MIT's Microphotonics Center is pleased to present this digest of summaries and highlights from Microphotonics: Hardware for the Information Age—the document that charts a course for the future of photonics technology and represents the culmination of a four-year effort by the Communications Technology Roadmap program.
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The MIT Communications Technology Roadmap program, sponsored by the Microphotonics Center Industry Consortium, was commissioned to evaluate the vast array of new technology that has disrupted the telecommunications industry—to serve as a guide for R&D investment and for the rational restructuring of the industry. The CTR document, *Microphotonics: Hardware for the Information Age*, more than four years after its initiation, has the same motivation, although the context has changed to reflect today’s market. The CTR program is guided by industry-led Technology Working Groups (TWGs), with the support of MIT faculty and student analyses.

The analyses performed by the TWGs yield three common insights.

1– Traditional revenue sources cannot support sustainable innovation due to long term, cyclical network capital investment; total addressable market reduction by product differentiation; and loss of pricing power with the inventory excess of 2002.  
2– High volume applications will drive standardization at the network edge and from the data (computation) appliance.  
3– The convergence of electronic and photonic functionality will deliver high volumes, create new markets, and drive integration and standardization. The electronics and photonics markets—and their technology roadmaps—will merge.

**Executive Overview**

The MIT Communications Technology Roadmap supports the vast array of new technology that has disrupted the telecommunications industry—to serve as a guide for R&D investment and for the rational restructuring of the industry. The CTR document, *Microphotonics: Hardware for the Information Age*, more than four years after its initiation, has the same motivation, although the context has changed to reflect today’s market. The CTR program is guided by industry-led Technology Working Groups (TWGs), with the support of MIT faculty and student analyses.

The future of components technology will be determined by electronic-photonic convergence and short (<1 km) reach interconnection.

This direction is triggering a major shift in the leadership of the component industry from information transmission (telecom) to information processing (computing, imaging).

The skill set required for this path does not exist at any single institution.

A precompetitive R&D Consortium should be established to create the new competence and to recommend standards.

The electronics and photonics markets—and their technology roadmaps—will merge.

**Technology Analysis**

Information technology has four frontiers: telecommunication, computation, imaging, and learning. Each is gated by performance expectations of bandwidth, power efficiency, footprint reduction, and cost reduction. The demarcation metric for optical interconnection was established by fiber deployment at 10 Mb/s x km. This crossover point has been maintained with limits both on electronic interconnection for DSL, ethernet, and backplanes and on the insertion of optical interconnection for WAN, MAN, and SAN applications. As the bit rate for short range (<1 km) interconnection increases beyond 10 Gb/s, optical technology will be required at product volumes and price points that are 2–3 orders of magnitude away from current market offerings. Pervasive deployment in this major market driver is expected in the 2010–2015 time frame, and the required R&D must be done now.
The interdependency between computation and communication has been expressed as Amdahl’s Law: every 1 MIPS of computing power requires 1 Mb/s of I/O. Computational power now demands distributed processing for reasons of speed and power dissipation. This architectural trend is driving high bandwidth interconnection, electronic-photonic integration with smart partitioning, and the emergence of low-latency, high-intelligence processing nodes.

Integrated component platforms will be driven by reduction of packaging cost and by increase in functionality (both optical subassembly and electronic-photonic partitioning). At the system level, smart links will lower the cost:function ratio. At the network level, complexity will continue to increase beyond ETDM (Electronic Time Domain Multiplexing) and DWDM (Dense Wavelength Division Multiplexing). Parallel processing for high speed computing will adopt an architecture based on low-latency optical interconnection.

Investment, markets, and technology standards are primed to emerge from computation and spread across other market platforms. Silicon needs a mixed signal platform; InP needs a common platform for electronics and photonics; organic materials need to provide solutions for hybrid integration. Transceivers must adopt a standard that will allow transistor-like replication with WDM. Based on the prevalence of CMOS process technology, a silicon electronic-photonic platform will be the first to be tested by 2010. As InP fabrication facilities move to a foundry infrastructure, a complimentary common platform could emerge by 2015.

**Economic Analysis**

The impact of deregulation of the telecommunications industry continues to reverberate in the industry business cycle. The recent overbuild of the long haul backbone has delayed the next network build and removed pricing power in the component replacement market. These conditions are amplified by the maintenance...
of performance expectations for a regulated monopoly. The traditional telecommunications customer metrics of ‘end-to-end’ user service and high-reliability ‘quality of service’ are less relevant in a disaggregated, competitive industry where “good enough” is the guide. Customized, discrete long haul component design continues to dominate industry thinking, even though the value proposition has changed. Hundreds of companies now compete where fewer than five existed before. Continued consolidation must occur to bring the industry to a sustainable level of activity. R&D must efficiently target new technology to create more functional products with a performance/cost scaling of a factor of ten every ten years.

The overpopulated components industry has responded to present market conditions by focusing on market segments that will maintain a current revenue stream. This survival strategy triggers a system dynamic known as the ‘death spiral’. By targeting a smaller addressable market through customization, a lower potential revenue stream results, followed by reduced investment in R&D for the next generation products. Systems integrators are now concerned that they will be unable to provide the expected value to their network customers if the component value proposition does not scale appropriately with time. This challenge is a major driving force for standardization to a platform that can be leveraged on industry-wide R&D.

High volume consumer devices dominate revenues and innovation in the electronics industry. The reliable, 20-year component life standard of the telecommunications industry is inconsistent with the 3-year life cycle consumer expectation. The convergence of electronic and photonic technology will shorten technology life cycles, deliver more value to customers, and create a restructured, sustainable components industry.

**Political Impact**

Government must define a path to encourage both the availability of broadband to the populace and the commercialization of new technology. The photonic components industry is not at equilibrium with attrition and consolidation as products of the first Information Technology wave. Technology, markets, and regulation need to move as a coordinated whole. High volume production and standard component platforms will provide the performance/cost scaling to support pervasive broadband.

**Summary**

A technology roadmap represents a consensus vision and a guide to its realization. The process develops a framework for understanding how technology, markets, and policy dynamics interact.
Incorporating two key methodologies—analytical modeling tools and industry-based working groups—the CTR program focuses on the definition of enabling technologies.

MIT’s Microphotonics Center is pleased to present this digest of summaries and highlights from *Micro photonics: Hardware for the Information Age*—the document that charts a course for the future of photonics technology and represents the culmination of a four-year effort by the Communications Technology Roadmap program.
Introduction

The MIT Communications Technology Roadmap (CTR) program focuses on the future of enabling photonics technologies for next-generation communications systems. CTR was initiated in 2000 and is funded by the MIT Microphotonics Center Industry Consortium. A multi-organization roadmapping program, CTR involves participants from more than 40 companies and universities. The program incorporates both expert-based working groups and analytical tools as input to the roadmapping process.

Goals

- Educate suppliers on critical technical, industry, and policy barriers and create a forum for discussing potential solutions or alternatives.
- Drive process development.
- Establish a common platform to drive higher scale in manufacturing.
- Encourage development of new tools specialized for photonics.
- Recommend the adoption of new standards.
- Ensure a sustainable supply chain for optical communications.
- Focus limited investment resources on critical problems.
- Develop and promote a successful foundry model for photonics.

A Roadmap to Growth and Stability

The photonics industry, whose contributions include the core technologies for fiber optic communications systems, faces many challenges in the aftermath of the dot-com/telecom boom and bust. Still recovering from the dramatic industry-wide downturn, many companies are struggling to survive and become profitable. Over the next decade the number of applications for photonics will grow, further adding to the challenges facing the industry. Markets for integrated photonics are diverse including: telecommunications (long haul, metro, submarine), datacom, storage area networks, optical backplanes, automotive, consumer electronics, interconnects (board-to-board, chip-to-chip), broadband internet connectivity, and more. The photonics industry provides an interesting domain to roadmap because it shares many features with the semiconductor industry, but is smaller and less mature.

Academic-industry consortia, government organizations, and industry trade associations have a crucial role in roadmapping because they can bring together representatives from across entire industries or value-chains. Since there are strong inter-dependencies among different parts of a value-chain, these linkages must be considered in any roadmapping process. Figure 2 shows a value-chain for optical communications. A roadmapping effort can focus specifically on the optical components portion of the supply chain or encompass the entire value-chain.

Industry roadmapping can accelerate progress of an entire industry and provide a forum for learning
that benefits all of the stakeholders. The discussion and roadmapping process facilitates the exchange of information and ideas. Roadmapping challenges an industry to ask difficult questions and consider alternative futures and/or disruptive innovations. Industry roadmaps can address issues that may be difficult for just one organization or company to manage alone; instead, cross-industry collaboration and planning may be required in order to make progress.

Industry roadmaps can be used to coordinate efforts aimed at assuring the long term health of an entire industry and its supply chain by reinforcing critical components of the industry’s infrastructure and reducing duplication of costly, commonly-needed research resources. Roadmaps can be used to advise and guide government funding of fundamental scientific research needed to sustain an industry in the long term. Development of necessary enabling technologies can be accomplished without violating the intellectual property rights or trade secrets of the participating companies.

**OPTICAL COMMUNICATIONS VALUE-CHAIN**

<table>
<thead>
<tr>
<th>MATERIALS &amp; PROCESS EQUIP</th>
<th>COMPONENTS</th>
<th>EQUIPMENT MARKERS</th>
<th>NETWORK OWNERS</th>
<th>SERVICE PROVIDERS</th>
<th>CONTENT &amp; APPLIANCE</th>
<th>APPLIANCES</th>
<th>END USERS</th>
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<tr>
<td>Silicon</td>
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<td>Routers</td>
<td>Wireless</td>
<td>Long Distance</td>
<td>Music</td>
<td>Computers</td>
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<td>Switches</td>
<td>Backbone</td>
<td>Local Phone</td>
<td>Movies</td>
<td>Phones</td>
<td>Consumer</td>
</tr>
<tr>
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<td>Other</td>
<td>Spectrum</td>
<td>MVNO’s</td>
<td>Surveillance</td>
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</table>

*Figure 2: Industry sectors that create and use technology for optical communications.*

The International Technology Roadmap for Semiconductors (ITRS) is one of the most well-recognized multi-organization technology roadmapping efforts. Roadmapping in the semiconductor industry began in the United States in the early 1990’s with *Micro Tech 2000*—a workshop organized to chart the technology strategy for semiconductors over the coming decade with the end goal of achieving a significant technical target by the year 2000. ITRS participation has now expanded to include over 900 people from the U.S., Japan, Europe, Korea, Taiwan, China, and other regions. The objective of the semiconductor roadmap over the past decade has been to sustain historical industrial productivity (Moore’s Law).

The ITRS has historically focused on target-driven roadmapping, although there is now a shift to incorporate exploratory mapping. For the first time in 2003, the ITRS included a chapter on “emerging
technologies.” The semiconductor industry is no longer scaling at its historical rate, as the industry apparently approaches the end of improvement rates aligned with the predictions of Moore’s Law. The photonics industry is in the initial stages of exploratory mapping, with a focus on surveying the technology landscape and assessing different technology alternatives. At this stage, the photonics roadmap output should not be expected to look like an ITRS roadmap.

**Technology Working Groups**

CTR decided to focus initially on optical transceivers as the technology driver for communications. Current Technology Working Groups (TWGs) are based on three layers: Applications/Market Drivers (market-pull), Modules/Systems, and Technologies (technology-push). Each TWG is comprised of experts in a particular area and focuses on addressing a specific set of issues. The linkages among the TWGs are critical in translating industry drivers to system requirements and from there to enabling technologies.

Working group meetings were used to assess different integration scenarios in each of the material platforms.

Complementing the TWGs, CTR has engaged in the development of analytical modeling tools to support the roadmapping process and provide in-depth analysis when needed. These models include, for example: device models, process-based cost models, and system dynamics models.

Device models serve to delineate that which is physically possible. These models can be used to project technologies from other areas (e.g. microprocessors) to understand how their development will impact optical transceivers. A set of predictive models for transceiver performance was developed to assess power dissipation of key components, including the multiplexer, thermoelectric cooler, and driver amplifier [3].

Technical cost models play an essential tool role in determining the costs associated with technical design decisions; they provide a link between physical manufacturing processes, performance, and device cost. A series of process-based cost models has been developed for the following design cases: an InP-based laser and modulator 10 Gb/s optical transceiver platform [4], integrated optical receivers [5], and large area InP wafers [6].

System dynamics models provide a quantitative framework for modeling the influence of policy decisions and technology choice on evolving markets. CTR has developed several system dynamics-based models to assess the impact of industry and policy dynamics on technology deployment. One model focuses on the adoption of broadband technology
in the Fiber-to-the-Home (FTTH) market and the impact of different regulatory policies [7]. Another model examines the dynamics of the transceiver industry and the trade-offs between product proliferation and standardization [8].

In the photonics industry, roadmapping has the potential to provide a mechanism for driving growth and sorting through the wide diversity of technical choices. Roadmapping can help to define the future and focus investment decisions for the benefit of the industry; there are also, however, many fundamental technical barriers to integrated photonics that need to be solved to advance the industry. Microphotonics: Hardware for the Information Age provides a groundbreaking compilation of market drivers propelling change, technology and organizational barriers impeding effective development, and solutions to realizing rationalized growth within a critical technology-based industry.

References


Any forecast about the promise of a communications technology must include an appreciation of its place within the larger communications ecosystem in which it will exist. This ecosystem comprises key elements such as transmission, distribution, switching, processing, storage, and display. Development of a viable communications infrastructure requires that those elements scale together. Photonic technology holds great promise for realizing this coordinated scaling within future high-speed communications—from the chip level through board interconnects, to enterprise and long haul. The key is to identify commonalities that drive scale and build the technical infrastructure necessary to enable optical technology to replace electrical devices (Figure 3). As the end-to-end infrastructure becomes increasingly optical, network latency will decrease to the point that communications become perceptually instantaneous to users.¹ The implications are enormous.

The Vision

Over a century ago, Alexander Graham Bell invited a reluctant public to communicate analog speech across distance electronically. Today, digital networks operate at greater capacity and speed; but despite the fact that optical fiber has been used since the 1980’s, current networks are still limited by the electrical interconnects at their termini. The opportunity to advance the speed of communications lies in replacing these slower components with photonic equivalents.

The realization of optical transmission networks will allow any connected individual to access vast computational resources. Unbounded applications, not dependent upon local storage or processing, will be limited only by the imaginations of those who create them. Many of the current economic and distribution barriers between intellectual property owners and end-users will evaporate.

The effect of such technology on transportation, commerce, education, entertainment, social interaction, and government will be dramatic. For instance, one only needs to look at the world ten years ago to understand the social impact of the cell phone. The shift to a real-time wideband network promises the same dramatic social effect. Many enabling components already exist in laboratories. The demand created by new long haul networks will allow them to be applied on a commercial scale. With the advent of this new communications infrastructure, twenty-first century society will be witness to a renaissance of applications spawned from the ability to extend computer-moderated information directly to the

¹Access time of \(\leq 20\) ms is perceptually instantaneous to users. Current wireless and ADSL systems include coding and interlace options that often result in access times in excess of 20 ms for local connections.
end user in real-time. Third generation applications will fuel the information vehicles. Photonics will speed the underlying highway.

The Need

History teaches that disruptive technologies are often met with corporate resistance, fragmented implementation, public fear or misunderstanding, and initial government indifference. Fully optical communications networks will experience similar problems. It will take a visionary commitment to replace antiquated infrastructure in order to realize the true nature of what French anthropologist Stephen Lévy calls “collective intelligence.”

Such promise will come neither cheaply nor completely without technical problems. While optics is the preferred method for transport, a mix of optics and electronics will be utilized until electronic components are replaced by pure optical or hybrid devices. Barriers to the adoption of these technologies are not technical, but economic, given the scale and life cycle of the present infrastructure. Nevertheless, we must look at the future through the perspective of historical projects such as the Rural Electrification Act. A visionary program such as the REA, applied to the communications infrastructure of the country, will yield the realization of a society where the flow of information will be in real-time, and all electronically accessible material stored anywhere will be available to anyone with access to the interconnected network. This capability will initially be most affordable to government and the military, but trickle-down will result in new applications to benefit the private sector. Once standardized and widely available, the link to the user will be complete, and anyone with a connection will have instant access to the greatest virtual repository of information in history.

Ubiquitous computing and communications will revolutionize medicine, education, and social interaction.

Medical personnel could have instant access to complete virtual patient files and schoolchildren could visit the great libraries and museums of the world from their desks.

While electro-mechanical switches provided the backbone of the 20th century’s analog networks, new optical components are needed to realize the potential of the digital age.

Lévy espouses a theory of the internet as a collective sum of world knowledge—effectively forming a “hive mind” where humankind will be able to realize the true promise of networked communications.
Although historically photonic components have been associated almost exclusively with the communications industry, they are now used in a variety of industries, including communications, information, lighting, displays, sensing and scanning, biometrics, manufacturing, and automotive. Across this range of applications, the total addressable market (TAM) for photonic components is large. The very different technical requirements for each of these applications, however, ultimately fragment the TAM into technology-specific slices. Focusing on communication applications as indicative of cross-industry trends, the state of the industry is discussed, acknowledging recent history, present-day challenges, and current trends.

The photonics industry is on the cutting edge of technical innovation and application. Innovations in this industry have helped enable high-speed and high-capacity worldwide communications, on-demand multi-media and broadband communications in one’s own home, extremely high quality music and video, the brightest displays, the fastest sensing networks, extremely accurate and non-intrusive surgeries, and even shorter checkout lines in the grocery market. The future of this growing industry is exciting, and new innovations will continue to change our lives.

In general, the role of a supplier in this industry is very challenging. Focusing in particular on the communications industry, the following items summarize a few of the key supplier challenges:

Challenge 1 – Photonics components, even in the simplest of applications, are sophisticated examples of hybrid integration of many types of materials, packages, and functionalities.

Challenge 2 – The performance requirements (wavelength, power, size, and speed) for photonic components vary widely across the aforementioned application space, challenging the ability to leverage any one component (via design, manufacturing infrastructure, supply base, reliability, quality, volumes, etc.) into an adjacent application.

Challenge 3 – The pace of innovation required for competitive market positioning is rapid, driven to date by the needs of the communications sector.

Key Points

| The entire photonics industry has a large and growing total addressable market (TAM). |
| The broad number of applications that are served by the photonics industry has resulted in technical and market fragmentation, giving rise to many micro-industries with smaller TAMs. |
| The communications sector of the photonics industry has recently undergone tremendous restructuring, and based on present market conditions, will require additional change. |
| The number of suppliers vying for a share of the communications-centered photonics TAM forces one of two behaviors: |
| — An outsourced manufacturing model, as the possible revenue/company doesn’t easily allow for profitable support of an internal manufacturing infrastructure. |
| — Large-scale consolidation of the present supply base. |
Challenge 4 – Many applications that are served by photonics components address consumers who are accustomed to, expect, and reward solutions that offer high rates of price erosion. The need for price erosion is shared with the photonics supplier.

Challenge 5 – The competition in the industry is fierce, where battles for market-share are hard-fought between companies that are profitable, companies that will operate at a loss to generate pull-through business for their other divisions, and well-funded ventures.

Given these challenges, one must also acknowledge the present market conditions. The outlook for photonics in all of the application spaces (communications, information, lighting, displays, sensing and scanning, biometrics, manufacturing, and automotive) is either stable or growing. The diversity of the technical requirements and the associated lack of overlap on the manufacturing infrastructure require separate treatment of the addressable market for each sector. The TAM for the photonics components industry with respect to communications (telecom, datacom, and storage) was approximately $2B USD in 2004. While the addressable market is significant, it pales in comparison to its former size of $10.7B USD in 2000. Consider this in the context of overall capital spending by telecommunication service providers, which changed from $310B USD in 2000 to ~$190B USD in 2003. Growth in global capital spending is expected to be relatively modest over the next five years (single digit compound annual growth rate), with most of that growth in investment for wireless communication infrastructures. As such, one should expect conservative growth of the current optical component TAM rather than a return to the spending level of the telecommunications bubble.

At the peak of the market, systems hardware companies owned photonic component manufacturing. These were spun out in order to remove the fixed cost of owning these facilities, as well as to promote industry-level standardization and commoditization. A second restructuring is now taking place.

The current $2B total addressable market is shared among numerous suppliers that coexist with relatively small market fractions. A natural consequence of this division is the limited affordability for internally-owned manufacturing infrastructures, which is one of the main contributing factors to the recent shift toward outsourced manufacturing.

These dramatic changes to the supply chain over a relatively short period of time expose a lack of true direction for the industry and have led to uncertainty and nervousness about competing in the present day environment. The current state of the industry points to an inevitable need for further restructuring of the supply chain. Micro photonics: Hardware for the Information Age will outline positive paths through which that restructuring could occur.
Optical technologies have grown in importance for communication applications—as continued innovations allow for a cost-effective means of transmitting large amounts of data over long distances—compared to electrical transmission over wires. Today’s optical transceiver, which co-packages a transmission laser and a photonic receiver, represents the market’s need for integration, physical design, performance, and cost efficiency. Going forward, the demand to transmit data will continue to grow; this creates new market opportunities, but also requires that optical transceivers evolve to address those markets.

The challenge to satisfy next generation applications is compounded by current challenges, which include a proliferation of standards, a large diversity in global requirements, little design convergence across various optical component applications, and challenging market conditions. There are other significant, but distinct, challenges in each sector of optical communications; Microphotonics: Hardware for the Information Age aims to identify these, as well as potential solutions.

Markedly different technical challenges will engage the telecommunications, data, and interconnect sectors over the next decade.

The DWDM grid maps out a single fiber capacity of 1.2 Tb/s, and all the necessary technologies to achieve this have been demonstrated or are commercially available; ‘intrinsic’ scaling with the demands of the next decade are therefore feasible. FTTH similarly places modest technical demands on the capabilities of fiber systems, and this is likely still to be the case in 2015.

The Future Evolution of the Transceiver

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Short-range data communications and inter-connects are currently commercially available up to 40 Gb/s using parallel optics approaches. This capacity is already in use or exceeded in high-end applications. While current demonstration of parallel optical interconnects operate at 0.5T b/s, scaling commercial modules to the capacity required in 2015 will require very challenging cost and performance goals to be met.

The ‘Digitalization’ of the home and the prevalence of consumer electronic imaging will create significant opportunities for optical communications, both guided wave and free space. Similarly, automotive wiring harnesses are already being replaced with plastic optical fiber systems, and there may also be opportunities for free space communications in range-finding and other telematic systems. For first generation devices, the extreme cost pressures but relatively modest performance requirements may offer compelling technology introduction opportunities for organic, silicon, and other integrated platforms.

Figure 4 (a and b) shows a possible evolution in telecommunications-based transceivers to meet the future needs of that market. In response to the need for mesh-based, reconfigurable backbones, it is anticipated that there will be an increasing
level of optoelectronic integration with multiple tunable sources within one device.

Electronic processing to gain enhanced system performance will play an important role. Whereas optical fibers replaced copper wires for high bandwidth transmission over long distances, it is now clear that additional electronic processing of the data stream can help overcome limitations in optical transmission. This is well represented by the introduction of electronic dispersion compensation to cost-effectively extend the performance of optical solutions.

Communication applications that focus on transmission of data will continue to grow at a feverish pace. The cost points are especially sensitive here, and the industry would benefit from a dramatic reduction in the cost of DWDM components.

The ‘Holy Grail’ for next generation optical transceivers is to address the disparate needs that presently exist over a wide range of applications with a single converged solution. Convergence may arise in a variety of ways, be it through standards, market requirements, component performance, packaging design, and/or manufacturing methodologies. Such a convergence offers the advantage of a larger potential market for any one component or technology, but requires that this gain outweigh the cost of the ‘over-engineering’ that will necessarily exist for some of the applications. Figure 5 shows a possible ‘Universal transceiver’ based on a silicon microphotonics platform where the low cost of integration might potentially balance the cost of excess capability for some applications.

It is extremely difficult to predict the future demand for—and the technical development of—transceivers. New applications may offer opportunities to organics and other material systems, but the challenges to the “traditional” transceiver industry are ones of very low cost manufacturing.

Conclusions

It seems likely that in higher performance applications, electronic processing will become an integral part of the NGT, increasing levels of optoelectronic integration will be used, and adaptive transceivers may be enabled by these two factors. In data communications there are significant challenges to be overcome and a number of potential futures.

Figure 5: Possible future transceiver—revolutionary path.
For several years, a collaborative group of university, industry, and professional organizations have researched the possibility of replacing expensive high performance photonic components with silicon-based counterparts. This research explored the technical obstacles to construct such devices, their expected benefits, and the market drivers sufficient to prompt suitable investment. Microphotonics: Hardware for the Information Age discusses the value proposition associated with such devices, including likely implementations and a collaborative industry/university plan of attack to realize the enormous potential.

Silicon-based microphotonics has been under great scrutiny in recent years. The prospect of extending a massive, low cost electronics manufacturing platform into the photonics domain is the subject of much research and debate. What has become more clear is that an important driver for the debate is the intrinsic distance x bandwidth limitation of electronic communications links. In other application domains, typically, photonic links are utilized once these electronic limitations have been encountered. Photonic link standards of many kinds have been developed to support such demands in the past. These standards represent a historical context for a silicon microphotonics roadmap—and yet they may impede its development. A roadmap is starting to emerge focused not on how silicon microphotonics can implement existing standards, but rather on how silicon microphotonics supports the migration of network bandwidth in an important way.

The key market driver for silicon microphotonics adoption will be significantly reduced cost, which will drive the transition from electronic to photonic interconnects. As was the case for VLSI, monolithic integration will be essential to reducing cost; but if silicon microphotonic is to take advantage of its potential, high yields will have to be maintained. Integration will achieve aggressive bandwidth scaling through both parasitic loss reduction and integrated functionality (e.g. WDM solutions).

Key Points

- There are bandwidth limits for electronic-based transmission of data, even for very short distances (< 2m).
- Major markets are approaching these speed limits now.
- Traditional photonic solutions will be too expensive for these short distance connections.
- Leveraging a silicon infrastructure, silicon microphotonic offers compelling possibilities.
- Compatible photonic integration, packaging, and interconnect strategies will be required.
This roadmap reviews the fundamental strengths of silicon microphotonics, along with its questions and challenges, the likely fit in emerging applications, and the necessary infrastructure. This roadmap also discusses the importance of an industry roadmap for all participants. Critical gaps exist in selecting compatible integration, packaging, and interconnect strategies. Such strategies are highly interconnected in the photonics domain. Roadmapping and directed research provides an invaluable venue for university/industry participants to develop and link required strategies.

Silicon microphotonics seeks to build optical devices on the platform that has enabled Moore’s Law: electronics-grade, single-crystal silicon. Beyond this, definitions diverge. At one extreme, hybrid integration on silicon involves the incorporation of non-silicon-based devices fabricated off-chip with microelectronic devices already integrated on a conventional CMOS silicon platform. At the other extreme, CMOS process-fabricated, monolithically-integrated silicon photonics achieves a complete set of microphotonic devices using processes available in existing CMOS fabrication facilities. The latter solution requires sources, detectors, and modulators, as well as passive components such as waveguides and filters, made from silicon and acceptable dielectrics and metals. Between the extremes intermediate solutions span the spectrum. For example, CMOS-compatible, monolithically-integrated silicon microphotonics does not interfere with CMOS processing, but could involve post-processing outside of the accepted CMOS process flow.

To provide a truly compelling solution, silicon microphotonics will likely need to achieve a high degree of monolithic integration with at most a small degree of hybrid integration, (e.g. laser sources) in order to offer low cost and increased functionality. This will probably involve new photonic materials, (e.g. Ge, BaTiO$_3$, SiON, and so on) near the process back-end. Although this adds manufacturing complexity, this trend is also occurring in advanced CMOS to allow Moore’s Law scaling and new functionality, such as high-k gate dielectrics and MRAM’s.
Photonic device integration in indium phosphide (InP) would drive down production costs through volume manufacturing efficiencies, greater functional integration, and increased device density. To date, integration in III-V material systems has largely been driven by the performance requirements of optical telecommunications networks. For telecommunications to fully realize the cost benefits of an integrated InP technology, however, this traditional market may have to “piggyback” on emerging high volume markets.

The photonic component industry’s focus and investment over the last decade has been on the InP material system, due to its ubiquity in both high performance datacom and longer reach telecom applications. Customer requirements for reduced footprint, power dissipation, and component cost, as well as opportunities for improvements in performance, reliability, and simpler device management, have driven a migration from discrete to hybrid solutions—and now to increasing levels of monolithic integration.

InP is the ideal material system for photonic integration of both passive and active optical functions and leverages significant industry experience in the design and high volume manufacture of high speed active optical devices. InP technology also has a proven record of monolithic integration of key elements such as the laser source and electro-absorptive modulator. Figure 9 demonstrates large scale photonic integration of 10 DFB lasers, modulators, variable optical attenuators, power monitors, and optical multiplexers on a single die, resulting in a 100 Gb/s DWDM transmitter on a monolithic substrate within a telecom quality package. These products are currently deployed in telecommunications networks, demonstrating the commercial potential for photonic integrated circuits.

III-V photonic integration will be defined around functional building blocks—some of which have become de facto standards, but commonality

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**Key Points**

- III-V material systems possess properties that achieve superior optical device performance, which cannot be achieved currently by silicon-based materials.
- InP has been the leading III-V platform for monolithic integration of active devices because of performance and reliability requirements and compatibility with optical requirements of fiber amplified telecommunication systems.
- Higher levels of monolithic integration are expected to continue and would include the addition of key passive optical building blocks to address next-generation fiber access architectures and protocols such as 100 Gb/s Ethernet.
- Process improvements, standards on functional building blocks, availability of simulation tools, and the evolution of a market driver permitting the achievement of economies of scale in manufacturing are necessary to meet cost objectives.
- Standardizing photonic integrated circuits (vs. full electronic/photonic integration) that can address a broad range of applications including non-telecom markets would enable an order of magnitude reduction of the cost curve.
and further development of building blocks are required. While silicon has been the material of choice for integration of electronic functions, we expect III-V technologies to remain the best choice for optical devices due to their ability to generate light efficiently and to provide a full range of the other required photonic functions. Electronic and photonic integration has been routinely demonstrated in III-V materials, but without a high volume market driver there will be less activity on the development of those technologies and products. In the absence of such development, integrated electronic building blocks may be limited to high speed applications where a high quality interconnect is a necessity. In many lower-performance applications, the electronic building block requirements will likely be more easily and cost-effectively implemented in silicon, making either hybrid integration or discrete assembly the more sensible approach.

While multiple opportunities for monolithic integration in InP are possible, some limits exist due to constraints with existing tools and technology. In order to evaluate the interaction of multiple design variables, we require further development of modeling tools for dynamic characterization of various electrical, optical, and thermal design options in integrated optoelectronic devices. The success of large scale integration in InP also depends on the development of novel techniques for managing power dissipation on a localized level, as well as some key process-related developments. One of the most important process developments required for optimization of large scale integrated devices relates to the ability to effectively control the type and amount of material present in spatially controlled segments of the wafer. While there are many methods currently used, convergence to a standard set of processes wherever possible will enable improved fabrication economics through volume consolidation.

Figure 9: A packaged photonic integrated circuit consisting of a monolithically integrated 100 Gb/s DWDM transmitter. (photo courtesy of Infinera)
Ultimately, the success of III-V integration efforts will rest with finding a high volume market driver. While metro and long haul telecom have been the drivers for InP device development and integration efforts to date, economies of scale will likely be achieved only through growth in other markets. FTTx transceivers and higher end transceivers for the networking markets offer some potential for volume, but the communications industry needs to be prepared to take advantage of advancements in storage and computing infrastructure technologies and free space optical links in next generation IrDA applications as possible cross-over markets to drive down cost. Additionally, as long as there is the potential for achieving acceptable performance, non-InP based III-V material systems used in some non-telecom applications should not be dismissed for cross-over possibilities into communications markets.
A healthy photonics industry will be built on standardized component platforms that can be manufactured in high volume at low cost. These platforms will deliver performance: cost ratios that scale exponentially with each technology generation. Organic materials provide a versatile set of properties and processes that meet this need for both hybrid and monolithic photonic circuits. Organic devices have been fabricated and tested for both passive and active functions. Photonic circuits constructed of organic components have been demonstrated. During the next decade, organic materials will be a critical ingredient in commercial, hybrid photonic circuits.

Organic materials will be an indispensable ingredient in hybrid integrated photonic circuits; as an example, a polymer-on-silicon hybrid integration platform is shown in Figure 10. In this optical bench, grooves for the insertion of various optical films are formed and subsequently filled and cured to form the polymer waveguide.

The application of these materials to low cost, short reach data links is being considered for fiber circuits in ‘Digital Home’ entertainment and control systems. Known as Plastic Optical Fiber (POF), this multimode, graded index transmission medium exhibits ease of splicing and connecting,

**Key Points**

- **Polymeric materials are ideal for planar circuit processing.** Deposition and pattern transfer are achieved with low cost and high precision by spin coating and photolithography, or by mechanical means such as embossing, molding, and stamping.

- **Plastic materials have been used extensively for packaging and transmission media.**

- **Organic materials can be processed with reduced temperature excursions.** This property allows rapid manufacturing and ease of integration with electronics.

- **Complex switching and routing circuits with state of the art performance have been demonstrated on a polymer waveguide platform.**

- **The success of hybrid integration on the organic materials platform depends critically on a cost effective ‘pick-and-place’ assembly technology.**
light weight, low bending loss, and resiliency to mechanical impact. With transparency windows at 850 nm, 670 nm, and 530 nm, POF is compatible with silicon or polymer photodetectors and with silica or polymer waveguide circuits.

Electronic-photonic integration is the major trend that is driven by complexity, performance, and cost. Passive organic photonic components with cutting edge performance and proven reliability are commercially available today, whereas active organic photonics and organic electronics are less mature and are not yet capable of high performance. The low thermal budget for device fabrication makes organic materials ideal components for advanced electronic-photonic partitioning.

Polymer waveguides can achieve a high refractive index contrast in a buried channel; this configuration is needed to avoid excessive loss and polarization dependence when metal electrodes are deposited on a photonic circuit for actuation. The low refractive index of these materials, however, will ultimately limit the number of devices on a chip to one million/cm². The ability to efficiently guide and control an optical signal carrier will drive the technology for the next decade and will enable a significant reduction in the cost of optical components (Figure 11).

The relatively low glass transition temperature of some classes of organics allows low stress and low polarization dependence in thermoset systems, and reflow and coalescence to smooth structures along with reduction of scattering loss in thermoplastics.

Organic materials have high thermo-optic coefficients. This property is exploited in commercial low-power-consumption digital optical switching fabrics (Figure 12), as well as in tunable couplers, variable optical attenuators, and tunable filters. This property, however, contributes to a high sensitivity to ambient temperature in interferometric devices such as arrayed waveguide gratings (AWG’s), which are better done in low thermo-optic coefficient materials such as silica (given that they are static devices and as such do not take advantage of the low power actuation). The photosensitive refractive index is a prime path for component performance trimming. Devices such as ring resonators have been clad with polysilanes and exposed to UV light to trim the device resonant frequency.
Organic materials can also have high electro-optic coefficients, enabling low voltage modulators. The major barrier for the commercialization of polymer modulators has been reliability. Adding a high concentration of nonlinear optical organic chromophore molecules to a polymer is necessary to achieve a large electro-optic effect in that polymer. Using a high concentration, however, results in electrostatic interaction between the highly polar molecules, thereby causing relaxation or reorientation—which in turn reduces the electro-optic coefficient over time. This commonly misunderstood and well-publicized degradation phenomenon is behind the perception of poor reliability in polymers. Isotropic thermo-optic polymers have none of the directional asymmetry that causes the instability of electro-optic polymers, and therefore do not suffer from this reliability problem. Dynamic optical components based on custom nano-engineered thermo-optic polymers have passed Telcordia 1209/1221 qualification tests, as well as high optical power and high temperature life tests.

Active organic optical components include amplifiers, sources, and detectors. An off-chip optical source (optical bus) architecture alleviates much of the thermal management required for source heat-sinking. Methods must be found for the effective application and patterning of a variety of organic materials, since each device is now based on a unique material. Optical amplifiers and index doping can be achieved with semiconductor quantum dot attachment on specific moieties.

Active organic devices

Organic photovoltaic elements were used to achieve photodetectors in the visible range for short reach data links as well as solar cells. A high value application for organic materials would be an optical solder equivalent for fiber attach.

Organic materials can accomplish the full array of optical functions and can be processed at temperatures that are compatible with CMOS integrated circuits. The main barrier to be overcome for active and electro-optic organics is reliability; high performance and reliable thermo-optic polymers, however, along with organic packaging and transmission media, are widely available commercially and are used extensively.
Microphotonics: Hardware for the Information Age has analyzed the current state of the photonic components industry, the role of emerging markets in the timeline for growth, and the key technology platforms that provide the building blocks for the future. The communications component industry was born with the mission of providing discrete components for long haul telecommunications. It experienced rapid growth with a first wave of integration in the form of DWDM on fiber. The next growth phase will launch it into high volume markets with the planar integration of electronics and photonics and with standardized platforms that have cross-market applications. This direction will require a major change in leadership of the industry from information transmission (telecom) to information processing (computing, imaging). It is the Roadmap consensus, however, that “you can’t get there from here” without extraordinary cross-industry teaming.

The optical components industry stands at the threshold of a major expansion that will restructure its business processes and sustain its profitability for the next three decades. This growth will establish a cost effective platform for the partitioning of electronic and photonic functionality to extend the processing power of integrated circuits. The traditional ‘dimensional shrink’ approach to the scaling of technology generations is encountering barriers in materials and power dissipation that dictate more distributed architectures. These short link interconnection requirements will cross the 10 Mb/s x km threshold for optical technology by 2010. The technology challenges involve design, fabrication, packaging, and testing.

### Materials

Three TWGs assessed the roles of silicon, III-V, and organic materials, respectively. The III-V materials have typically led in performance; silicon has followed with high volume and low cost manufacturing; and organics have supported hybrid integration and packaging. These roles are not expected to change, but the importance of high volume manufacturing will become the dominant issue. The key challenges for a cost effective, planar technology are large area substrates and component integration capability.

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### Key Points

- **Customization will be replaced by standardization.**
- **Planar integration will drive cost reduction.**
- **Electronic-photon convergence will drive new functionality.**
- **Circuit simulation and wafer-level test platforms will be essential.**
- **The packaging hierarchy will include optical chip carriers without a permanent fiber attach.**
- **The required breadth of capability and resources does not currently exist in one place.**
- **We recommend that the new Industry Consortium expand its focus toward the creation of the necessary competence and the recommendation of standards.**
**Design** – No methodology exists for electronic-photonic integration. Most photonic simulation tools are based on fundamental physics rather than higher levels of abstraction. A higher level of abstraction should evolve to a photonic circuit theory that will support design and simulation tools. The new design tools should be common among a range of applications, address common form factors, and focus on reducing complexity and increasing functionality. In particular, a methodology for electronic-photonic partitioning should be included.

**Processes** – Development of a standardized infrastructure to support manufacturing is critical. This factor can evolve in one of two ways: adoption of the silicon CMOS infrastructure, or growth of the industry to $20B revenues on a standard platform to drive an independent infrastructure. The choice and timeline will depend on the constraints posed by the silicon infrastructure. The leading issues are tool standardization, common processes, process control, and process integration.

**Packaging Infrastructure** – The current standard of ‘fiber pigtails’ packages is inconsistent with planar integration. Receptacle connectors will require self-cleaning to be effective. An optical chip carrier without permanent fiber attach is absolutely necessary. A common design hierarchy for board, backplane, intrabox, interbox, LAN, FTTH, MAN, and WAN applications will be developed.

**Test** – Testing remains among the most costly aspects of optical component manufacturing. Among the top priorities for the integrated platform are wafer level testing, a common test platform, and a global standard test for most applications.

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**Figure 13: Roadmap for electronic-photonic convergence; dates represent a decade for commercial deployment.**

<table>
<thead>
<tr>
<th>Year</th>
<th>1990</th>
<th>2000</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PHOTONICS</strong></td>
<td>Driver</td>
<td>Fiber, lasers, detectors,</td>
<td>MUX, EDFA</td>
<td><strong>Metro-fiber, PLC Transceiver</strong></td>
<td>Mph IC's FTTH, Pervasive, Mph IC's</td>
</tr>
<tr>
<td>Transmission Application</td>
<td>ETDM</td>
<td>WAN</td>
<td>DWDM</td>
<td><strong>Security Access</strong></td>
<td><strong>SAN/LAN</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Security Access</strong></td>
<td>10Gb/s Access, 10Tb/s WAN</td>
<td>Optical switching systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trend</td>
<td>Fiber</td>
<td>Fiber pigtails</td>
<td>Boards, Servers</td>
<td>Optical MCM</td>
<td>Optical Nodes</td>
</tr>
</tbody>
</table>

|**ELECTRONICS**| Driver | IC: Al/SiO₂ | IC: Cu/SiO₂, InP | **Optical bus** | On-chip optical interconnects, Optical switch |
| Trend | Yield | Yield | Shrink | Optical interconnection | EP design, Photonic logic |

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**Success Strategy and Future Objectives**

The CTR success strategy for the industry has a two term structure. During the next five years, the key issues are abandonment of the differentiation strategy that reduces the total addressable market and adoption of a cooperative strategy that supports standardization. The evolution of standards will need to neutralize the major barriers to market penetration.
entry that have limited the growth of photonic interconnection. These barriers include performance (bandwidth x distance / cost); disruption of critical applications; capital cost of upgrade vs. legacy sunk costs; backward compatibility; complete value chain availability; new skills required for adoption; and insertion to a growing market. The goals for the next ten years are:

- A standard component platform,

- A common manufacturing infrastructure,

- Industry-wide R&D that is leveraged to reduce the product development cycle time, and

- Establishment of a common architecture platform across market sectors with a potential $20B in annual revenue.

The overarching expectation is that such an industry will then be driven by technology obsolescence through performance scaling with product lifetimes significantly shorter than the network build cycle. Optical communications technology provides the ultimate performance for speed, reliability, and security. Microphotonic integration will enable instant access to the greatest virtual repository of information in history.
Contributors

Bruno Acklin, JDS Uniphase
Sang Ahn, Applied Materials
Howard Anderson, MIT
Arvind Baglia, AXSUN Technologies
Marc Baldo, MIT
Jerry Bautista, Intel
Mark Beals, MIT
Al Benzoni, Xponent Photonics
Elizabeth Bruce, MIT / Analog Devices
Vladimir Bulovic, MIT
Dennis Buss, Texas Instruments
Katherine Butler, MIT
Matteo Cherchi, Pirelli Labs
David Clark, MIT
Richard Clayton, Bookham / Clayton & Associates
David Cleary, Optical Solutions
Larry Coldren, Agility Communications / UC Santa Barbara
Robert A. Craven, VTR Optoelectronics

Martin Culpepper, MIT
Luca Dal Negro, MIT
Thomas Dudley, TriQuint Semiconductor / Pelorus Strategies
David Eaton, DuPont
Louay Eldada, DuPont Photonics Technologies
Daniele Faccio, Pirelli Labs
Geoff Fanning, Flextronics
Harold Fetterman, UC Los Angeles
Charles Fine, MIT
Yoel Fink, MIT
Nicholas Fiore, Walsin USA
Eugene Fitzgerald, MIT
James Foresi, Clarendon Photonics
Erica Fuchs, MIT
Fuwan Gan, MIT
Fabrizio Giacometti, Pirelli Labs
Karen Gleason, MIT
Dominic Goodwill, Nortel Networks
Giacomo Gorni, MIT / Pirelli Labs
Giorgio Grasso, Pirelli Labs
Yuji Hamasaki, Excelight
Peter Hankin, Infrastructure Fund
Hermann Haus, MIT
Jerry Hausman, MIT
Gang He, Vitesse Semiconductor
Randy Heyler, Newport Corporation
Gloria Hofler, Agilent
John Hryniewicz, Little Optics
Alan Huelsman, Vitesse Semiconductor
Erich Ippe, MIT
Waguih Ishak, Agilent
John Joannopoulos, MIT
Franz Kaertner, MIT
Sarah Kaplan, MIT / University of Pennsylvania
Jeffrey Kash, IBM
Mikihiko Kato, Fuji Photo Film Co.
Andjelka Kelic, MIT
George Kenney, MIT
Sang-Gook Kim, MIT
Lionel C. Kimerling, MIT
Randolph Kirchain, MIT
Kevin Lee, LNL Technologies
Fred Leonberger, JDS Uniphase / MIT
Frank Levinson, Finisar
Desmond Lim, LNL Technologies
Brent Little, Little Optics
Karen Liu, RHK
Yanming Liu, Walsin USA
Francisco Lopez-Royo, Pirelli Labs
Stan Lumish, JDS Uniphase
Cecilia Mak, Applied Materials, AKT
Elisabeth Marley Koontz, Texas Instruments
Gillian McColgan, Nortel Networks
Roger Merel, Luxtera
Brian Merz, LNL Technologies
Jurgen Michel, MIT
Mamoru Miyawaki, Canon Development Americas
Michael Morse, Intel
Martin Muendel, JDS Uniphase
Ed Murphy, JDS Uniphase
Bob Norwood, Photon-X
Dominic O’Brien, University of Oxford / MIT
Masahiro Okawa, Hitachi Cable
Daniel Pace, Unaxis
Sanjay Patel, Lucent Technologies, Bell Labs
Erik Pennings, ASIP
John Petrilla, Agilent
Gopal Raghavan, Inphi
Rajeev Ram, MIT
Sabbir Rangwala, JDS Uniphase
David Reamer, Veeco Instruments
Marco Romagnoli, Pirelli Labs

Caroline Ross, MIT
Aileen Sansone, JDS Uniphase
Edward Sargent, University of Toronto / MIT
Michael Schabel, Lucent Technologies, Bell Labs
Frank Shi, UC Irvine
Joseph Shmulovich, Inplane Photonics
Terry Smith, 3M
Michael Speerschneider, MIT
John Stankus, Nortel Networks
Tetsuya Suemitsu, NTT
Jeffrey Swift, Analog Devices
Edwin Thomas, MIT
Maurizio Tormen, Pirelli Labs
Scott Trask, Newport
Jean Trewhella, IBM
Harry Tuller, MIT
Kazumi Wada, MIT / University of Tokyo
Jeff Walker, Genoa

Bruce Wallace, Nortel Networks

Hongsheng Wang, Alphion

Andreas Wankerl, Thomas Swan Scientific Equipment

Christopher Weaver, Media Technology / MIT

Fred Welsh, OIDA

Alice White, Lucent Technologies, Bell Labs

Richard Williamson, Lincoln Labs

Art Wilson, JDS Uniphase

Bill Wilson, Little Optics

Chee Wei Wong, MIT / Columbia University

John Yasaitis, Analog Devices

Yiwen Zhang, MIT / Raytheon