip system
(Courtesy of Infinera: F. Kish)

The advantage of photonic integration is that it reduces system level functionality to on-chip functions. The ideal device would have optical input and output connectors, and a package foot-print similar to that of a silicon IC package. The main obstacle, however, is optical output/input management. On-board or on-chip waveguides offer one potential approach. This approach is analogous to the mode-converted laser or photodiode bonded to a silica waveguide, except that the waveguide is on the surface of the device itself. Several materials are suitable for waveguides. Alternatively, the light from the optic device couples evanescently to a deposited and etched waveguide. Figure 33 shows an example of a device using a deposited waveguide approach.

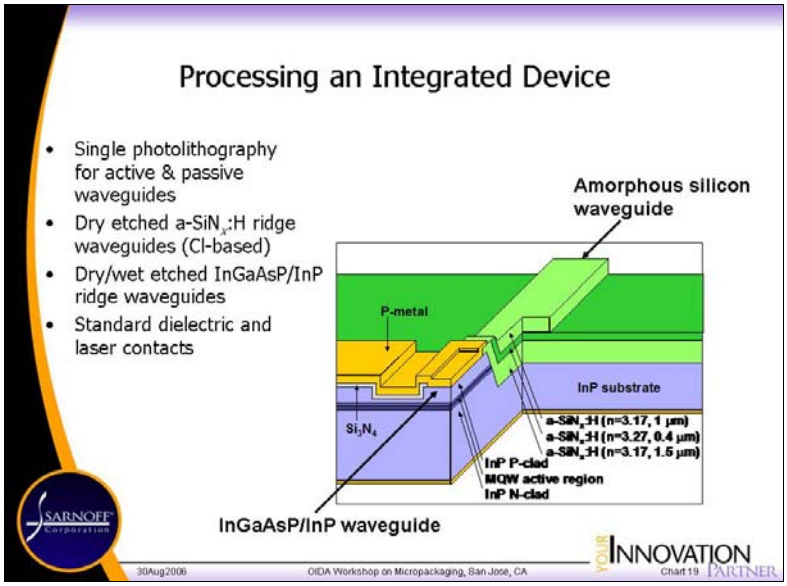

Figure 33: Processing example of an integrated waveguide to an active optic device
(Courtesy of Sarnoff Corporation: J. Abeles)

This type of integration is an alternative method to the AWG on silicon. The device replicates AWG functionality without the need to bond or align the optic device. Figure 34 shows an example of such a device:

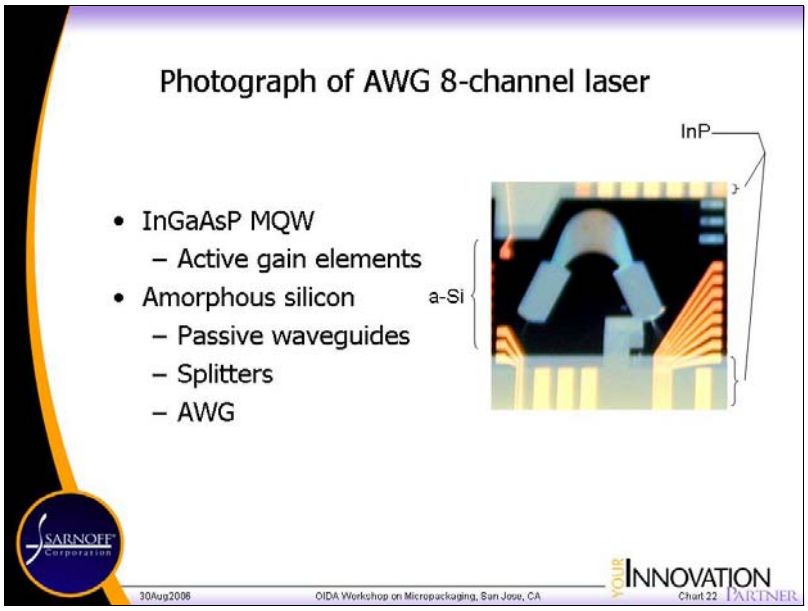

Figure 34: Processing example of an AWG active optic device
(Courtesy of Sarnoff Corporation: J. Abeles)

This approach is similar to the InP waveguide, but utilizes deposition and overlay processing. The planarity of the underlying semiconductor material and alignment are critical to this type of integration. Alternatively, the waveguide material could be a polymer. The stability of the index of refraction of the polymer over the product life is a key requirement for the polymer.

In the design of photonic integrated circuits layout and functionality of the embedded devices needs to be modeled. There is a limited choice, however, of commercially available modeling software. Furthermore, there is a limited inventory of design rules. As a result, the design process relies heavily on the experience of the process engineers. Optical cross-talk and the impact on receiver sensitivity for photonic integrated circuits must be analyzed. Figure 35 shows an integrated device based on an InP substrate.

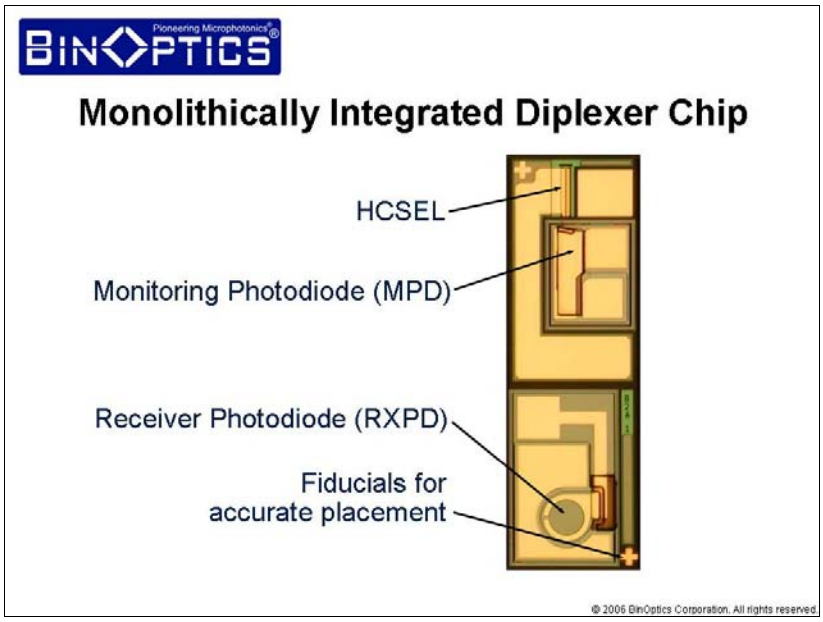

Figure 35: Integrated laser and receiver chip aimed at the FTTx market
(Courtesy of BinOptic: A. Behfar)

The merits and benefits of this approach compared to the silicon hybrid approach require careful consideration. The management of the output and input of the signal becomes a packaging exercise. In the end, even in photonic circuits, some form of hybrid packaging is likely. The question is, “where is the correct cut-off point?”

The current roadmap for packaging photonics ICs is still not clear. In the communications sector, the change in communication elements is driving change in the network. The peer-to-peer applications and wireless back haul over the wired network is increasing bandwidth demand. This has led to the requirement for a network upgrade at the carrier level. The forecasted demand indicates that data rates greater than 100 Gbit/s on the core network will be required within the next five years. Photonic integration, not just co-packaging of optical components, offers the higher levels of functionality to support this transition. The principle issues that remain for photonic integration are:

1. Is there a market with sufficient volume to enable proliferation and development?
2. Is the current industry structure of vertically integrated companies the right business model to enable photonic integration on a level commensurate with electronics?
3. Are the cost drivers and applications there to drive and support photonic integration?

Low production costs combined with increased functionality are the key elements that would enable photonic integration. The next section reviews the cost structures of hybrid or wafer scale photonic integration.

7 Cost structures and manufacturing

The cost structure for photonic packages is complex. The actual production cost for the component vendors is determined by several elements:

- Capital equipment
  – Sunk cost
  – Depreciation
- Engineering cost
- R&D cost
- Operational overhead
- Materials and consumables cost
- Selling and administration expenses

Many component vendors are unprofitable, reporting negative operating expenses. Most companies have shifted their packaging operations to Southeast Asia in an effort to reduce the labor and overhead content of the cost of goods sold (COGS) of their product. Several companies have experienced increased efficiency and productivity because of relocating their manufacturing. The wage imbalance between Asia and North America/Europe has also prompted several U.S. technology companies to begin to move development and other engineering functions to Asia. This trend will affect new development and research for optical companies both in the U.S. and Southeast Asia.

Photonic integration and the wafer scale production can influence this manufacturing trend. An analysis is difficult, since it needs to recognize and account for several underlying factors. If it does not, then the financial models will not provide an accurate understanding or industry picture. Any analysis needs to consider the final user of the product, his location, local government taxes and duties, and shipping costs. These can increase the actual manufacturing cost and are part of the transfer cost included in the cost of a product.

A comparison of the cost of a module or packaged component needs to integrate the semiconductor cost and the package build cost. Typically, fabrication facilities are capital intensive with low labor content, and the general overhead structure includes the cost of support engineering. A wafer yields thousands of devices so the actual cost per die can be relatively low when the cost of the fabrication facility is amortized over the individual die.

Wafers are batch processed and fabrication capacity is expressed as a multiple of X wafers/day output. The total volume of product shipped each year for the optical communications market, however, is low. A recent forum held by OIDA analyzed the long wavelength market and concluded that one fabrication facility alone could support the total world demand. Figure 36 shows this analysis.

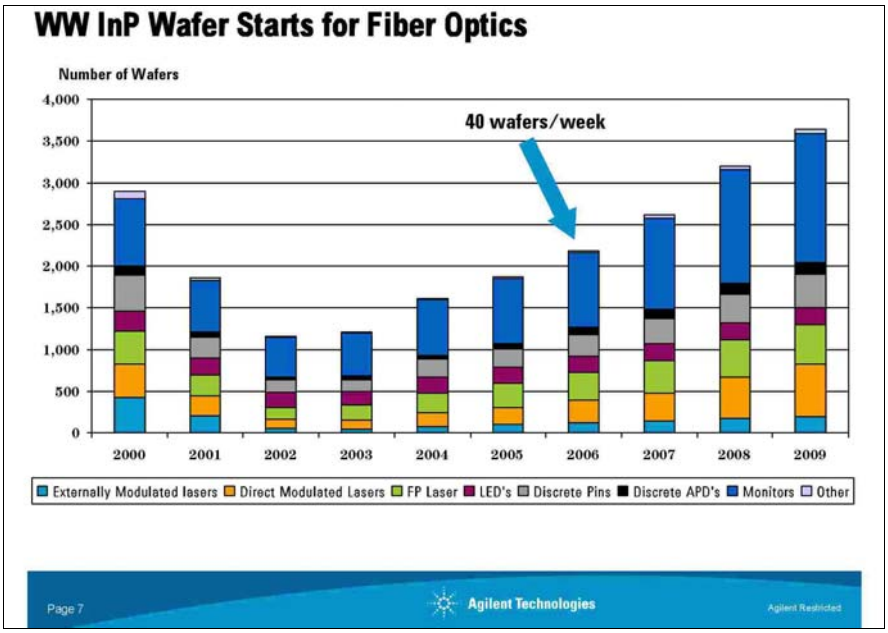

Figure 36: Estimated number of InP wafer starts for the optical communications market
(Source: OIDA InP Foundry Workshop Report 2005)

For the wafer fabrication model to be efficient, the production volume needs to be greater than the entrenched worldwide wafer fabrication capacity. It is evident in the photonic arena for optical communications networks that this is not the case. As industry moves toward higher data rates such as 100 Gbit Ethernet, InP devices will play a greater role. This can be understood by looking at the transition of the 1 Gbit/s transceiver to 10 Gbit/s transceivers. The mix of product is 30:70 for GaAs:InP at the lower rate but reverses at the higher rate.

As industry moves to higher data rates and functionality, integration becomes more important. The path it will take will depend on the financial models of the companies involved. MIT presented a study at the meeting that provides a good perspective. The study examined the cost of integrated vs. discrete devices and the manufacturing costs for North America vs. Asia. The financial model incorporated:

- Equipment
- Materials
- Variable overhead
- Fixed overhead

The analysis did not include sunken wafer fabrication cost. Figure 37 shows the model results for a simple integrated device, the electro-absorption modulator.

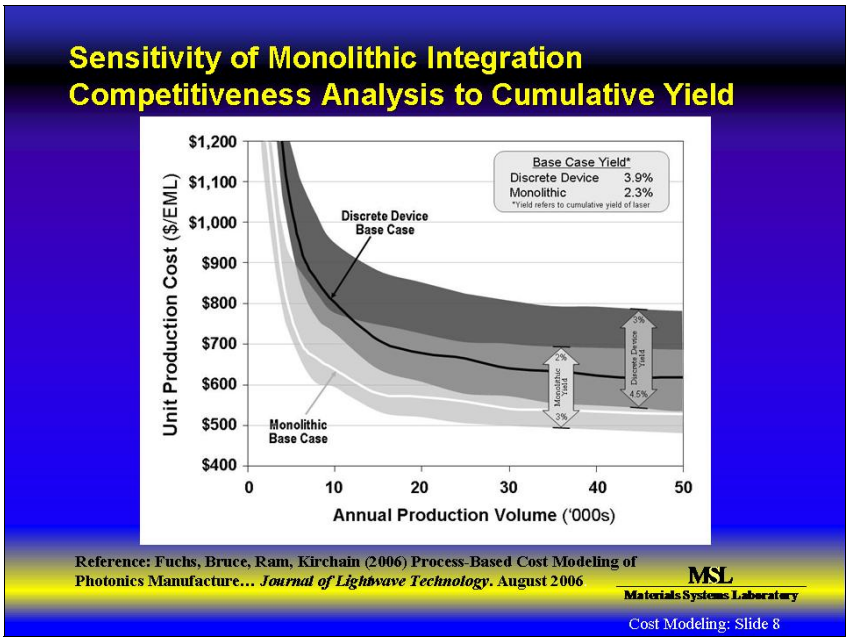

Figure 37: Cost of an integrated EA device vs. monolithic for East Asian vs. North American production

(Courtesy of MIT: E. Fuchs)

The model is sensitive to the inputs. It is evident that integration is on the edge of providing an advantage over discrete devices. Figure 38 compares the manufacturing location on the competitiveness of discrete devices.

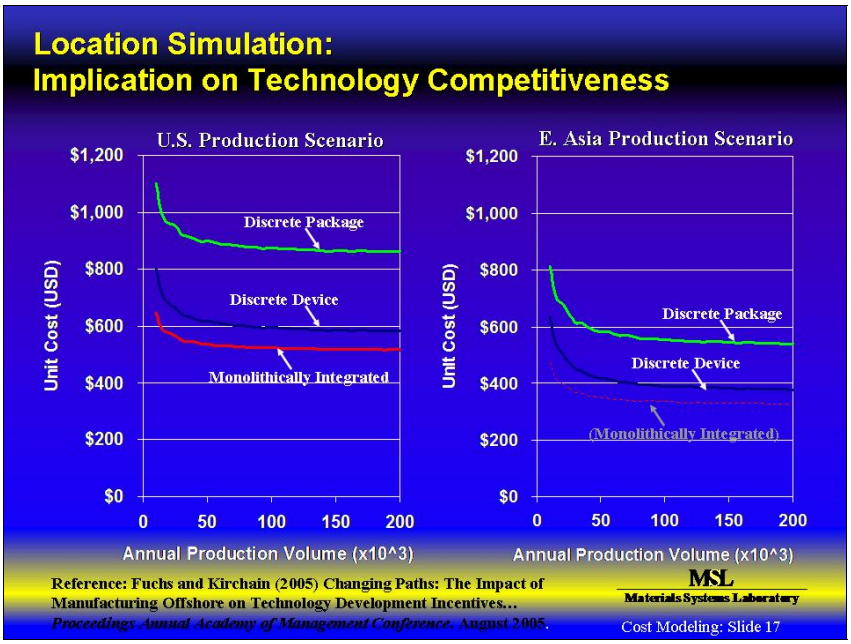

Figure 38: Cost of discrete vs. monolithic devices for East Asian vs. North American production

(Courtesy of MIT: E. Fuchs)

The implication of the cost analysis is that offshore packaging and production will be lower cost than in North America. The principle factor is labor cost. This analysis assumes the infrastructure cost of production is equivalent. Figure 39 highlights the implication that lower wages reduce the short-term incentives for integration.

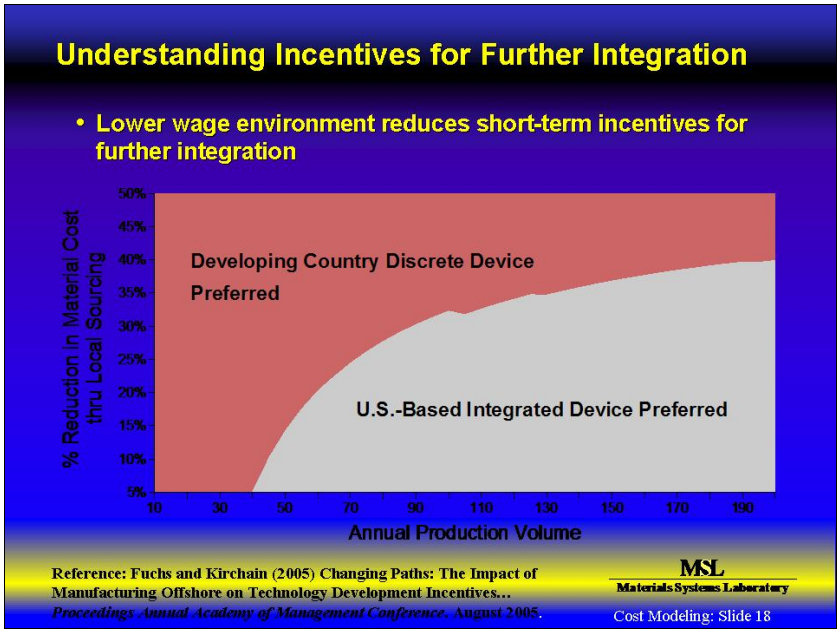

Figure 39: Incentives for discrete vs. monolithic photonic device manufacturing for low wage country vs. U.S.-based production
(Courtesy of MIT: E. Fuchs)

The model and its results depend on the underlying assumptions. If local sourcing and material provide no advantage in Southeast Asia, the model also shows that it is more cost effective to produce integrated photonic devices in the U.S. This analysis highlights that the current industry model presents a challenge to photonic integration.

Is the industry ready for photonic integration? If we compare the silicon industry model to the optical device model, the structure today splits into two segments:

1. Vertical wafer production of silicon ICs
2. Wafer foundry production

Semiconductor chips are fabricated in either a foundry or an in-house fabrication facility. Intel dominates the microprocessor market and continues to invest in new technology in the U.S. They follow “Moore’s Law” to yield more die per wafer by reducing the lithographic line width. This requires constant investment in new, more sophisticated equipment, making this fabrication model extremely capital intensive. In the optical industry, on the other hand, the line width does not need to continuously decrease and so the fabrication facility cost can be much lower. Looking at the different materials in production today, the cost per square inch is different. This actually depends on the maturity of the production material and volume.

This is illustrated below:

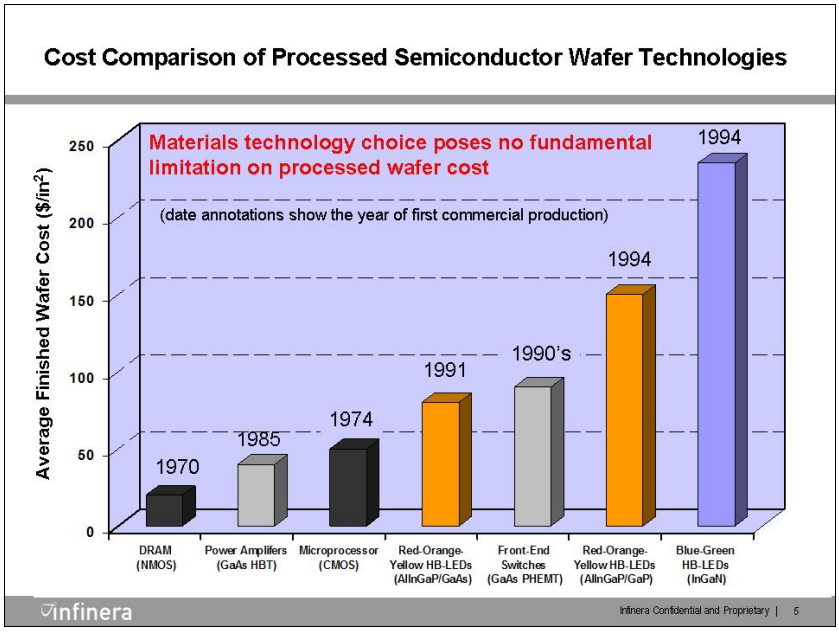

Figure 40: Cost of different semiconductor materials and the year introduced
(Courtesy of Infinera: F. Kish)

The cost of integration depends on how much packaging at a higher level can be eliminated vs. the functionality that can be introduced. For example, the actual wafer production cost of an integrated device depends on the fabrication process flow and the yield. Is it cheaper to package discrete devices or to integrate them? For the next generation of photonic devices and modules, integration is a method to avoid investment in serial technology. For example, it is currently easier to use 10 x 10 Gbit EA modulators with a combiner waveguide than develop a serial laser that operates at 100 Gbit/s. Photonic integration has a place in the optical community. The applications and volumes are not currently available in the communications space. The business structure of the industry does not promote integration and the supply chain is not balanced in terms of profitability and profit sharing. These factors impact how photonic integration will advance.

8 Breakout sessions

The Micropackaging Forum focused on three questions:

1. Which is the right approach: hybrid packaging or system on chip?
2. What are the technology roadblocks and how will integration play a role in the next generation of equipment development?
3. What issues are going to drive micro optic packaging: placement, thermal, EMI or signal integrity (optical and electrical)? How far down does the functionality need to reach?

Groups of participants addressed these questions in breakout sessions. The next sections highlights the points raised during the discussions. The summary section discusses some of the issues raised and how they led to the Forum's recommendations.

8.1 Session 1

This session addressed the question of whether hybrid packaging or a system on chip approach is ideal. The main points raised were:

1. Right approach depends on the volume and ultimately the cost
    a. No standardized approach
    b. Need for platform for multiple applications
    c. InP foundry – standard process to choose from
2. Need high volume driver for monolithic to make sense.
3. Hybrid approach using silicon takes advantage of low cost of silicon processes and adds small amounts of InP devices as required.
4. Can we leverage Si IC packaging to reduce costs?
5. Although not currently at full monolithic integration, the trend is more and more integration – whatever makes sense based on $.
6. Hybrids will be more successful if alignment tolerances can be relaxed.
7. Cost, capability, and yield will drive choice between discrete, hybrid or monolithic.
8. What is the next generation consumer optics packaging platform and how can the industry design into this capability?
9. Leverage existing market for low cost hybrid packaging technology – automotive, DVD.

8.2 Session 2

In this session participants addressed some of the key technology questions. Are there technology roadblocks for higher speed and more functional components? How will integration play a role in the next generation of equipment development? The main points that were raised included:

1. Market and money?
    a. A good question
2. Material choice for integration
    a. No real path is defined
    b. No optics design rules for integration (integrated photonics circuits)
3. Manufacturing infrastructure
    a. No design rules
    b. Yields of single mode lasers from the manufacturer is low
    c. Equipment infrastructure – custom, NO industry standards
    d. We need a foundry model for photonic integration development
4. Alignment technology
    a. For hybrid on silicon
        i. Visual alignment features on a die for pick and place assembly in a hybrid technology has issues
    b. What is the right technology?
5. Technology roadblocks
    a. Process integration can cause problems
    b. Optical cross talk
        i. talking of the transmitters and receivers
        ii. disparity in transmitter to receiver power
        iii. wide dynamic range
    c. Layout
    d. Electronics

8.3 Session 3

This session addressed the technology concerns. These included the drivers for micro-packaging and the interlinked physical parameters. The basic questions asked were, "which issues are going to drive micro-optic packaging: placement, thermal, EMI or signal integrity (optical and electrical)? How far down does the functionality need to reach?" The main points raised in the discussion were:

1. Thermal
    a. Need for temperature insensitive components
        i. New materials / 850nm attractive due to lower sensitivity to temp
    b. Thermal fatigue needs to be mitigated
        i. Coefficient matching doesn't work – specific temp
2. Cost
    a. Managing customer expectations (plasma TV)
    b. Value proposition for micro-optic packaging?
    c. Packaging represents 60% to 70%, where is the cost savings?
    d. Price elasticity – will lower cost drive volume
    e. **REAL** customer requirements to drive packaging
3. Reliability will drive packaging
    a. Non-hermetic package require lost of data for customer buy-in

    b. Are standards too high–being asked to over engineer? Point of failure.
4. RFI
    a. Underestimated…will be a real issue
5. EMI / signal integrity / cross talk

These questions raise significant concerns for an industry where stratification along the business lines has made significant investment on new technology take a back seat to product development and customer support.

9 Summary

Micropackaging is a broad field and continues to evolve and expand. The Forum limited the discussion of next generation micropackaging to the optical communications field. The optical communications market is reaching the production volumes of 1999, but the cost structure of the components has changed. The size of the communications network and the volume of traffic are increasing. The next generation of communication devices is driving the need for increased data rates and bandwidth. In the carrier market, upgrades to the core network are moving forward. The next generation of optical transport equipment (OTN-based) is being deployed with the requirement for 100 Gbit data rates by 2010. Several options and technologies can achieve this next level of system requirement. The packaging is getting smaller, increasing the challenges for the optical components. The industry is still not healthy and a shift in business structure is potentially the only solution.

The Forum and this report examined the technology and capabilities of optical components today. Optical packages can follow different paths, which are often set by the application. The switch and router vendors want transceivers. The micropackaged component must interact with the other aspects of the system. The electronics, intelligence, signal transport and packaged footprint define the requirements for the component.

The optical industry is immature in terms of photonic integration compared to the IC industry. Over the last 20 years, many diverse developments addressed optical component manufacturing issues, including:

1. Device design and integration on a single substrate.
2. Electronic circuit development on the native substrate such as InP drivers for high-speed applications.
3. Hybrid packaging to mate the native optical semiconductor to the silicon electronics.
4. High accuracy placement technology for die bonding and passive alignment. Improved wire bond processes.
5. Modules and more sophisticated packages.
6. Non-hermetic packaging.
7. Optical waveguides and functionality.
8. Lower cost microwave PCB material.
9. Signal recovery electronics.

Packages used in communications today remain similar to those developed over 20 years ago. The performance of butterfly and traditional telecom packages has improved but the packages remain essentially the same. The TO-can technology for CD and DVD players has allowed lower cost communications components. The TO package continues to meet the requirements of high data rates. Devices utilize the lead frame package and plastic optics, but not to the same extent as other market segments.

There has been no real driver for photonic integration. Cost and the health of the industry have limited its development. The optical communications market does not provide the necessary business incentives for the device industry. A transition to a foundry model similar to that of the silicon industry would change the cost structure and provide incentives for photonic integration. Another issue is the immaturity of tool sets and functional design models. Again, to justify industry investment, volume applications are necessary. Network upgrades to higher data rates may provide a driver for integration, but the volume for this market is currently small and not expected to grow exponentially.

Several different types of integration and higher level packaging are in use today. The silicon optical bench continues to find a place in different product incarnations. It offers an alternative to the pure photonic integration approach, but requires high levels of automation or some self-alignment processing. The integration of a waveguide either on III-V chip or on the silicon chip enables a low-cost alternative. VCSELs emit light from the planar surface, which then requires focusing into a waveguide. Parallel transceiver modules use this approach. The integration of control electronics next to a III-V device introduces the issues of reliability and thermal control. It achieves integration, but scalability is questionable.

The Forum briefly examined the cost arguments for discrete vs. photonic integration. It is clear that integration can provide some cost advantage but is cost- model dependent. Yield of devices from the wafer plays a crucial role. Certain scenarios and models of onshore vs. offshore production indicate that under certain conditions discrete packaging is lower cost. The advantage of integration depends on your view point. The model needs to consider a company's "sunk" investment costs.

Micropackaging continues to advance in the optical communications industry. The financial health of the component vendors will determine if they will continue to develop the next generation of products. Research and development is pursuing the approach with the lowest manufacturing. Innovation in silicon optical bench packaging continues and provides a clear alternative to the wafer-processed photonic integration device. At some point, the device still requires a package. The level of functionality in the optical component needs to increase so that it provides a clear cost advantage. As network providers move to higher data rates and greater bandwidth, it is clear that some level of photonic integration will be required. As industry changes, it will require a foundry model to drive innovation.

The next section highlights the recommendations from the Forum.

10 Recommendations

The Forum deliberately restricted its discussions to packaging for optical components and communications. The principal reason for this was the significance of the emerging requirements for 100 Gbit/s transport. Many different markets use micropackaging technology. Although each market segment presents different challenges, the optical communications industry can leverage advancements in other segments to its own advantage. The Forum made the following recommendations:

System companies

- The large system companies currently require the component supply chain to develop the next generation components for their fiber optic systems. The component industry is still not healthy, with many companies still reporting operating losses. The new technology investment requires both the network and switch/router companies to strategically align their supply base and aide in the development of next generation product.
- The large commercial companies should continue to develop and support links with universities and the government to enable the next generation of technology for both electronics and optoelectronics components. Industrial companies, in association with the government and OIDA, should sponsor hybrid packaging and wafer development at universities that will enable photonic integration.
- The venture community should understand that a new wave of upgrades in the core and metro networks is occurring. The network providers and carriers are forecasting that they will require 100 Gbit Ethernet technology in the core by 2010. Currently, the component suppliers are concentrating on the current generation and incremental improvements to technology. There is a gap in technology which needs to be funded either by the venture community, the network providers, or switch router companies.
- The outsourcing of packaging to Southeast Asia is limiting the assembly base within the U.S. This has a direct impact on the defense industry and the ability of North America and Europe to develop new technology and packaging. The ”sunk” investment cost for wafer fabrication companies should be utilized to enable low cost photonic integration solutions within North America and Europe. This could change the cost paradigm.
- Industry must change to enable integrated photonics development. The development of a foundry structure within the optical community would enable the more rapid commercialization of photonic integration technology and platforms. OIDA should work with industry and government to help foster this change.

Government/regulatory measures

- The U.S. government must continue to recognize the importance of packaging as a key enabler for the U.S. technology sector. The development of photonic inte-

gration within the North American sector will require direction and funding that enable the industry to move forward in a progressive manner.

- The U.S. government should work with OIDA to enable a change in the optical communications industry. Leveraging a virtual foundry with existing fabrication companies would enable this. Startup companies could then concentrate on design and design rules to develop new applications and technology for integrated photonics.
- With the outsourcing of most optical assemblies to Southeast Asia, the U.S. government should consider establishing a packaging capability through consortia of small, specialized companies or major OEMs to ensure that U.S. defense manufacturers will have access to competitive and advanced packaging technology.
- The development of next generation micro-optic technology and packaging in Asia and Europe should be monitored and their impact on the domestic leadership understood and evaluated.

11 Appendix A – Forum Agenda

Micropackaging for the Next Generation of Optical and Electrical Components

Wednesday, August 30th, 2006 – San Jose, CA

7.30 – 8.00 a.m.	Registration and Continental Breakfast
8.00 – 8.10	Welcome *Michael Lebby* – OIDA
8.10 – 8.15	Introduction – *Bill Ring*, WSR Optical Device Solutions

8.15 – 10.05 a.m.	**Micropackaging: Discrete and Hybrid Approaches**
8.15 – 8.35 a.m.	CyOptics – *Jim Dormer*
8.35 – 8.55	Bookham Technologies – *Robert Keys*
8.55 – 9.15	EM4 – *Alex Rosiewicz*
9.15 – 9.35	Tyco Electronics – *R. Smith/TBD*
9.35 – 9.55	Intel – *Marc Finot*
9.55 – 10.15	AOC/Finisar – *Jim Tatum*
10.15 – 10.25	Moderated Discussion
10.25 – 10.45	**Coffee Break**

10.45 – 12.35 p.m.	**Micropackaging: Discrete and Hybrid**
10.45 – 11.05 a.m.	Digital Optics – *Michael Feldman*
11.05 – 11.25	Infinera – *Fred Kish*
11.25 – 11.45	Xponent – *Jeff Rittichier*
11.45 – 12.05	EMCORE – *Rob Bryan*
12.05 – 12.25 p.m.	Worcester Polytechnic Institute – *Ryszard Pryputniewicz*
12.25 – 12.35	Moderated Discussion
12.35 – 2.00	**Lunch**

2.00 – 3.50 p.m.	**Micropackaging: Hybrid and Integrated**
2.00 – 2.20	IBIDEN R&D USA – *Chris Keller*
2.20 – 2.40	Massachusetts Institute of Technology – *Rajeev Ram*
2.40 – 3.00	Sarnoff Corporation – *Joseph Abeles*
3.00 – 3.20	BinOptics – *Alex Behfar*
3.20 – 3.30	Moderated Discussion
3.30 – 3.40	Organize breakout sessions
3.40 – 4.00	**Coffee Break**

4.00 – 5.10 p.m. **Breakout Discussions**

1. Which is the right approach: hybrid packaging or system on chip?

2. What are the technology roadblocks and how will integration play a role in the next generation of equipment development?

3. What issues are going to drive micro-optic packaging: placement, thermal, EMI or signal integrity (optical and electrical)? How far down does the functionality need to reach?

5.10 – 5.30p.m. Reports from breakout leaders

5.30 – 5.45pm Workshop summary and concluding remarks

12 Appendix B – Forum Attendee List

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