iNEMI OPTOELECTRONICS ROADMAP FOR 2004

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ABSTRACT
The iNEMI Optoelectronic Roadmap for 2004 is focused on optical communication. After reviewing the business picture – which includes the probable irreversible move of commodity-like volume manufacture to Asia and low cost labor geographies, it identifies technology changes on the horizon. The chapters are divided by packaging level into Level 0 (on chip interconnections), Level 1 (packaged devices), and Level 2 (modules and card assemblies). Emerging technologies may impact optical interconnects are also discussed. The appendix describes global standards including the JISSO packaging levels and the IPC standards development work..
Key words: Optoelectronics, VCSEL, transmitters, emerging technologies,

BUSINESS OVERVIEW
The scope of the 2004 iNEMI Optoelectronics roadmap is confined to the area of optical communications which is the one of the most concern to the members of the Optoelectronics Technical Working Group. The roadmap focuses on the trends for the optoelectronic components that will be required to support the evolving communications infrastructure.

In the 2002 Optoelectronics Roadmap we reported on the dramatic drop in optoelectronic capital. It now appears that capital spending for optoelectronic components and systems has stabilized and has started to grow again albeit at slower rates than was experienced in the 1990's.

In the 2000 to 2001 period, much of the optical fiber installed was dark – with less than 1 or 2 % of the installed fiber lit – and little revenue generated from the capital expenditures made. The chart shown below which was reported on in March 2, 2003 issue of "Lightwave" shows that this is not currently the case.

Furthermore, since the 2002 optoelectronics roadmap, there have been mergers of component and equipment suppliers resulting in financially sounder and more stable firms with broader optoelectronic product portfolios.

Currently the optoelectronics (OE) industry is undergoing major and probably irreversible change. As components and modules become more standardized and commodity-like, volume manufacturing is shifting to Asia and other low labor cost geographies. An increasing fraction of production goes to meet domestic demand in developing countries. It appears likely over time that the EMS (electronic manufacturing service) and ODM (original design manufacturing) providers will also perform more of the R&D, product design and system-level assembly.

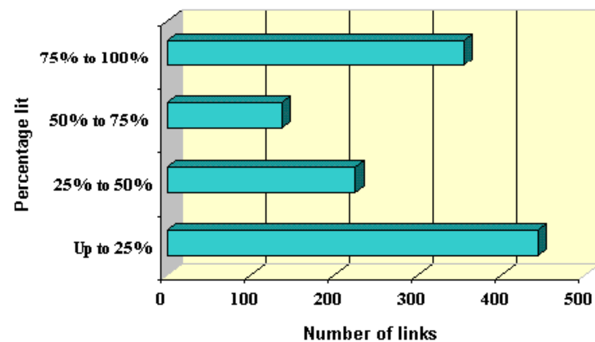

Figure 1. The capacity utilization in North America on Long Haul Wavelength Division Multiplexing (Wdm) links has increased since 2000 when less than 1 – 2 % of the installed fiber was lit.

In North American and Europe some of the knowledgeable people and companies formerly in the communications sector have moved into other areas of photonics, diversified their product and customer bases, or formed new companies. This is helping to drive new photonics applications and improvements in cost reduction and manufacturing efficiency beyond the traditional OE component and OE enabled product sectors.

- Global internet data traffic continues to grow 50-100% annually, primarily driven by web browsing, file swapping and e-commerce. Comparable traffic growth is likely to continue for the next few years as voice over internet protocol (VOIP) and video move to IP.
- Traffic growth will be supported by turning on unlit fiber for the next few years, increased data rates and number of useable wavelengths. Growth in the long haul fiber market will remain flat, as long as legacy fiber can support higher bandwidths. Strongest growth will occur in the terminal equipment, access and fiber to the premises (FTTP) sectors.

- Capacity in the backbone will push out the need for 40 Gbps transmission for several years since 40G represents a significant increase in capital expenditures based on current costs.
- Implementation of “real” broadband access (>100 Mbps) for fiber to the home (FTTH), using Gigabit ethernet or passive optical networks (PON), may be driven by future demand for high definition digital TV. Current FTTH growth has begun in Japan and Korea and USA service providers have announced plans to run fiber to 1M homes by 2006.
- The trend to network simplification and convergence to IP will reduce the need for protocol conversion at the line card.
- Wavelength reconfiguration and optical packet labels will enable the adoption of all-optical networks (AON). In the future, fast packet (and possibly bit level) switching will be optical and the network intelligence (adaptation to equipment failure, traffic, power and wavelength control) will be based on optical performance monitors.

OPTOELECTRONICS LEVEL 0 (JISSO 1)[1]

The iNEMI Optoelectronics Level 0 (JISSO 1) chapter describes chip technology developments for optical communication and solid-state lighting.

Photonics plays an important role in many aspects of our lives. Figure 2 gives an overview of the world of photonics.

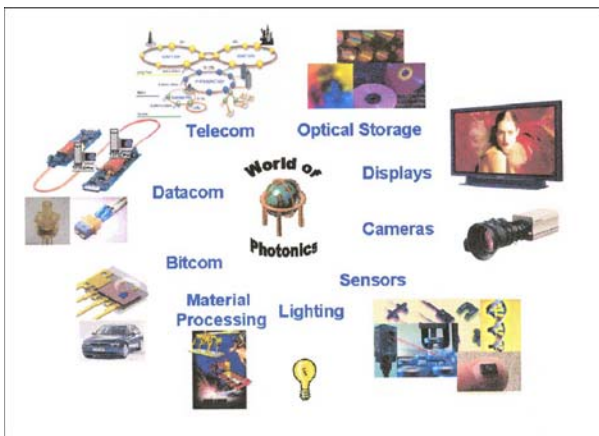

Figure 2. The world of photonics.

Photonics is used in the area of information technology for information generation (cameras, sensors), for information transportation (optical communication: telecom, datacom, bitcom), information storage (optical storage), and information display (displays). Non-information related applications of photonics are lighting and material processing including medical surgery. Semiconductor technology is present and most often dominant in all area of photonics.

Economic Technology Drivers

The economic figure-of-merit (EFM) is the cost ($) per information (bit) per time transmitted (s) per distance (km) (Figure 3). New technology is always driven by the desire to decrease the EFM number by reducing cost of components or getting more bits transported per time (higher speed) or going longer distance without the conversion back to electrical signals.

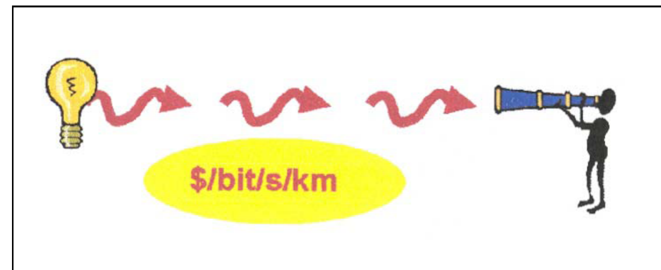

Figure 3. Economic figure-of-merit (EFM) is cost per bit/time/distance (ASTRI)[2]

Wavelength Range

The optical medium glass fiber (or plastic optical fiber) and the systems requirements determine the wavelength of the optical communication system. For long-haul systems, single mode operation is required. Therefore the wavelength is 1300nm (dispersion minimum) or 1550nm (loss minimum). For shorter distances, multimode fibers and VCSELs (Verticle Cavity Surface-Emitting Lasers) operating at 850nm offer cost advantages for packaging. Nowadays multimode fibers are optimized for 850nm operation, because of the low cost VCSEL sources. Plastic optical fibers require visible red (650nm) or even shorter wavelengths (around 500nm visible green) in order to keep the loss to an acceptable minimum.

Transmitter Devices

Transmitter elements (laser diodes and modulators) have to provide the optical signal at the right wavelength and spectral quality for the emission system. For lower speed operation, directly modulated lasers are preferred. For very fast and long distance systems running at 10 GB/s or more, external modulators are used because of higher speed and/or lower chirp.

VCSELs are currently used in multimode fiber systems for datacom applications. The maximum distance is a few hundred meters (300m or 550m depending on standards). The current speed is 2.5Gb/s up to 4Gb/s for the new emerging Fiber Channel standard. Some VCSELs have been demonstrated at 10Gb/s. However, available reliability/ qualification data is mainly based on the slower speed

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[1] JISSO refers to the Japanese packaging levels, the details of which can be fund in the Appendix of the Roadmap.

[2] Applied Science and Technology Institute Company Limited, Hong Kong.

devices. VCSELs have a great potential to replace Fabry-Perot lasers and some DFB lasers at 1300nm and even 1550nm in the future. This would expand the field of VCSEL application to the 20km range and 10Gb/s. However, it has been difficult to develop long wavelength VCSEL for many years.

Solid State Lighting

The field of solid state lighting has attracted a lot of interest following the development of the blue and UV-LED (ultraviolet light-emitting diodes). Solid state lighting requires a white spectrum from a semiconductor source. Two main approaches have been developed. One uses the light of three LEDs (blue, green, and red) mixed together resulting in a white spectrum. The other uses the light of a blue (or UV) LED and a phosphorous encapsulation to convert the higher energy photons into white light. This approach is quite similar to the principle of fluorescence lamps. The key figure is the overall light efficiency and cost of the solid state solution compared to conventional light sources. Solid state lighting also offers additional advantages over conventional lighting. These include: low voltage operation (for battery and humid environment), small size, long lifetimes, high environmental stability, low power consumption, and easy control (low EMI noise). Solid state lighting will continue its rapid development in the years ahead.

Future Trends

Table 1 summarizes integration roadmap developments for the next ten years. The reduction of the overall system cost will be the main driver for integration. At high speed levels of 40Gb/s and beyond, performance reasons (low parasitic) will also play a role.

Table 1. Roadmap of integration Technology

2005	2007	2009	2015
Tunable lasers and high speed modulator	**1310 nm electro-absorption modulated laser (EML), uncooled**	**Multi-channel tunable lasers**	**Multi-channel laser array**
Tunable laser integrated with op-amp and modulator	**1550 nm EML with op-amp and photo-detector**	**Tunable laser array with op-amp and optical switch**	**Pin/avalanche photodiode (APD) with integrated electronics for 100GB/s**
	Pin/APD with integrated amplifier for 40 GB/s	**Photodectector array with integrated demultiplexer**	

The drivers for future technology developments on the chip side are higher performance, lower packaging complexity/cost, integration of optical components to reduce packaging cost, and integration of tunability to reduce inventory cost and enable flexible networks.

It should be pointed out that solid state lighting also offers additional advantages over conventional lighting. These include:

- Low voltage operation (for battery and humid environment)
- Small size
- Long lifetime
- High environmental stability
- Low power consumption
- Easy control (low EMI noise)

Solid state lighting will continue a rapid development in the following years. Lighting efficiency is expected to improve from 30 lm/W in 2005 to 150 lm/W in 2015.

LEVEL 1 – (JISSO 2)

General Trends in optoelectronic packaging technologies over the next 3-10 years:

- 3 Year: Hermetic Packages: Same basic packages and assembly technologies not yet optimized for manufacturing; smaller form factors, higher levels of optical and electronic integration (System-In-Package (SIP)), non-hermetic packages for some applications (cable TV, premise networks) and introduction of plastics and molded optics.
- 5 Year: Increasing use and application of SIP and "System on a Package" (SOP) integration approaches, wide adoption of plastics and composite materials for packaging and optics.
- 10 Year: "System on a Package" technologies with a mixture of III-V materials and organics embedded for both electrical and optical functions, plastic packages replace hermetic packages for high volume applications. The trend will be alignment tolerant packages allowing looser optical placement accuracy.

Transmitters/Receivers

Package constructions are still coaxial, mini dual in-line, butterfly and flat-pack, but with a significant trend towards the smaller packages. Increasingly, electronics are included in the packages, and in many applications, devices remain uncooled (typically a thermoelectric cooler is employed). The military and space market is pressing the industry forward in the areas of high precision and thermally stable packaging.

Laser Diode Arrays

As individual lasers mature with longer wavelength in the infrared region included, there will be an increasing need to package these devices in arrays for sensing applications. Developments in this area will include the integration of optical elements into the package to enable efficient utilization of the laser output.

VCSEL Packaging

The vertically emitting nature of VCSELs enables the easy adaptation of a variety of packages. Packages most commonly used for LEDs are easily transferred to VCSELs. Most VCSELs are packaged in transistor outline (TO)

headers (Figure 4). The VCSEL is placed flat on the pedestal of the header using a conductive epoxy, and wire bonded such that the light is emitted from the top side of the chip through a window in the can which usually has only a flat glass window , but could also incorporate a lens.

VCSELs have been packaged in a variety of other packages such as plastic lead packages, ceramic surface mount packages, and chip-on-board or chip-on-flex packages. Future trends will include higher speed packages, array packages, and integration of VCSELs with lenses, other optoelectronic devices, and integrated circuits.

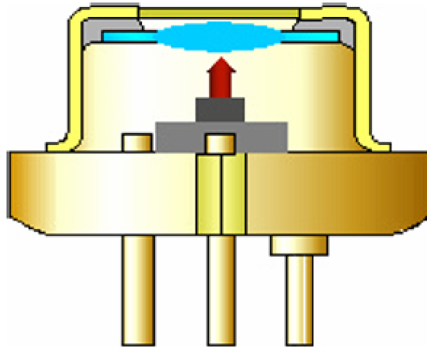

Figure 4. Example of TO Packaged VCSEL (courtesy of Torsten Wipiejewski, ASTRI)

TO packages with improved performance have been designed and are currently being applied in 10G product development projects by several manufacturers. However, 20 or 40Gbps projects may necessitate a move toward a new type of package.

BGA Packages

Ball Grid Array (BGA) Technology has been introduced as a surface mountable device in the 1990s to overcome the high pin-count crisis with leaded packages. In general, the BGA package types show a lower capacitance and inductance - compared to leaded packages - and are therefore more suitable for RF applications. Thermally enhanced BGAs are available for dissipation losses of several watts. PBGAs are moisture sensitive but BGAs based on ceramic or metal frame could be used for hermetic housing.

Packages For Single Optical Components And Optical Modules

Single optical components (lasers, photo diodes) are mainly used for simple electro-optical as well as opto-electrical conversion. Package types depend on device functionality and application standard. Interfaces are generally by pigtail, optical connector or free-space optical transmission.

Level 1 Assembly: Automation vs. Mechanization

Manual – The use of mechanical devices to aid in the manual manufacturing of a device, in this case, a photonic assembly. A micrometer stage would be considered "mechanized."

Semi-Automated/Semi-Manual – Processes that are implemented with a combination of manual and automated tools; manual processes are reserved for those that are difficult to automate (connection of multiple fiber connectors (FC) or require more repeatable or accurate control than an operator can provide.

Full Automation – The complete control of an assembly, inspection, or other process that requires no user intervention, other than the bulk presentation of raw materials and bulk removal of finished products. This is sometimes described as an island of automation.

Inline Automation – Fully automated processes whereby incoming and outgoing material flow are from adjacent machines.

Table 2, based on 2002 data, compares the factors affecting automation (operators, time, yield, cost and market share for the various assembly processes. In 2005 the predominant level 1 assembly processes are expected to be semi- or full automation, in 2007, full or in-line automation and by 2012 it will be all in-line automation for Level 1 assembly. The trend towards subcontract manufacturers doing optoelectronic assembly is what will accelerate the predicted introduction and adoption of automation tools and process improvements, as they can aggregate larger volumes, drive a faster experience curve and achieve cost reductions.

Table 2. Summary of automation technologies characteristics in 2002

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2002	Machines/ Operator	Time/Part	Yield	Cost	Market Share
Manual	1	Up to 1 hour	50=75%	$5K-$50K	70%
Semi	1-3	1-15 min	80-90%+	$50 – $200K	24%
Full	5-10	1-5 min	90-99%	$250K-$350K	< 5%
In-line	Several	2-4 min	90-99%	>$400K	Rare

New Technologies

The integration of chip technologies, micro optical components and packaging for building up a real system in a package (SIP) (for optoelectronic application) needs developments in many areas. Microelectronic integrated circuits (ICs), optical components and functionality as well as tailored packages should be co-designed in order to optimize the overall size, performance and cost. For this goal, extended material and process characterization will be needed in order to provide accurate mechanical, thermal, electrical and optical models for system simulation before starting technological activities. The integration of microelectronic (e.g. ICs, embedded passives) and micro optical (e.g. wave guides, lenses, beam deflectors) components either on a chip (above IC MOEMS), in a carrier substrate or inside of package parts, will be the next generation of system oriented packaging in optoelectronics (Figure5).

LEVEL 2 – (JISSO 3 AND 4)

OE level 2 refers to the sub-systems (higher level modules and OE card assemblies) that comprise one or more packaged optical or OE components, e.g. fiber pig-tailed passive and active components. Increasingly the component is a multifunctional OE module, such as an add-drop multiplexer or pluggable transceiver or transponder.

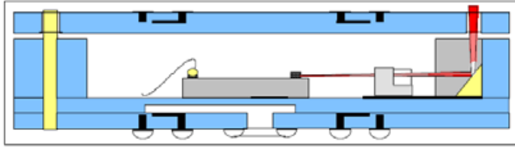

Figure 5. Concept of optical system integration inside ceramic or PCB multilayer packages (Source: Fraunhofer IZM)

Some key industry drivers and technology trends for Level 2 relevant to OE communications business are:

- Increased electrical and optical integration and functionality in devices, components and modules will continue (level 2, (JISSO 3))
- At level 2 the move to low cost labor and pluggable modules may avert the need to automate some manual assembly operations, e.g. fiber handling. Automation is viable for higher skill operations, such as fiber splicing, as long as the volumes and yield improvement justify the equipment cost of ownership.
- The performance of copper-based electrical systems continues to advance at the module and card-to-card levels. Effective data rates of 10 Gbps over 0.5 meter in FR4 can be achieved using current technology.
- There is growing interest in using optical links at the chip or module levels in high speed systems, to overcome bandwidth bottlenecks, thermal dissipation (>100 W per ASIC) and signal integrity issues, e.g. for clock distribution, high I/O and low memory latency.

Optical Modules

Level 2 (JISSO 3&4) assembly is complicated by the common need to hand solder optoelectronic modules. The fiber management of optical fiber pigtails, commonly extending from these modules, adds further complexity. Many datacom modules are being designed to simplify level 2 (JISSO 3&4) assembly. Modules with connector receptacles are now widely used. Such modules offer the promise of eliminating pigtail fiber management at level 2 (JISSO 3&4) via the use of optical connectors. Fiber patch cords with precision connector ferrules are providing separable low loss connection to modules on the resulting optoelectronic system boards.

Test

There are two key aspects that determine test strategy: where a product fits in its value chain (component, module, board, or system), and where the product fits in its development lifecycle (R&D, Design Verification, New Product Introduction, and Manufacturing). In less mature technologies, test must be exhaustively applied also in manufacturing, since either unspecified parameters or immature designs cause yield problems. As technology matures, only the value added by the particular manufacturing step must be tested, assuming the design is sound. This is the direction that optical manufacturing has been heading since the early 2000s. Figure 11 graphically shows the degree of test for each product dependent on where it fits in the value chain and it's own development cycle. [8]

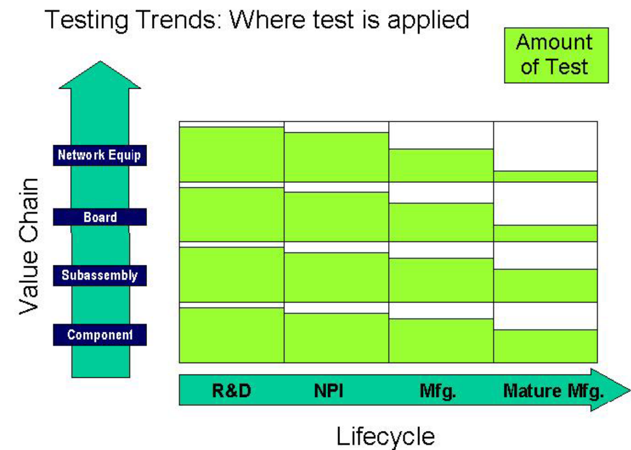

Figure 6. Testing Trends.

Emerging Technologies

There are a number of new technologies that are emerging. Table 3 lists a number of them with their possible application.

Table 3. Emerging Technologies

Technology	Possible Application
Photonic band gap materials (photonic crystal, holey fibers, etc.)	**Wave guides, light turning, improved device form factors, higher power, non-linear properties**
Grating systems	**Manipulation of light in all sorts of geometries**
Holograms	**Fast (ns) optical switching, possibly bit/packet-level**
MEMs devices	**Wavelength switching and reconfiguration in all optical networks**
Semiconductor electronic optical modulation	**Switching, modulation to eliminate components**
Negative index materials	**Multiple**
Quantum entanglement	**Secure communications**
Tunable lasers	**Real-time network and system reconfiguration**
Carbon nanotubes	**Heat spreader components where high thermal conductivity improves performance**
2-Photon absorption	**Waveguides and optical elements**
Silica nanowires	**Sensors, OE devices requiring small form factors**

Finally, global industry standards are covered in the Appendix. This includes a discussion of the JISSO levels and a description of the number scheme for the optoelectronic standards being developed by IPC.

SUMMARY

This paper represents a summary of the key factors identified in the 2004 iNEMI Optoelectronics Roadmap. It has discussed the business issues and some key technology developments expected in the future for the various levels of packaging. The roadmap represents the input of almost 50 individuals from around the world.

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