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## Optical Interconnects Penetrate Local-Network Realm

*Thanks To Advances In Laser, Packaging, And Test Technology, Optical Interconnects Prepare To Give Moore's Law New Life.*

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The evolution of computer systems over the past two decades shows a tremendous increase in processing ability per square inch, as postulated by Moore's Law. However, a closer look at the progression of interconnection technologies shows growth trends that, while impressive, have not kept pace with processing capabilities. As a result, the movement of acres of data generated by high-speed processors has been hampered, making the interconnect a major bottleneck. To relieve it, systems and network designers are moving away from copper-based interconnects, with their inherently high capacitance, noise susceptibility, and relatively poor signal-loss/distance ratios, to more advanced, high-speed optical connections.

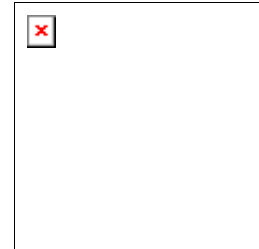
While copper links still carry the bulk of the load for workgroup-level networks, optical links are emerging as the preferred media for campus backbones, central-office networks, and WANs. These systems demand the low noise, faster transmission rates, zero crosstalk, and wide bandwidth that only optical systems can provide. Despite inherent advantages, the proliferation of optical connector technology has been slow, due to its relatively high cost of implementation. Recent advances in laser, packaging, and testing, however, are lowering this technology's cost premium, such that it is now penetrating both WANs and LANs.

As costs come down, technologies such as Gigabit Ethernet (GbE), which leverage existing Ethernet standards, are ideally positioned to provide the bridge between existing, copper-based, 10/100Base-T local networks and new, higher-bandwidth optical infrastructures. At the same time, fiber-based, high-speed data-storage networks, such as Fibre Channel, are rapidly being deployed to support enterprise-wide data warehousing strategies.

### Implementation Challenges

A major challenge to the effective implementation of these new, high-speed

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optical links will be the creation of cost-effective, robust, standards-based optical transceiver components that can support Gbit/s bandwidths. As the demand for gigabit optical links accelerates, system designers need access to readily available, high-volume supplies of reliable, electro-optical, physical-layer components.

These optical transceivers will spark the gigabit revolution in much the same way the availability of standard Ethernet physical-layer components (PHYs) helped fuel the ubiquitous deployments and falling cost curves of 10Base-T and 100Base-T over the past decade. However, the design and production of optical interconnects presents a totally new and unique set of problems. These are associated with the cost-effective production of gigabit-speed lasers using standard semiconductor processes, and the effective packaging and alignment of these devices to optimally launch light into standard optical fiber.

The evolution of higher data rates and the migration toward optical links has created a need for greater flexibility in interconnect form factors. For instance, link distances and data rates in 10Base-T or 100Base-T links could typically be handled by a single type of physical-layer component, which could cost-effectively be soldered directly onto a system-level pc board, whether it's a network interface or a switch card.

But, the greater data rates required by optical gigabit links present network-configuration challenges that cannot always be cost-effectively resolved by a common interconnect or transmission methodology. For example, GbE links may be implemented either as 1000Base-SX links using less expensive, short-wavelength (850-nm) laser technology over multimode fiber, or as 1000Base-LX links using more expensive, long-wavelength (1300-nm) laser technology over multimode or singlemode fiber. Depending upon the fiber diameter used, 1000Base-SX can support distances up to 550 m on 50- $\mu$ m multimode fiber, and up to 275 m on 62.5- $\mu$ m multimode fiber. On the other hand, 1000Base-LX can support distances of 550 m on either 50- or 62.5- $\mu$ m multimode fiber, and up to 5000 m on 9- $\mu$ m single-mode fiber (*see the table*).

<b>EVOLUTION OF NETWORK INTERCONNECT TECHNOLOGIES</b>			
<b>Network standard</b>	<b>Data rate</b>	<b>Maximum distance per link</b>	<b>Media flexibility</b>
Ethernet	10 Mbits/s	2 km	Soldered discrete components
Fast Ethernet	100 Mbits/s	2 km	Soldered 1 by 9 transceiver
FDDI	100 Mbits/s	2 km	Soldered 1 by 9 transceiver
Gigabit Ethernet 1000Base-SX	1.0 Gbit/s	550 m (multimode fiber)	Soldered 1 by 9 transceiver or pluggable GBIC transceivers
Gigabit Ethernet 1000Base-LX	1.0 Gbit/s	550 m (multimode fiber) 5 km (single-mode fiber)	Soldered 1 by 9 transceiver or pluggable GBIC transceivers

Because long-wavelength transceivers for 1000Base-LX interconnects are inherently more expensive than short-wavelength, 1000Base-SX components, it's important to instill a higher degree of configuration flexibility into the deployment of optical transceivers. Along with the traditional 1 by 9 (1 row by 9 pins) solderable component form factor used throughout copper-based Ethernet and Fiber Distributed Data Interface (FDDI) implementations, GbE links can also be

implemented using complete module-level pluggable transceivers based on the widely-adopted industry-standard Gigabit Interface Converter (GBIC) form factor.

Not only do interchangeable GBICs give network administrators the flexibility to tailor network topologies and link distances and costs to specific requirements, they also allow for subsequent network reconfiguration as needs change--without wholesale replacement or system-level investments.

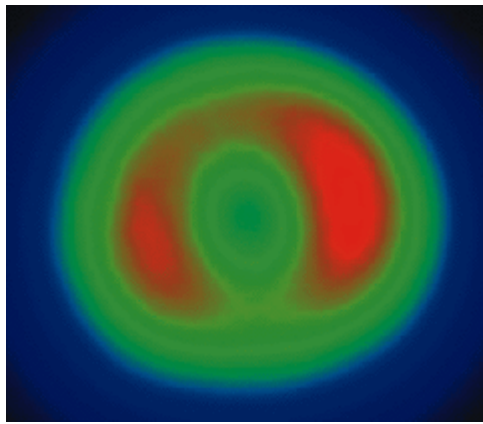
### **Design Issues**

The design and manufacture of cost-effective, optical interconnect solutions for use in Gbit/s GBICs, hinges on successfully meeting reliability and distance requirements of the GbE specifications. At the same time, companies need to drive down packaging, alignment, and test costs of these devices to support high-volume deployments.

*Reliability and distance:* The most critical factor impacting the reliable transport of optical signals over practical distances is differential mode delay (DMD), important because light traveling through multimode optical fibers tends to bounce through the fiber at different angles, depending upon its distance from the center of the fiber. This results in different propagation paths (modes) for different parts of the fiber. As a result, a signal launched across the entire fiber tends to "smear" as it goes through the fiber. In essence, the same signal is being simultaneously propagated down the fiber following different path lengths in the center than at the edges. Thus, a digital pulse of a given output power will tend to move toward a bell-shaped curve as the signal is smeared over a given distance.

Ideally, the fiber is constructed to compensate for this by allowing light travelling on the outside of the fiber to move at a higher velocity. In some fibers, however, construction is non-optimal, resulting in increased DMD. With uncontrolled DMD, a string of pulses can spread out so much that they interfere with each other to the extent that data cannot be recovered reliably.

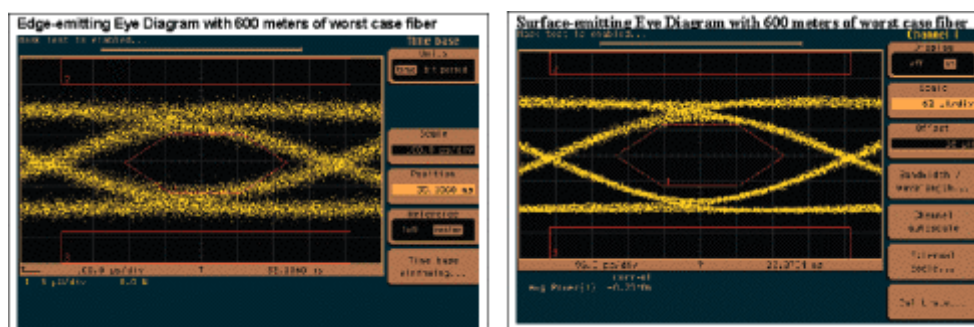
Extensive analysis of DMD characteristics in today's fiber-optic cabling system has shown that optimum signal-propagation distances can be achieved by selectively launching light into the fiber in a donut shape that uniformly encircles the fiber's center (*Fig. 1*). This allows for maximum light output across a minimum number of propagation modes. This eliminates smearing over distances up to three times longer than broadly launched signals of the same output strength.



**1. The unique laser-launch profile from a vertical-cavity, surface-emitting laser (VCSEL) shows a donut pattern of light. This eliminates the differential-mode delay effect that may occur when light is launched uniformly across worst-case multimode fiber. Launching the light in such a fashion eliminates smearing over distances as much as three times longer than broadly launched signals of the same output power.**

*Packaging and alignment:* The main contributor to packaging cost is the process of aligning light coming out of the semiconductor with the optical fiber. Physical packaging of optical transceiver components involves all of the normal semiconductor packaging issues--plus a giant step in difficulty with regard to alignment. The effective launching of light from the semiconductor into the fiber demands precise and consistent alignment relationships between the internal positioning of the semiconductor and the external plug points for the fiber connector. In addition, these critical coupling-efficiency alignments must remain intact during subsequent shipping, handling, and systems assembly, as well as throughout a wide range of operating conditions.

*Test:* The nature of optical interconnects, combined with the wide range of operating environments for gigabit-speed networks, makes rigorous testing critical in component manufacturing. To meet specification requirements, every optical interconnect component must be able to consistently produce an eye diagram that conforms to a predetermined eye-diagram mask (*Fig. 2a and b*). Only by ensuring that light pulses actually emitted by the component are consistently grouped within the GbE standard's eye diagram, can the designer predictably rely on it to produce the required propagation distances.



- 2. To meet the rigorous specification requirements of gigabit-speed networks, every optical interconnect component must consistently produce an eye diagram that conforms to a predetermined eye-diagram mask. Using a "worst-case" fiber at 600 m, the vertical-cavity surface-emitting laser (VCSEL) still meets the conformance eye mask designed for Gigabit Ethernet**
- (a). Under the same conditions, the edge-emitting CD eye diagram shows significant degradation in the eye-opening (b). At extreme degradation, the link integrity will be compromised.**

It's also vitally important to keep in mind that the component must meet the eye-diagram mask test at more than just a single-point operating temperature. Typically, today's network-equipment manufacturers must design their systems for full test compliance at operating temperatures across a range from 0° to 70°C. Therefore, it is important that optical-interconnect component-level suppliers ensure compliance with the specification over the full operating range. This is especially true at the high end (70°C) where it's difficult to maintain output stability. Vendors can deal with this by extensive over-temperature device characterization and on-going production verification testing.

Initially, GbE implementations were cost constrained due to the need to use expensive, edge-emitting lasers for both long-wavelength (1000Base-LX) and short-wavelength (1000Base-SX) implementations. While edge-emitting designs remain the primary method for producing long-wavelength, Fabry-Perot (FP) transceivers, vertical-cavity, surface-emitting lasers (VCSELs) have emerged as a more effective method for creating short-wavelength transceivers. It does this at less than half the cost of edge-emitting FP lasers.

As gigabit-level optical networks move into wider deployment levels, requiring greater configuration flexibility, VCSEL-based GBICs open the door for cost-effective volume installations of 1000Base-SX solutions. VCSEL technology meets and exceeds the critical challenge of providing reliable signal propagation up to, and beyond, specified distances, all while allowing for straightforward packaging/ alignment methodologies and efficient production-level testing and verification.

As its name implies, a vertical cavity laser is formed through the vertical stacking of crystalline mirrors. Sandwiched within these mirrors are the epitaxial layers of an active, light-emitting semiconductor. As many as 120 mirror layers may be combined within a total thickness of <10 µm, to accomplish the required lasing action for a gigabit-speed communications interface. Unlike edge-emitting lasers, the output from a VCSEL is emitted from a relatively small area (5 to 25 µm) on the chip's surface, directly above the active region. An edge-emitting laser requires much more wafer area, due to the relatively long waveguide needed (200 to 500 µm).

From a practical standpoint, a VCSEL's physical structure yields many inherent design advantages like compact size and surface area, high reliability, and size and shape flexibility in the output aperture. Through tight fabrication control, VCSEL crystalline structures can also be specifically tailored to overcome DMD. This is done by optimizing their launch patterns to match the specific

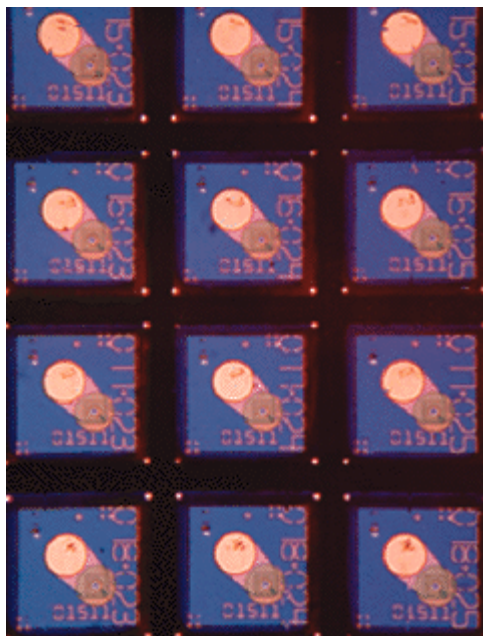
characteristics of existing multimode fiber-optic cabling installations.

A VCSEL's smaller size means that it requires much less operating current to turn the light pulse on and off. For example, a VCSEL's lasing threshold can be as low as 1 to 2 mA, while larger, edge-emitting FP lasers need about 30 mA to drive the lasing activity. VCSELs thus use less power and dissipate significantly less heat during normal operation. Not only do their lower power requirements increase circuit reliability, VCSELs also greatly simplify overall design challenges for the system designer. They do this by minimizing support-circuitry and power-supply requirements, while reducing the complexity of EMI compliance for the transceiver module.

VCSELs greatly reduce both the cost and complexity of creating a complete, fiber-coupled transmitting device. Traditionally, the need to hermetically seal edge-emitting lasers, combined with the alignment difficulties associated with their asymmetric diffraction patterns, drives up overall packaging costs. VCSELs provide high reliability without hermetic sealing because their active regions are buried several microns beneath the surface, with no exposed active facets. Non-hermetic VCSEL packaging can be designed with plastics instead of ceramics to further reduce materials costs.

Also, the output aperture of a multimode VCSEL is typically a 5- to 20- $\mu\text{m}$  circular aperture, producing a low-divergence circular beam. The VCSEL's vertically-emitted beam presents a straightforward mechanism for simple coupling of the device directly to the optical fiber. This minimizes the cost and complexity of packaging and alignment.

Because the VCSEL fabrication process produces a complete lasing device on the wafer, prior to scribe-and-break operations, it is possible to fully test every device while still in a wafer state. This allows designers to use highly efficient, semiconductor-oriented, step-and-test methods (*Fig. 3*).



**3. The VCSEL fabrication process produces complete lasing devices on the wafer. This way, every device can be fully tested while it's still in a wafer state, and therefore, take advantage of lower-cost semiconductor techniques. In contrast, edge-emitting lasers must be cleaved and separated to form their mirrors prior to testing.**

Unlike edge-emitting lasers, which must be separated and assembled with their mirroring structures prior to testing, a VCSEL allows interconnect component manufacturers to push the yield loss up into the lower-cost, wafer-state arena. Ultimately, this translates into the lower optical-interconnect-component costs that system designers need to meet higher volumes in the short-distance, fiber-optic-link GbE market.

The ability to monolithically produce VCSEL arrays also opens the door for expanded architectural options at the transceiver-module level. The combination of closer edge-to-edge spacing for discrete VCSEL devices, consistently uniform alignment characteristics, low power consumption, reduced heat dissipation, and minimal crosstalk susceptibility, allows designers to pack more interconnects within existing size and power constraints. The monolithic nature of VCSEL device manufacturing also has the potential to be adapted to support multiple lasing devices within a single chip-level package. Such configurations could someday provide the key for the practical implementation of parallel, optical-gigabit links.

As gigabit-per-second networks and data communications systems begin to rely on optical-interconnect technologies, the current combination of surface-emitting VCSEL technology for short wavelengths, and edge-emitting Fabry-Perot technology for long wavelengths, provides optimal cost/performance trade-offs for both 1000Base-SX and 1000Base-LX transceivers. It's also likely that future improvements to VCSEL fabrication processes will pave the way for cost-effective VCSEL implementations of long-wavelength (1300-nm) lasers. That will allow all of the VCSEL's reliability, alignment, testing, and cost advantages to migrate into 1000Base-LX transceivers as well.

From a systems standpoint, the flexibility to configure systems with hot-swappable transceiver components, instead of 1-by-9 soldered solutions, will provide a significant cost reduction. At the same time it will shrink the inventory levels needed to meet customer demand. The widespread adoption of the GBIC transceiver form factor allows today's solutions to be easily deployed within dynamic and diverse network topologies, laying the foundation for a smooth migration to tomorrow's innovations in optical transceiver technology.

*Tim Bour, president and CEO of Cielo Communications Inc., has over 20 years experience in manufacturing, product development, business planning, financial planning, and strategic marketing, including eight years in high-speed fiber optic components and transceivers. He received a BS in Chemical Engineering from the University of Cincinnati, Ohio, and an MBA from Ohio State University.*

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