Characterizing the Business Environment

The manipulation of information in the medium of light can provide some revolutionary benefits compared to the incumbent electronic approaches. Nevertheless, realizing those benefits requires significant changes in technology and in the supply chain that delivers and supports that technology. It is not surprising then, that a broad range of issues come in to play around the question of the adoption of optical interconnects. Ultimately, this adoption will only occur if it provides value. However, because of the fundamental change represented by the shift from electrons to light, this value must be evaluated from the perspective of the entire product life-cycle – from the cost implications in production to the installation implications in deployment to the operational implications in use. Additionally, the industry must be based around a level of revenue and investment that can continue to deliver the technological evolution needed to support the changing needs of emerging markets. This chapter will attempt to summarize some of the key issues within the business environment across this scope that encourage and impede the adoption of OI technologies.

**Working Conclusions**

1. The O-E-O interface is the critical focal point for understanding the future of the optical components industry. This is where the evolution of solutions will address communications costs.

2. The 10Gbps to 100Gbps transceiver are the relevant technologies concerning broad-scale optoelectronic adoption. Serious comments on Terabit Ethernet are emerging, but the interesting economic crossover will occur at these data rates.

3. The data rate for a single channel will likely standardize at 10Gbps (possibly as high as 20-25 Gbps) due to EMI and density/complexity limits of electronics.

4. Optical interconnects will migrate to a single mode, WDM standard in the long run (beyond the roadmap 2016), but initially we see short reach being multimode.

5. Standard transceiver components are entering the market in the sequence: telecom/datacom, server clusters, SAN, consumer electronics, mobile appliances.

6. The defining attributes for microphotonics markets will be total net COST, system density, power consumption, cable management, EMI shielding, heat management. Many of the technical and reliability issues have already been well demonstrated in telecom applications.

**Summarizing Fundamental Drivers and Barriers**

Central to this investigation is the role of the transceiver in the marketplace. Data generation and utilization continue to be electrical, and the role of optics in the communication system is as a transport technology. Conversion of electrical signals to/from optical signals, with the associated
improved information transport, is the core of the industry segment. Comparing the total costs and values of optical and electrical signaling within specific systems are then the issues of most interest.

Opportunities for convergence will occur in core device technology and packaging systems, allowing various products to be produced from common platforms -- analogous to the electronics platform. Historically, improved interconnect performance has not been viewed as yielding the same increased product functionality as data processing advances; nevertheless, it can become critical to realizing that value. However, emerging changes to computational design strategies and architectures increases the importance of the interconnects, as such, these are now, or soon will be critical to realizing performance improvements. Convergence onto existing low cost infrastructure technologies, ideally with the ability to integrate the processing and the transport drivers, is expected to provide the most benefit, reducing the need for dedicated equipment and devices and so reducing overall costs. The convergence to a common platform for optics and electronics will be driven by and limited by a combination of bandwidth density (bit-meters per second per (area | length | watt)) and packaging and interconnect costs.

The market driver for the transition to optoelectronics has been and continues to be the increasing requirement for high bandwidth links in many different applications. Requirements for 1 Gb/s transport in cell phones, 10 Gb/s transport in home entertainment, 100 Gb/s transport in home computers, gaming consoles, and communication clusters, up to 10,000-100,000 Gb/s in proposed high performance computing systems all lead to an unprecedented Bandwidth*Unit Volume requirement from the market and opportunity for the technology, while requiring drastic cost reductions compared to the existing optical systems.

In addition to the primary driver of bandwidth, optoelectronics are attractive because they overcome (or at least drastically limit) several other issues that hamper electrical data transport. These include

- resistive losses that compound over distance
- unconfined E-M radiation and
- power required to transmit and receive useable high speed signals.

Each of which are issues that have always challenged electronic based communication. As the aggregate transport rate has grown, the demand for higher line rates has pushed electrical transport to the limits of acceptable power, cost and complexity. EMI and crosstalk limit the achievable density, advanced signaling systems burn too much power trying to overcome non-idealities, and advanced assembly technologies and materials to improve the signals take the
systems off of standard platforms while providing limited improvements. O/E transceivers with optical transport provide an opportunity to radically improve the economics of data transmission.

Although market surveys indicate that the performance attributes around EMI and power consumption are becoming increasingly limiting for electronics and, therefore, may play a bigger role in adoption decisions. Because the value of these attributes is difficult to quantify, it is likely that optical systems must provide a distinct advantages before these alone would prompt adoption.

Initial results from these same surveys show that penetration of optics in the target markets is primarily hampered by

- costs
- lack of suitable infrastructure
- fragmentation of opportunities
- the general acceptance of the capabilities of electrical interconnect, even while the ability of electrical transport to deal with future requirements is limited
- additional investments required to change technologies, and
- risk, both at the firm and personal level, presented by implementing a new technology.

The latter reasons should not be downplayed. Optoelectronics, irrespective of the benefits they offer, represent a change from current solutions. As such, they face all of the challenges associated with unseating an incumbent. At an objective level this includes the investments required to implement the novel technology. More broadly, this includes the very real barriers of acceptance and comfort with a known solution and the risks, real or perceived, that go along with adopting something new. In the case of optics, these risks involve not only the economic risk of additional capital investment, but also some amount of technological risk as well.

In this context, we can see that the range of market demands from optical technology could continue to fragment the technology base, leading to the same poor economics identified in the phase I CTR. The goal here is to identify and promote the development of generally applicable technological solutions which can break out of the trap of small volume, customized solutions. An important consideration is the total addressable market, and the resulting sustainable R&D expenditure it can support. This R&D is most effectively used if it is making use of existing infrastructure, such as the large investment in Si CMOS fabrication facilities, and is globally focused on one (or a few) core platforms. (See chapter on Si photonics).

---

**The Inexorable Drive towards Optics: Trends in Data Communication Volumes**

The worldwide growth in servers [4], has a 5-year forward compound annual growth rate (CAGR) of 7% with a base of nearly 30 million units in 2007. Each server acts as source and sink for data communications as well as a host for intra-server data communications.

Storage growth [10], is experiencing a 5-year forward CAGR of 52%. This is a doubling about every 20 months. For 2007 the base rate is slightly more than 5 exabytes ($10^{18}$) per year. … The 5-year backward CAGR (on Internet Nodes [7,11]) is 27% with the 2007 base at nearly 500 million nodes. Finally, … The 2007 (internet [2, 3]) traffic is 6.5 exabytes per month and the 5-year forward CAGR is 46%. Using the Library of Congress number from above this amounts to some 650,000 passages of its printed content over the Internet every month in 2007.

With some poetic license we contemplate the union of the(se) four trends … to appreciate the implied increases in data communications. We could debate the precise quantification but it seems noncontroversial to appreciate that the increased number of servers, increased amounts of storage, an increased number of nodes on the Internet, and increased backbone traffic are all contributors to a rapid rise in data communication within the data centers.

Note that storage, Internet nodes, and Internet traffic are growing more rapidly than is the server unit count. A likely conclusion is that, over time, there is more data communication per server. This passes other litmus tests such as the increasing use of server consolidation and the use of virtualization in data centers.

A final, and important, point is that for each byte considered … there is a multiplier to be applied to quantify (still in a approximate sense) the data communications at all the levels in the data centers on which we are focused. Specifically, we estimate each byte read or written to disk storage causes $O(10^{10})$ bytes of overall communications. Each byte of traffic traversing the Internet causes perhaps $O(10^{9})$ bytes of data communications within one, or more, data centers. All of this places additional stress on the already pressured copper interconnects used throughout current servers and data centers.

**Emerging Technology Trends and Issues**

The O-E-O interface is a channelized system, which may also include physical multiplexing such as WDM or multi-fiber ribbon cables. Circuit trends (see the CMOS TWG) lead to a limiting bit rate of about 10 Gb/s (possibly up to 20 Gb/s) for the output from typical data sources through the span of this roadmap and beyond. At that rate electrical transport is at the limits of practicality across even 10” of circuit board. Conventional opto-electronic transceivers are typically used to provide improved transport over distances of more than a few meters. In these segments, there are an increasing number providing ever higher capacities in shrinking footprints. These transceivers are often pluggable into cages on the board and, combined with the pluggable optical cable, provide a flexible, interchangeable, interface between circuit cards.

The evolution of these transceiver offerings is to incorporate the transceiver module with the cable to form an electrically pluggable Active Cable¹ with guaranteed specifications between the two electrical interfaces. This approach hides the optics within the framework of the cable itself, relieving the manufacturer from having to maintain standards compliance with the other end, and relieving the user from needing any knowledge of optical link design.

---

¹ For the purposes of this discussion, an active cable is any point-to-point optical connection system with a natural separation from the system occurring in the electrical domain.
Beyond the current markets for data centers, active cables are particularly suited for applications such as Home Video or Handsets; the data rates and BW densities are not large and do not require technologically advanced optical solutions. These optical links provide an opportunity to mitigate the EMI associated with electrical links - a popular consideration in the mobile handset market.

The reliance on the suitability of a “standard” electrical interface leads to active cables being useful with total I/O densities up to about 200 Gb/s/cm². Beyond this density the electrical access between the active cable and the source IC becomes a significant impediment. Minimum pitch between conductors in the connectors is large, due to the effects of electrical signal density and line to line crosstalk. While some applications are concerned with areal density, many card-edge applications require maximized linear card-edge density. High density 2008 vintage 10 Gb/s connectors achieve about 30 Gb/s/mm.

Electrical signal spacing in PCBs goes up with increasing frequency (EMI shielding, crosstalk reduction, skin effect loss reduction), while optical waveguide pitch is independent of bit-rate. This provides a large advantage for optical waveguides at high frequencies.

In general, one would expect the transition from electrical transmission to optical transmission to occur closer and closer to the data source/sink as the aggregate BW increases. Obvious breakpoints are on-chip, chip-to-chip (and chip-board), board-to-board and box-to-box optical communication. (See Figure 1.) Some of these applications are expected to evolve rapidly, requiring ever larger bandwidths and bandwidth densities with lower power, size and cost. For very high I/O density circuits, it is expected there will be “active sockets” feeding the optical links.
These will allow conventional packaged circuits to interface over very short (low parasitic) electrical distances to the O/E conversion elements. These sockets may also provide an additional level of spatial fan-out to facilitate I/O access. Eventually the optics are expected to move out of the socket and into the chip package, possibly with stacked die, or possibly moving directly to optical I/O incorporated directly on the chip. The next stage would be to use optical communications within the chip. (See Figure 2 for a schematic representation of this progression.)

![Figure 2. Expected evolution of interconnection architectures](image)

A limiting case is the I/O requirement from a circuit card with multiple processors as envisaged in the ITRS roadmap around 2017. With each processor die or SiP operating at up to 80 Tb/s bidirectionally (160 Tb/s total I/O) the package area required for the 16,000 I/O pins, even at the limiting 0.5 mm BGA pitch, is about 60x60 mm$^2$. Optical pins provide an opportunity to spatially multiplex the signals using WDM. 40 channel WDM would require each wavelength cell to have about 80 $\mu$m 2-D pitch to match the 500 $\mu$m 2-D pitch of the BGA package.

The transition from evolving commodity products to radically different solutions for certain markets appears to require the input and nurturing of a large, vertically integrated, company. The company must be able to place large bets, deal with excess costs, and be able to make profit from one layer in the product space while introducing cost at other layers. Often, especially with early technologies, the value of an innovation occurs at a location in the balance sheet far removed from
the cost. This is almost untenable, due to typical accounting pressures to reduce costs, for a stratified commodity market. Only time will tell as to what industry structure is necessary to realize the adoption of optical interconnects on a broad scale. However, it is clear that there have been many trials and demonstrations of the technologies for optical interconnects. The fundamentals have been shown to work. The lack of commercial success results more from the introduction costs and market barriers than from missing key technologies.

### Understanding Total OI Systems Costs

As with any new technology, optical interconnects (OIs) in their various forms will be adopted based on the interdependent issues of the value\(^2\) that OIs bring to the end-user and the associated net cost of deploying and operating OIs to realize that value. Given that reality, it is interesting to explore what issues should be considered in trying to estimate this cost/value proposition. Much of the roadmap discusses the performance (e.g., bandwidth-distance, bit-error rate) characteristics of OIs that ultimately provide value. As such, that topic does not need further elaboration. However, it is useful to identify the characteristics of OIs that can translate into reduced net life-cycle cost—so-called cost-of-ownership (COO). Within various roadmapping discussions, three direct expenses have been identified as potentially contributing significantly to the COO of OIs: i) acquisition and deployment, ii) operating expenses, and iii) maintenance.

The first is the upfront cost of acquisition and deployment. Generally, when compared simply in terms of cabling and transceivers, OIs are more costly than their copper-based analogs. However, this perspective can overlook other significant deployment costs. Specifically, for installations with sufficiently high distance-bandwidth requirements, OIs can eliminate the significant expense of repeaters.

The second COO issue of note is operating costs, or more specifically, energy costs. OIs have the potential to significantly reduce the energy required for data transmission. The realizable amount of this savings is strongly dependent on design and layout decisions. For copper-based installations requiring repeaters, OI-derived energy savings can be large. For other cases, the savings may be limited due to system hardware design limitations. In the case of Active Optical Cable (AOC) installations, energy savings may be small unless the electronic transmission hardware is able to throttle back energy usage. For large datacenters, the value of any energy savings associated with OIs may be amplified by the reduced cooling requirements associated with the inefficient supply of that energy to the interconnects. However, the larger energy benefit associated with OIs may derive from their smaller physical dimensions compared to copper interconnects. In some contexts, this smaller size can translate into reduced impediment to airflow and, therefore, more efficient (and less energy intensive) cooling.

Another operational benefit of AOCs, resulting from the full encapsulation of the Optical Interfaces between the pluggable electrical connector interfaces, is the elimination of requirements for the training of installers in the use of optics and optical link design, and the elimination of optics related procedures such as power monitoring, connector cleaning, and eye-safety related processes.

The final pertinent direct COO issue is hardware maintenance. Changes in interconnect failure rates translate directly into changes in requirements for maintenance labor and replacement components. Indirectly, significant changes in reliability may alter the extent of required redundancy within a system. Future work is needed to characterize the specific impact of OIs on maintenance frequency.

It is worth pointing out that some of the above changes associated with OIs can indirectly lead to other forms or value or cost savings. In particular, for installations that are constrained by available space, energy input, or cooling power there should be cases where the performance associated with OIs (e.g., reduced footprint or reduced energy use) could translate into the ability to install more compute power within the facility. The increased computational or data-handling throughput of that change can have a high value for some potential users of OIs.

---

\(^2\) Because of the inherent ambiguity between value and cost, value here is being used to represent performance attributes that would increase revenue. The same term is frequently used to describe performance attributes that save money. The latter will be ascribed to the heading of net cost.
**Market Insights**

**Automotive Market**

In a 2006 social trends report on the travel behavior of people in the US, the Pew Research Center observed that people are spending more time in their automobiles each year; the number of trips and vehicle miles traveled per person as well as the average time spent in traffic delays per person have all increased between 1991 and 2003 [7]. Over the past decade, the amount of time that the average person spent waiting in traffic increased 56 percent from 16 hours in 1991 to 25 hours in 2003 [7]. The increase in the time spent in cars has helped promoted an increase in consumer demand for additional “electronic functions that benefit drivers directly: safety, entertainment, information and comfort” [8]. The response of automobile manufacturers to this shift in consumer expectations could provide opportunities to incorporate optical interconnects in automobiles. To gain a preliminary understanding of the automobile market, qualitative interviews with the leading automakers and industry associations were sought. Ultimately, representatives from two companies participated in qualitative interviews. A broad literature search was also executed to further investigate the technology attributes and market volumes of the emerging applications identified in the interviews.

The insights gained through interviews suggest that most optical interconnect adoption opportunities in the automobile market are driven by a growing number of wired in-vehicle networks installed in automobiles. Available literature regarding wired in-vehicle networks indicates that twelve different network protocols are currently offered in the automobile market [9]. Depending on their intended use within a vehicle, the different types of networks are organized into three broad categories: Body Control, Advanced Driver Safety, and Infotainment [10]. In any given vehicle, one or more of wired networks “can co-exist to deliver the right combination of data rates, robustness, and cost” as shown in Figure 3 [10].

---

3 Based, with minor edits, on the thesis of CTR Fellow Johnathan Lindsey.

4 Alternative in-vehicle network categories have been offered. SAE classifies in-vehicle networks based mostly on speed (Class A – low speed, Class B – medium, Class C – high speed). Frost and Sullivan has group network protocols into four categories (General Purpose, High-Speed Safety, High-Speed Infotainment, and Low-Speed Smart Sensor) [8].
Most “Body Control” networks installed in passenger vehicles today control safety and comfort applications that span from engine management to anti-lock brakes to power locks and windows. In this market space, the Controller Area Network (CAN) and Local Interconnect Network (LIN) protocols are the most used.

CAN is a two-wire serial bus system that supports high-speed communication among microcontrollers, sensors and actuators throughout a vehicle using a multi-master architecture where devices can broadcast messages asynchronously. CAN operates under two internationally recognized standards: ISO 11592 standard for low speeds up to 125 Kb/s and ISO 11898 standard for high speeds up to 1 Mb/s [9]. CAN is utilized mostly for power train management and safety applications [10].

LIN is a low cost serial communication system that connects intelligent sensors and actuators throughout the vehicle via a single wire. LIN operates up to 20 Kb/s over a maximum cable length of 40 meters. The devices supported by LIN have very specific functions and do not require the higher bandwidth made available by CAN [9]. These networks are generally implemented as subsystems of a larger CAN network structure.

Advanced Driver Safety networks in vehicles allow sensors from multiple subsystems (braking, steering, and suspension) to communicate with each other in order to achieve a safer, more comfortable driving experience. In order to operate effectively, these systems must transfer data at high speeds as well as include multiple layers of redundancy. One example of an advanced driver
safety network is Flex Ray, which includes an optical bus to control serial communication in a vehicle’s adaptive drive chassis. In 2007, BMW became the first to use this technology in standard production vehicles when it began installing Flex Ray in its X5 series.

Infotainment networks allow multiple media devices such as phones, MP3 players, video, and navigation systems to connect and communicate with each other in an automobile. The dominant technology standard that has emerged in this market space is the Media Oriented Systems Transport (MOST) Network, which was designed around a single optical fiber bus. The most recent specifications require possible network bandwidth to reach 25 Mbps over optical fiber. Current roadmaps forecast network bandwidth to increase 150 Mbps over optical fiber in 2013 with the goal of supporting 64 total consumer electronic devices in an automobile. There are two major advantages that are contributing to the success of MOST in this market space. First, MOST networks are designed to scale easily to accommodate new components added to the system. Second, these networks are designed to minimize added costs and their use of plastic optical fibers instead of copper decreases the overall weight of the vehicle.

Of the three types of networks, infotainment systems represent the greatest opportunity for optical component adoption in the automotive market. Although CAN and LIN network components enjoy greater market penetration among passenger vehicles in North America (shown in Figure 4), the low data transfer rates achievable using these protocols are insufficient for future applications. As CAN and LIN continue to reach maturity in the market, the overall number of applications supported by each of these protocols could decrease over time with the continued development of higher-speed, higher-bandwidth protocols (such as Flex-Ray and MOST).

---

5 In vehicles with the Adaptive Drive Chassis System, each axle has its own independent motor that can adjust the dampers on each individual wheel. When the road surface under one side of the vehicle differs in character from that on the other side, the Flex Ray instantly adjusts the suspension settings of the wheels on one side to practically eliminate any perceptible unevenness in the road.


7 Copper is much heavier than plastic optical fiber.
However, the deployment of such networks in the light vehicle market has been limited mostly to the luxury vehicle segment of the automotive market over the next five years. While many of the advanced driver safety networks that require optical components and optical fiber have still yet to be introduced, the MOST network remains the only major viable opportunity to incorporate optical interconnects in the automobile industry.

Furthermore, extended forecasts from 2005 to 2010 suggest that the number of higher-bandwidth MOST components installed in vehicles worldwide will continue to rise as infotainment networks become more common in mid-range and possibly low-end, compact vehicles. [11]

Interestingly, trends within components adoption across these network types may also facilitate the migration to advanced optoelectronic integration strategies. This is the case because these networks rely heavily on relatively thick SOI substrates. These substrates should be also suitable for the fabrication of SOI-based silicon waveguides and other photonic components, thus facilitating monolithic photonic-electronic integration.

As described above, the automobile industry has already begun to utilize optical interconnects; however, cost remains the major limiting factor to the increased installation of these wired networks across a broad range of light vehicles. The average cost per node for these emerging networks remain much higher than cost levels desired by automakers.  

---

[8] At the end of 2005, both MOST and Flex-Ray node costs averaged around six dollars per node [9].
High-Performance Computing

High-Performance Computing (HPC) refers to computer systems that provide close to best currently achievable sustained performance on demanding computational problems. As defined by the *Dictionary of Science and Technology*, an “HPC system can be an extremely powerful, large capacity mainframe computer that is capable of manipulating massive amounts of data in an extremely short time or a [single] computer within a larger set of networked computers” [12]. Originally limited to scientific research only, use of HPC systems have been extended to a broad range of applications including business, defense, and even media. Over the last decade, there has been continuing rapid improvement in the capability of HPC systems; a cursory review of the Top 500 fastest systems in the world show that mean performance has improved by roughly 80 percent annually since 1993 [13]. As computing processor performance for systems in this market space continues to improve, the performance of interconnect network has become a critically important factor that must be considered when evaluating the overall performance of an HPC system.

Servers in a modern data center environment can employ a hierarchy of interconnects that span a wide range of link distances, costs, and bandwidth requirements. Interview participants identified three areas in the HPC market where optical interconnects could be implemented: Box-to-Box, Board-to-Board, and Chip-to-Chip.

Box-to-Box interconnects are used to connect multiple server backplanes together within a single rack or across several adjacent racks in order to transfer information between each other. Depending on size, there maybe tens to thousands of box-to-box interconnects between individual servers depending on the size of a given system. Link lengths for box-to-box interconnects can span wide range. For shorter connections, link lengths can range from one to ten meters. For much longer connections, link lengths can range from ten meters to as much 100 meters. Optical box-to-box interconnects can be implemented using optical transceivers natively installed in the server backplane or by using Active Optical Cables (AOCs) connectors to perform the electrical-to-optical (or vice versa) conversions externally to the server⁹.

---

⁹ Active Optical Cable (AOC) Connections are optical fiber connectors that are delimited by optical transceivers. These connectors plug directly into servers, network switches, and storage devices that use electrical interconnects; AOC’s perform the electrical-to-optical conversion externally to the device, and transmits data using light.
The Market Potential of Active Optical Cables


Active optical cables offer a significant leap in performance over their copper cable cousins. While they are aimed to connect to the same electrical interfaces, their innate design characteristics allow them to offer their users significant benefits, including: i) Longer effective cable length limits; ii) Lighter, thinner, more flexible cables; and iii) Far better low Bit-Error-Rate (BER) and EMI/RFI characteristics.

Few new markets for optoelectronic interconnects offer the opportunity for revenue and revenue growth shown by active optical cables. Revenue is expected to increase from $221 million in 2009 to over $2.4 billion by 2013. Over the same period, shipments are expected to grow from 2.0 million units to 74 million. A large portion of this growth derives from faster digital interface usage, causing a significant shift from copper cable usage. One of the drivers for this success is tied to advances in fiber core materials. These changes have yielded cost savings which are being passed on to the end customers.

High Performance Computing Centers (HPCC) have led the traditional active optical cable focus in terms of volume and revenue. By 2009, HPC will be matched in revenue from the PC segment, and more than doubled by the HDTV segment, all at a time when HPC is still growing. By 2013, HPC will be reduced to ~5% of overall AOC revenue, even after ~4.5x growth from $52 million to $134 million. Over this same period, HDTV will continue to grow over 8 times, from $102 million to nearly $825 million, but slip to 34% share. This displacement in both HPC and HDTV is caused by PC active optical cable revenue growing nearly 30 times from $55 million to nearly $1.36 billion, giving this segment a 56% share by 2013. The following charts illustrate the overall active optical cable market segmentation by application type. Separate charts are given for Years 2009 vs. 2013 so one can identify shifts in market share over this time period.

The costs of the optoelectronics devices used to create AOCs are expected to continue to decline as volume demand for these units grows. Make no mistake, copper cabling will still be around for many years, especially in the shorter cable versions, but we should start to see a shift towards optical interconnects which should only grow as systems OEMs continue to press for higher performance both inside and outside their boxes. While many people are attracted to wireless linkage of their equipment, in many cases a cable connection using AOCs will prove far more effective in terms of overall delivered bandwidth and connection reliability, especially in areas where real-time data delivery is critical.

For further information regarding this article, kindly contact Tom Rossi at tbits@mac.com or KaanapaliTom@yahoo.com

Board-to-Board interconnects are used to connect subsystems on different boards. The normal link length range of these interconnects is 0.3 meters to 1 meter. For larger systems, two to 16 boards are often plugged into a central backplane that contain the interconnect links between the boards.
Because of the high cost required to implement optically, board-to-board connections and backplanes are generally electrical. For the highest performance systems, “the pluggable interconnect between a board and the backplane are pushing the limits of incumbent copper interconnect technology; [in some systems], the total bandwidth through the board edge can be bottleneck” [14]. In order to enable the photonic transfer of digital information at the board-level would require the integration of optical components on or at the board’s edge.

Several interview participants also expressed interest in the possibility of creating optical interconnects between multiple chips on a board. Current chip-to-chip interconnects are usually implemented with electrical pathways between two or more processor chips on a single board. The link lengths for this category of interconnects range from 1 cm to 50 cm [15]; and depending on its size, a given system could employ thousands of chip-to-chip interconnects [14]. Replacing the incumbent electrical technology with optical components would require a solution that tightly integrates the printed wire board and optics.

Figure shows the Optoelectronics Industry Association’s (OIDA) estimates of production volumes for optical interconnects at the different levels within the HPC market. As one moves closer to the board and realize decreasing link distances, the potential market for short-range optical interconnects within the HPC market increases dramatically.

![Figure 6: Potential Optical Interconnect Volumes in HPC Market [15]](image)

Challenges to optical interconnect adoption exist at all three levels of the HPC market. At the box-to-box level, optical transceivers are currently mass-produced; however, the relatively high cost
premium persists as a factor limiting increased adoption of these components in servers, networking, and storage equipment employed in data center facilities. Interviews and literature suggest that the biggest technical hurdles to further optical interconnect adoption lie at the horizon of board-to-board and chip-to-chip interconnects. For those studying both board-to-board and chip-to-chip interconnects, the biggest challenge is to design printed circuit boards that integrate optical components and are amenable to suitable manufacturing processes. While the potential number of electrical pathways that can be replaced by photonic technology increases dramatically at the board and chip levels (shown in Figure ), the degree of integration between photonic and electronic technologies on printed circuit board have only been demonstrated in laboratory research [16, 17].

In the end, all of the traits that make HPC applications a promising market for optoelectronics adoption are rapidly becoming characteristics of a broad array of IT applications. The rapidly growing demand for communication and computation continue to drive up the number and size of server and storage clusters. As the performance demands of these climb, so does the opportunity for optical interconnects.

**Identifying Emerging Drivers**

Historically, most interconnect selection decisions have centered around the performance metrics of cost and bandwidth*distance capabilities. Given the trends occurring within the HPC markets a number of decision-makers in this industry were asked: “How important are the following metrics for trade-offs made during interconnect technology selection?” The interview participants were largely in agreement when asked to identify metrics considered useful in their evaluation of HPC interconnects. Table 1 shows the average of responses. While nearly all respondents ranked cost effectiveness as possibly the most important metric, most viewed that energy density as a very important ancillary metrics to consider when evaluating the trade-offs for an optical interconnect technology.

---

10 In interview process, some participants noted that the PCB manufacturing is a dirty process that is often unsuitable to the strict requirements for a clean manufacturing space necessary for optical components.
Table 1: Important Metrics for Component Adoption in HPC Markets

<table>
<thead>
<tr>
<th>Metric</th>
<th>Possibly the Most Important</th>
<th>Very Important</th>
<th>Important</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faceplate Density (Gb/s/inch)</td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Board Density (Gb/s/in^2)</td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Energy Density (Gb/s/W)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost Effectiveness (Gb/s/$)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Energy is a major concern that is also echoed at higher levels in the HPC market as data center managers and professionals have expressed similar concerns at larger, system-wide levels. In a 2006 study, the Aperture Research Institute conducted interviews with more than 100 data center professionals working across a wide range of industries [26]. From those interviews, the study concluded that energy has become a major area of concern for the IT industry. Highlighted in red in Figure 5, the growing pressures on power distribution systems and cooling infrastructure top the concerns that data center managers have when assessing the capacity of their facilities. Furthermore, interview participants also expressed concern that their businesses were being put at risk as the tools and processes needed to manage growing infrastructure demands have not evolved even as data centers have grown in complexity.

Figure 5: Managing Data Center Capacity – Important Factors [26]
Over the last decade, network traffic has been increasing by nearly 2X every year. This trend has been driven by the explosive popularity of video-sharing services such as YouTube. P2P, VOD, and emerging “remote presence” services, are expected to further increase the demand for network bandwidth. This trend, however, casts a shadow of looming energy issues to power the ICT that satisfy the bandwidth demand.

Figure 1 plots the total electrical power consumption of just IP routers in Japan (Source: METI and MIC). From the figure, it is obvious that power consumption tracks closely with network traffic. The figure also indicates that the IP routers consumed approximately 1% of Japan’s total electricity supply in 2006. Following the traffic forecast, it is paradoxical that IP routers would soon require more power than the country’s entire electricity supply.

Further compounding the problem, it is not just IP routers that drive ICT energy consumption. In fact, the energy consumption of the data centers as well as wireless networks is also becoming critical. In 2004, the data centers in Japan already used more than 10 TWh only for servers (MIC), and therefore a few percent of the total electricity supply of Japan if we include the power consumption for air-conditioning. Additionally, the power consumption of wireless mobile networks tends to increase more critically with the bandwidth increase than wired ones [J. Baliga et al., OFC NFOEC 2008, OThT6].

Although the statistics mentioned above are for Japan, the energy issues would be expected to grow more serious when we generalize to the world. First, the ICT-advanced countries are more or less in similar situations to Japan’s case. However, the more concerning trends emerge outside of the developed countries. According to the White Paper on Information and Communications published by the Japanese Government in 2005, the global penetration ratio for broadband services is merely 3.35%. Clearly this will grow significantly as will the energy requirements to drive it.

Likewise, the energy reduction of ICT is a critical issue when we discuss the energy reduction ‘by’ ICT. Given these trends, we must develop a technology that can meet bandwidth demand at almost the same energy consumption as the today’s equipment. One possible solution involves the incorporation of optical interconnects. That is, what if we replace IP routers by optical switches where the line rates are larger than 100 Gbps in the future network? The use of optical switches has a truly outstanding feature in terms of energy savings, as is illustrated in Fig. 2. Consider a network accommodating 256 users with an 160 Gbps interface, equivalent to an aggregate throughput of approximately 82 Tbps. This bandwidth requirement is comparable with that of the fully loaded Cisco CRS-1 router that requires a power supply of more than 1 MW. By comparison, a 256 x 256 MEMS switch in the star topology requires only half the number of optical transceivers and less than 100 W [S. Ide, et al., ECOC2003, MO3.5.1], a reduction of energy by four orders of magnitude.
Figure 2. IP router based packet switching versus MEMS based optical path switching for a user line rate of 160 Gbps.

Of course, to compare these two solutions completely we should take into account the additional energy consumption for the optical components necessary to scale the network such as large-scale optical switches, optical amplifiers, dispersion compensators, wavelength converters, performance monitors, optical regenerators, etc that are yet to be developed. Despite this, the massive energy savings suggested by the switches and transceivers alone raises the question as to whether photonic devices could enable a novel, dramatically energy-saving high-capacity network.

Obviously, identifying the ultimate role of photonics in future ICT equipment is not an easy task: It may take global research activities in which proactive, cross-layer, interdisciplinary processes under academic and/or governmental initiatives are the key. Although the exact roles of photonics in future networks has to be studied much further, it is almost certain that, as a result of the forthcoming network-computer-storage convergence, agile all-scale optical path networks will play a major role in both energy savings and high capacity at every level of ICT equipment.

---

**Consumer Handhelds**

The consumer handheld industry encompasses a broad range of devices such as cameras, mp3 players, mobile phones, and personal digital assistants. In the consumer handheld industry, mobile phones have become a particularly interesting market segment as the current trend to consolidate multiple communications and web applications into a single device continues to strengthen. Real-life examples of this trend include camera phones and smart phones\(^\text{11}\) that can access digital information through wireless internet and proprietary cellular networks. As a major consequence of that trend, higher bandwidth requirements for high-definition handset displays and higher download speeds to transfer information from a personal computer to the device have become major drivers for optical interconnect adoption in the mobile phone market. Experts in the mobile phone industry agree that future bandwidth requirements for handset displays are a driving motivator to integrate optical interconnects in their devices. Figure 6, below, shows the handset display bandwidths required by high-end phones between 2001 and 2007; since 2002, pixel

\(^{11}\) No industry standard definition exists for smart phones, but many smart phones resemble miniature personal computers as they can include operating systems, wireless internet/email, digital organizers [18].
bandwidth in phone displays has roughly doubled annually. A similar trend has also been observed in the pixel-resolution of phone cameras; image quality has increased from 110 K pixels in 2000 to three million pixels in 2004 [19]. Over the next five-year period, several analysts and reports predict that the growing bandwidth required by imaging applications will continue; by 2012, high-definition displays could be a common feature in high-end mobile phones.

**Figure 6: Bandwidth Trends for Mobile Phone Displays [19]**

Though not cited as often, some have also noted that a higher speed connection to external devices as a driving force for utilizing optical interconnects. Converged mobile devices and smart phones are quickly becoming portable gateways that enable constant wireless connectivity to a wealth of online information and communication. Though there are multiple factors pushing this trend, trends in memory technology for consumer devices is a disproportionately significant factor. As one of the top three cost components in camera phones and smart phones, the mobile electronics industry has benefited enormously from “dramatic increases in storage densities of flash memory” [20]. Larger storage capacities allow smart phones and other mobile devices to take advantage of more complex software and media; thus, the files that need to be transferred from device to another are growing and the time needed to transport those files is taking longer. Optical interconnects could be useful in accommodating the larger transfer loads at higher data rates capable with current copper connectors.

It is worth noting that despite these trends, many familiar with more traditional markets for optical interconnects would not view these projections for bandwidth requirements as sufficiently high to warrant the transition from an electronic to an optical solution. The consumer handheld market, however, presents some additional constraints that motivate this interest. In particular, the tight
packaging requirements for handhelds put pressure on every aspect of interconnect footprint. In the interest of saving space even conventional shielding may not be feasible. As such, optical components may have an opportunity to deliver connection functionality without being susceptible to EMI issues. In addition to saving on package space, optical interconnects offer the opportunity to reduce energy consumption in an environment where power is highly valuable.

A cursory examination of worldwide mobile phone sales is useful to illustrate the shift in technology trends that later create the aforementioned opportunities for the adoption of optical interconnects in the mobile phone market. Figure 7 shows the mobile phones sold between 2004 and 2007; the estimated sales forecasts up to 2011 were derived from the historical data using linear regression. By 2004, sales of camera phones more than doubled that of basic phones. Between 2004 and 2007, this segment of the market continued to see strong growth in popularity; sales of these phones jumped from 442 million units to 742 million units annually. Beyond 2008, sales of camera phones are predicted to grow but at a more moderate pace of 4 percent CAGR compared to 14 percent CAGR between 2004 and 2007. During the same period, smart phone sales rose rapidly from 16 million in 2004 to over 121 million in 2007. And, between 2008 and 2011, smart phones sales are expected to grow at 21 percent annually. In contrast, demand for basic phones flattened in 2004 and 2005; however, sales in this market segment have begun to fall and will continue to do so in the foreseeable future.

![Mobile Phone Market (2004-2011)](image)

Figure 7: Worldwide Mobile Phone Sales, 2004-2011 [21]

Like the HPC market, significant technological barriers limit optical interconnect adoption in mobile phones and consumer handhelds; the successful integration of optical interconnects in
future mobile devices will require substantial architectural and manufacturing challenges to be solved. However, incorporating optical interconnects in mobile electronics has its own unique set of challenges. First, manufacturers will have to find a way to incorporate optical interconnects without increasing the overall footprint of the device. Since the introduction of the first cell phone to the market, manufacturers have consistently found ways to decrease the physical dimensions; between 1983 and 2006, major mobile phone producers have reduced the average size and thickness from 50 mm to currently 10 mm [19]. Second, efficient power consumption is critical to component adoption. Currently available mobile phones are expected to achieve a certain amount of talk time and idle time using a single charged battery. Phone manufacturers must design an optical interconnect that, when used, will not significantly reduce the level of battery performance currently expected by consumers. To achieve this goal, principal scientists at the Nokia Research Center estimate that power consumption by future interconnects would need to undergo “an order of magnitude reduction” from current levels to approach 1mW/Gbps for each connector [22].

Furthermore, mobile phone manufacturers will also have to address the above technical concerns under tight unit cost constraints caused in part by intense competition for market share among producers of mobile phones and other handheld electronics. In the compiled set of public statements, all subjects expressed the necessity for future optical interconnect solutions to approach a cost comparable to current electrical interconnect solutions. Displaying a breakdown of the 14 most expensive components in two different phone models, Figure 8 gives a rough estimate for the target costs for potential optical interconnect solutions. In each case, the printed circuit board and connectors (the two more important components in an integrated opto-electronic solution[12]) comprised approximately six percent of the total unit production cost. For future optical interconnects, the research scientists estimate the unit cost to approach $1 per Gbps in three to five years for internal serial connections reaching 5 Gbps in their public statements. Assuming the average smart phone or camera phone will require 5 Gbps in bandwidth in the next three years, mobile phone manufacturers will need to decrease the cost of an integrated solution by at least one dollar [23].

[12] In an April 2007 presentation, Opportunities in Optics for Mobile Devices, Leo Karkkainen noted: “Main possibility of taking into use higher level of optical interconnections in mobile multimedia computers is seen with the development of direct optical interfaces integrated in CMOS chips. These would provide high bit-rate serial connections, mainly for imaging applications.” [22]
Targeted Application

Table 2 summarizes the barriers, potential market volumes, and estimated time to adoption of optical components for several industries. Considering these three factors, HPC Box-to-Box (and the broader data center market of which it is a bellweather) and the automobile markets are the most significant emerging markets for optical interconnects in the near term. Although they may have smaller potential volumes relative to other market segments, the barriers to adoption do not seem to be as challenging as those for mobile phones, HPC boards and computer chips. In each of those industries, the adoption of optical interconnects would require a level of integration between electronics and photonics that is yet economically feasible to produce; furthermore, both the literature and interview responses collected thus far suggest that the technology and manufacturing processes necessary to create the integrated opto-electronic PCB will not be available in the mid-term (less than 5 years).
Table 2. Primary Market Insights

<table>
<thead>
<tr>
<th>INDUSTRY</th>
<th>BARRIERS</th>
<th>POTENTIAL MARKET VOLUMES</th>
<th>TARGET TIME TO ADOPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automobiles</td>
<td>Cost</td>
<td>Tens of Millions</td>
<td>Now</td>
</tr>
<tr>
<td>Mobile Phones</td>
<td>Cost, Power, Size</td>
<td>Hundreds of Millions</td>
<td>5 Years</td>
</tr>
<tr>
<td>HPC Box-to-Box</td>
<td>Cost</td>
<td>Millions</td>
<td>0-5 Years</td>
</tr>
<tr>
<td>HPC Board-to-Board</td>
<td>Technological</td>
<td>Tens of Millions</td>
<td>5+ Years</td>
</tr>
<tr>
<td>HPC Chip-to-Chip</td>
<td>Technological</td>
<td>Billions</td>
<td>10+ Years</td>
</tr>
</tbody>
</table>

Results from additional quantitative interviews conducted with professionals specializing in the HPC market segment indicate that energy is a primary concern that is considered when evaluating the merits and disadvantages of new interconnect technologies.

Interestingly, adoption of AOCs in the HPC arena, has the potential to drive down the cost of that technology and, thereby, provide the market seed needed to accelerate the acceptance rates of optical links in other markets such as home entertainment application. At least one study suggests that in 2009 HDTV applications will begin to be a significant consumer of AOCs, and that by 2013 such uses could dwarf the HPC usage. As a consequence, the HPC and broader datacenter market is a key testing ground for high volume optical interconnects.

**Examining Revenue and Possible R&D**

Examining the implications of even just one of the emerging markets outlined above provides some insight into their potential for the future of optoelectronic components. To explore this in detail a series of interviews were conducted with key decision makers throughout the datacom and compute market value chain (chip, component, and system manufacturers.) Table 3 summarizes the averages of the responses to those interviews. Clearly the interview respondents project that the datacom and compute markets will represent a strong source of growth for the optical components market.

Table 4 combines this information with data from IT Hardware Research (2007) that projects the market for high performance computing and servers to project the financial implications of this market. As these calculations make clear, although the compute market in 2007 was a small fraction of total optical component sales, by 2016 survey respondents expect that the compute
market could easily dwarf current-day telecom markets and could represent billions in components revenues.

Table 3. Cross market survey results, Datacom

<table>
<thead>
<tr>
<th>Year</th>
<th>Data rate per link (Gbits)</th>
<th># Link/system</th>
<th>Data rate per system (Gbits)</th>
<th>Data rate per system (Tbits)</th>
<th>$/Gbit/s</th>
<th>% Optical (of server market)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>11</td>
<td>158</td>
<td>1,500</td>
<td>1.5</td>
<td>$4.40</td>
<td>1%</td>
</tr>
<tr>
<td>2010</td>
<td>36</td>
<td>634</td>
<td>12,908</td>
<td>12.9</td>
<td>$2.00</td>
<td>10%</td>
</tr>
<tr>
<td>2013</td>
<td>72</td>
<td>1,640</td>
<td>52,333</td>
<td>52.3</td>
<td>$1.15</td>
<td>20%</td>
</tr>
<tr>
<td>2016</td>
<td>122</td>
<td>4,348</td>
<td>247,500</td>
<td>247.5</td>
<td>$0.74</td>
<td>35%</td>
</tr>
</tbody>
</table>

Table 4. Server volume projection (IT Hardware Research 2007)

<table>
<thead>
<tr>
<th>Year</th>
<th>Server volume (k)</th>
<th>Optical server volume</th>
<th>Optical system volume</th>
<th>Aggregate BW (Tbit/s)</th>
<th>Projected Associated Revenue ($M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>7,100</td>
<td>71,000</td>
<td>1,775</td>
<td>2,663</td>
<td>$12</td>
</tr>
<tr>
<td>2010</td>
<td>9,450</td>
<td>945,010</td>
<td>23,625</td>
<td>304,963</td>
<td>$610</td>
</tr>
<tr>
<td>2013</td>
<td>12,578</td>
<td>2,515,617</td>
<td>62,890</td>
<td>3,291,265</td>
<td>$3,785</td>
</tr>
<tr>
<td>2016</td>
<td>16,741</td>
<td>5,859,500</td>
<td>146,488</td>
<td>36,255,656</td>
<td>$26,829</td>
</tr>
</tbody>
</table>

This funding consideration is critical to establishing a viable route for profitable evolution of optical penetration. High volume deployments require significant investment in R&D as well as operating capital for factories. The evolution from AOC for HPC toward more price sensitive AOC for Consumer Video demonstrates a symbiotic evolution path. Similar models may need to exist for on-board optical interconnects (e.g. re-use of low cost AOC engines from consumer for high-end applications on the board. Silicon Photonics, with its ability to ride the Si electronics fabrication development, is likely the only platform which can provide the cost and size scaling needed to provide a single source technology capable of meeting the requirements of the high pin-count, low cost-per-pin market.
Thoughts on Long-term Industry Structure
(This section based, with minor edits, on the Master’s Thesis of CTR Fellow Shan Liu.)

The competitive landscape of the OE components industry is fierce. It is characterized by sophisticated technologies, diverse performance requirements, fast paced product development cycles, and high rates of price erosion [16]. As outlined in Table 3, the OI industry differs from the broader microelectronics industry in many ways.

Two possible business models for the OI components industry are platform and vertical. In the platform model, a company owns in house R&D, sales, and marketing, but outsources the majority of its manufacturing to third parties. On the other hand, in the vertical model, a company owns the entire product delivery chain, from R &D, to manufacturing, to sales and marketing of the product [13]. The OI components market could also be divided into high-end and low-end market segments. High-end usually consists of telecom components that have high performance requirements but with low volume (e.g. tunable lasers, 300 pin MSA’s). Low end consists of enterprise components that have much higher volume but lower performance variability (e.g. gigabit Ethernet, 10G XFPs).

Common beliefs from the semiconductor industry support a vertical model for manufacturing low-end products because vertically integrated companies can take better advantages of economies of scale than companies that outsource their manufacturing. The best model for the OE components industry is less clear. Both of its high-end and low-end market volumes are quite low compared to the semiconductor industry. Therefore, the platform model may benefit both markets in combining low volume segments to reach economies of scale in production. As a consequence, standardization, industry coordination, and the availability of third party foundries would be beneficial to both high and low end markets.

Table 5 A Comparison between the Optoelectronic and the Semiconductor industry [7]

<table>
<thead>
<tr>
<th></th>
<th>Optoelectronics</th>
<th>Semiconductor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Performance</td>
<td>Undefined</td>
<td>Moore’s Law drives device minimum feature size</td>
</tr>
<tr>
<td></td>
<td>Mostly discrete</td>
<td>Highly integrated</td>
</tr>
<tr>
<td>Material Usage</td>
<td>High diversity</td>
<td>Predominately Si</td>
</tr>
<tr>
<td>Processing Capability</td>
<td>Wafer size: 2 to 4 inch</td>
<td>Wafer size: 8 to 12 inch</td>
</tr>
<tr>
<td></td>
<td>Diverse processing equipments</td>
<td>Common equipments</td>
</tr>
<tr>
<td></td>
<td>Low volume</td>
<td>High volume</td>
</tr>
<tr>
<td></td>
<td>Low yield</td>
<td>High yield</td>
</tr>
<tr>
<td>Foundry Model</td>
<td>Die-None</td>
<td>Die-Mature</td>
</tr>
<tr>
<td></td>
<td>Packaging-Mature</td>
<td>Packaging-Mature</td>
</tr>
<tr>
<td>Product Focus</td>
<td>Device (O-E or E-O converters) plus management functions</td>
<td>Highly integrated circuit functions</td>
</tr>
<tr>
<td>Monolithic integration level</td>
<td>&lt; 100 devices</td>
<td>&gt; 1,000,000 devices</td>
</tr>
</tbody>
</table>
## SWOT for Optical Interconnects

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low EMI</td>
<td>Marketing Barriers</td>
</tr>
<tr>
<td>Low Power</td>
<td>• Volume</td>
</tr>
<tr>
<td>High Edge Density</td>
<td>• Backwards Compatibility</td>
</tr>
<tr>
<td>High Reach</td>
<td>Supply Chain / Infrastructure Barriers</td>
</tr>
<tr>
<td>High Bandwidth</td>
<td>• Personnel Knowledge Base</td>
</tr>
<tr>
<td></td>
<td>Standards &amp; Policy Barriers</td>
</tr>
<tr>
<td></td>
<td>Technological Barriers</td>
</tr>
<tr>
<td></td>
<td>• Design Tools</td>
</tr>
<tr>
<td></td>
<td>Supply Chain / Infrastructure Barriers</td>
</tr>
<tr>
<td></td>
<td>• Packaging size</td>
</tr>
<tr>
<td></td>
<td>Personnel Knowledge Base</td>
</tr>
<tr>
<td></td>
<td>Standards &amp; Policy Barriers</td>
</tr>
<tr>
<td></td>
<td>Cost barriers</td>
</tr>
<tr>
<td></td>
<td>• Expensive Packaging</td>
</tr>
<tr>
<td></td>
<td>• Expensive Fiber Termination</td>
</tr>
<tr>
<td>Opportunities</td>
<td>Improved Electrical Connector Density</td>
</tr>
<tr>
<td>Cable Replacement</td>
<td>Low Cost &amp; Low Power Electrical Transmission</td>
</tr>
<tr>
<td>• Ease Of Cable Management, Low EMI</td>
<td>Using Advanced Materials</td>
</tr>
<tr>
<td>HPC Systems:</td>
<td>Very High Density Systems (E.G. SiP) Providing</td>
</tr>
<tr>
<td>• Edge Density, Low Power</td>
<td>Performance in Very Small Volumes</td>
</tr>
<tr>
<td>Si-CMOS And III-V Integration/ Hybridization</td>
<td></td>
</tr>
<tr>
<td>Low Cost Packaging</td>
<td></td>
</tr>
<tr>
<td>Low Cost Cu Competitive Fiber Termination, Alignment, Coupling</td>
<td></td>
</tr>
<tr>
<td>Design Tools - Signal Integrity Optical and Electrical, O-E And E-O, Coupling, Link Simulations</td>
<td></td>
</tr>
</tbody>
</table>