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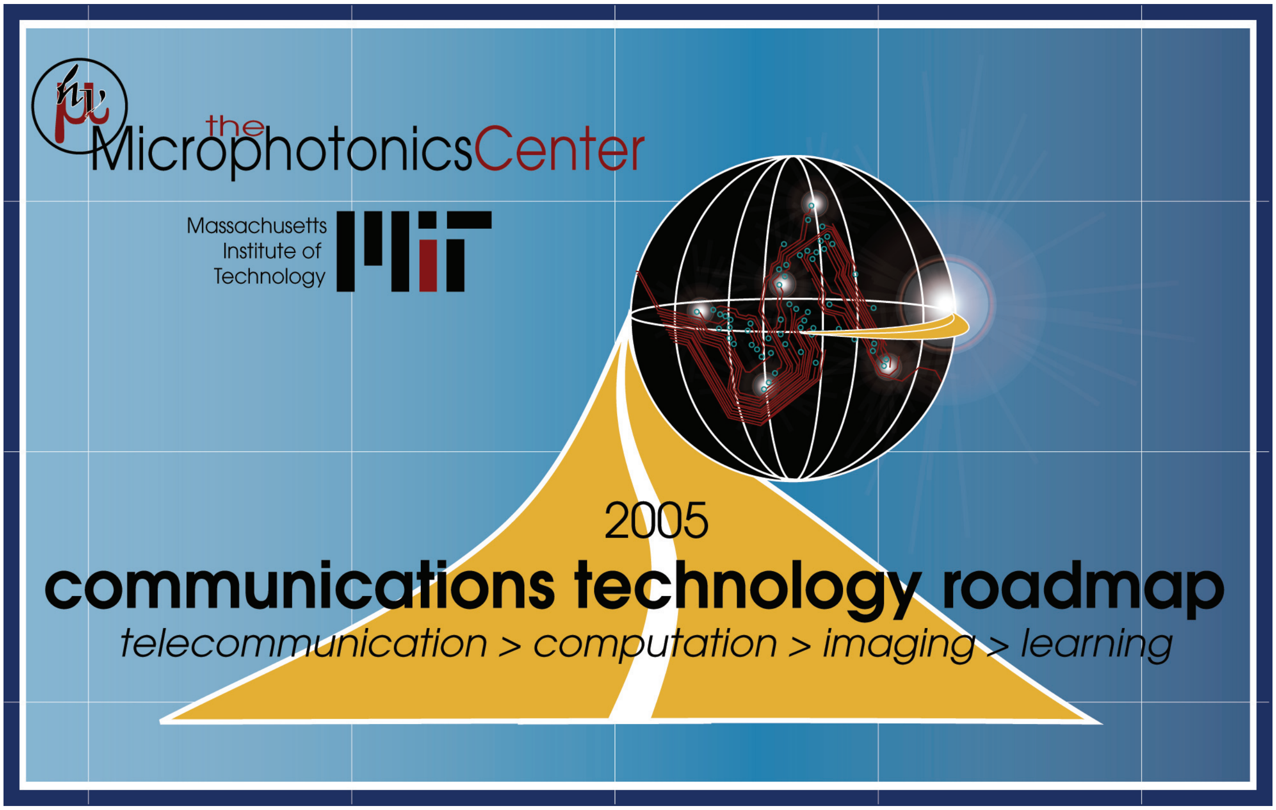

Microphotonics:
Hardware for the Information Age

Next Generation Transceivers

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Definitions

BGA	Ball Grid Array
CMOS	Complementary Metal Oxide Semiconductor
CWDM	Coarse Wavelength Division Multiplexing
DFB	Distributed Feedback (laser)
DPSK	Differential Phase Shift Keying
DVD	Digital Versatile Disc
DVI	Digital Video Interface
DWDM	Dense Wavelength Division Multiplexing
EM	Electromagnetic
EMI	Electromagnetic Interference
ESD	Electrostatic Discharge
FSO	Free Space Optics
FTTH	Fiber-To-The-Home
GbE	Gigabit Ethernet
GBIC	Gigabit Interface Converter
HDTV	High-Definition Television
IC	Integrated Circuit
IrDA	Infrared Data Association: www.irda.org
IrFM	Infrared Financial Messaging
ISO	International Organization for Standardization: www.iso.org
ITU	International Telecommunication Union: www.itu.org
LAN	Local Area Network
MAUI	Multi-wavelength Assemblies for Ubiquitous Interconnects
MEMS	Micro Electro-Mechanical Systems
MIT	Massachusetts Institute of Technology
MOST	Media Oriented Systems Transport
MSA	Multi-Source Agreement
O/E	Opto-Electronic
POF	Plastic Optical Fiber
PON	Passive Optical Network
RF	Radio Frequency
ROSA	Receiver Optical Subassembly
SAN	Storage Area Network
SFP	Small Form-factor Pluggable (transceiver)
TE	Thermoelectric
TIA	Transimpedance Amplifier
TOSA	Transmitter Optical Subassembly
UWB	Ultra-Wide Band
XENPAK	Multi-source agreement defining a 10 Gb Ethernet transceiver form-factor
XFP	10 Gb small Form-factor Pluggable (transceiver)

Next Generation Transceivers

Introduction

Transceivers are electro-optical modules that transform bi-directional electrical data streams into bi-directional optical data streams, and couple the optical signal into an optical fiber. This chapter presents a brief survey of the wide range of transceiver markets and highlights the nature of specific challenges that they may face when addressing their market applications and evolutionary paths. More generic challenges that are common to all different applications are discussed in later sections.

Telecommunications

DWDM

Current

The use of DWDM is well established and the International Telecommunications Union (ITU) grid maps out a capacity of 1.2 Tb/s per fiber. All the building blocks to achieve this are commercially available, so for the foreseeable future, demand can be met with existing technologies. The point at which this capacity will be exhausted is difficult to forecast and will depend on the geographic distribution of capacity, but this is thought not to present a near term challenge. There is significant activity in using more complex modulation schemes to achieve data rates greater than 10 Gb/s—for instance, using schemes such as DPSK. These lower the symbol rate, and hence dispersion becomes a smaller problem. Electronic dispersion compensation is also gaining much interest for similar reasons.

Figure 1 shows a block diagram of a transceiver used for long-haul telecommunications. Although transmitter and receiver are most often separate, the diagram illustrates the complexity involved with manufacturing these devices and the disparate materials systems that are used. Transceivers are in generally engineered so that each component uses appropriate materials for the highest performance possible, leading to the complex hybrid shown in the figure. The challenges in fabricating such a transceiver are discussed in later sections.

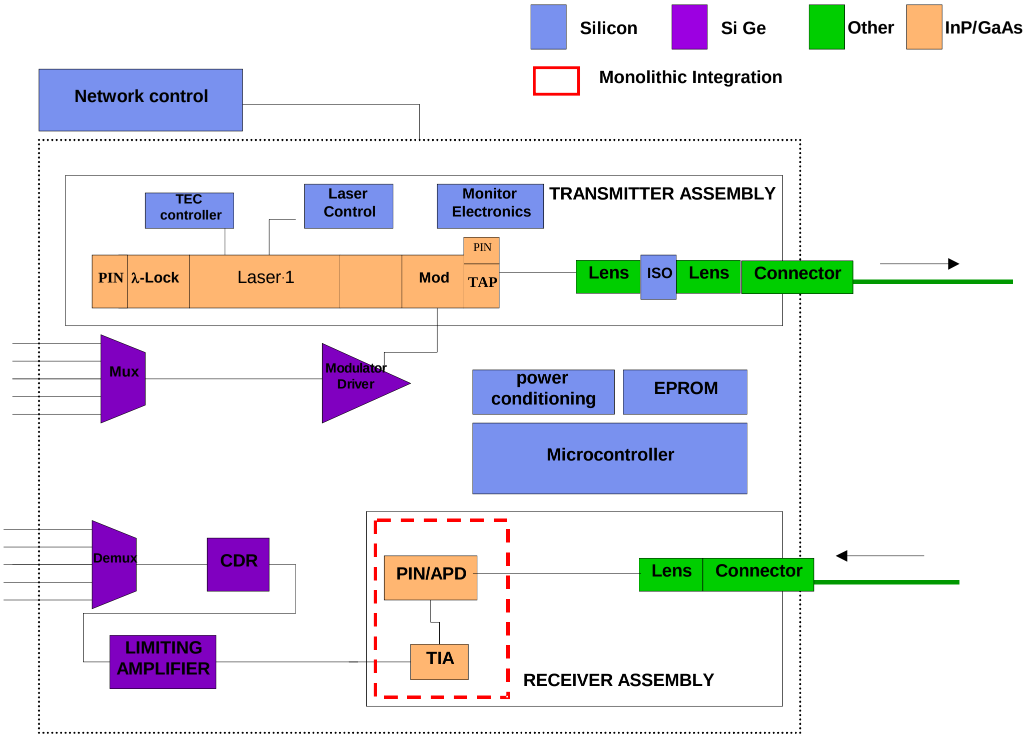


Figure 1. Block diagram of current transceiver.

Evolution

Figure 2 shows a potential evolution of a transceiver component. Tunable lasers offer the potential to reduce inventory and to give network operators the ability to use wavelength variability as a degree of freedom in controlling or reconfiguring their networks. Integration of one-dimensional arrays of lasers within a single package would also offer such enhanced functionality, but this must be balanced with the aggregate data rate that electrical interconnects can and must support based on down stream interfaces. Integration of high quality modulators with the lasers, design of lasers with higher temperature tolerances, and similar trends will lead to higher functionality optoelectronics at lower cost.

The ability of CMOS and processes such as SiGe to operate at 10-Gb/s line rates and to provide complex signal processing should allow a single electronic IC within the transceiver, so that a separate amplifier might be integrated with the digital electronics. The exact nature of this partition will depend on application, but it is likely that more complex functions will be built into fewer electronic and optoelectronic parts. Within this framework there will always be innovation and competition to provide incremental improvements in reach, power consumption, and other parameters. At the highest performance levels, it is likely that hybrid integration will continue to be required, as this allows each material system to perform to its strengths.

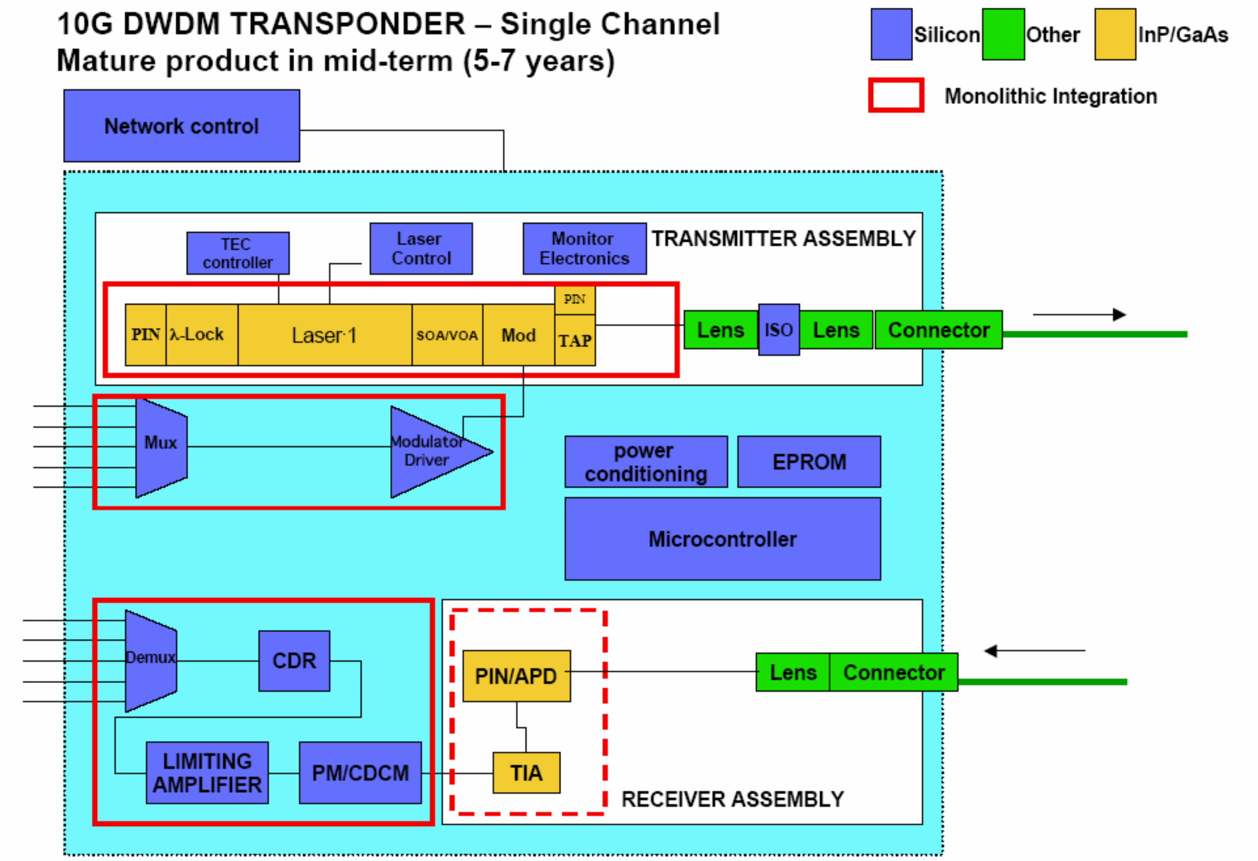


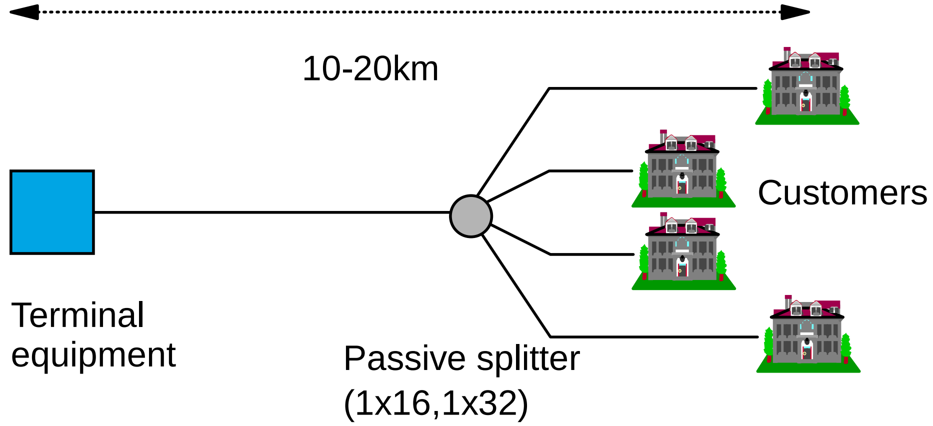
Figure 2. Single channel transceiver evolution.

Specific Challenges

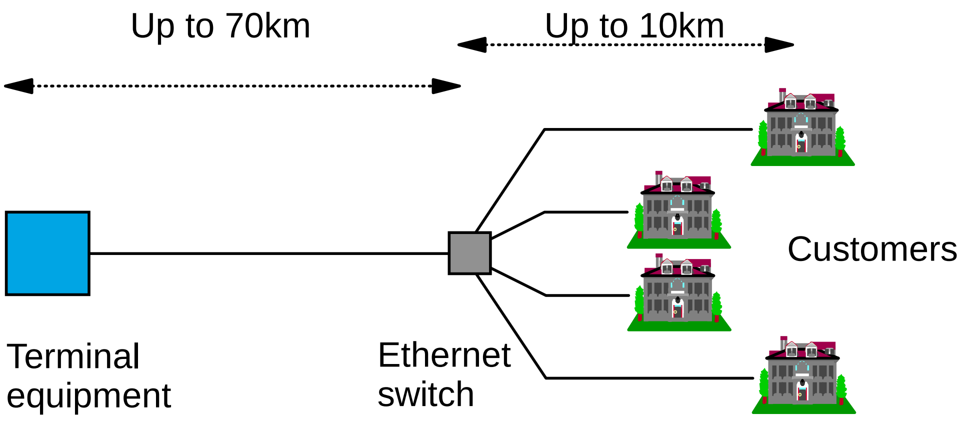
Several specific challenges were identified for DWDM transceivers:

- Integration of the TE cooler into the optoelectronic die to lower complexity and cost
- Integration of the isolation into the optoelectronic die to lower complexity and cost
- Increased dispersion tolerance to allow greater flexibility in network design and reconfigurability

Fiber to the Home (FTTH)



PON architecture



Switched architecture

Figure 3. Fiber to the home configurations: PON and Switched.

Current

FTTH is beginning to become a substantial market opportunity, both in the US and worldwide. This either uses a ‘switched-Ethernet-like’ geometry, or a Passive Optical Network (PON) as shown in Figure 3. The switched standard either uses single down-stream (to the user) and up-stream (from the user) fibers, or works on a single bidirectional fiber using 1310/1500 nm. The PON approach uses a single fiber with bidirectional transmission, using either 1310/1500/1490 nm depending on the particular standard and implementation.

The bidirectional approaches require a more complex transceiver, with a diplexer to separate up- and down-stream data flows. There is often a third wavelength delivered for analog cable television transmission; this requires a triplexer at the consumer installation.

A study at MIT shows 28 possible transceiver designs based on the two sets of standards [1]. Figure 4 shows a typical triplexer component that is required to separate up- and down-stream wavelengths, and forms part of a consumer terminal in a PON. This clearly differs markedly from typical transceiver designs. This high quality component requires multiple simultaneous precision alignments and is therefore difficult to fabricate at low cost. In any case, the diversity of standards makes the addressable market for each smaller than it would have been otherwise.

There is an approximately equal split in the deployments of switched and passive networks in the US, which appears to be in contrast with a preference for switched systems elsewhere in the world. There are widely differing data rates offered to consumers, the lowest being on the order of 10 Mb/s and the highest being 100 Mb/s. In Korea and Japan there is a move to provide 100 Mb/s to the consumer in the near future [2].

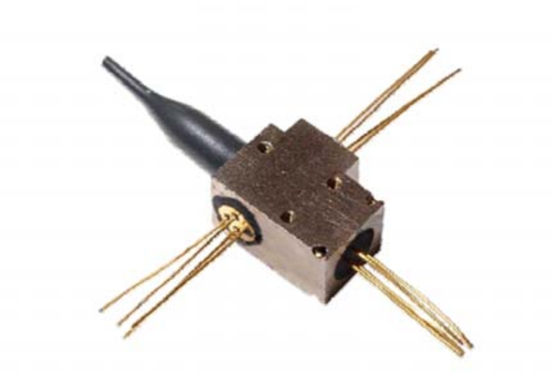


Figure 4. A typical PON triplexer.

Evolution

The growth of demand for high-bandwidth services is difficult to predict, and drivers such as gaming, video telephony, and services associated with imaging may mean the growth is rapid. Bandwidth asymmetry may evolve with services such as video telephony. Estimates of 100 Mb/s to the user in 2010 have been made, due to the requirement for transmission of high definition (HD) TV [2].

The nations with strong governmental policies aimed at “Broadband for all” have the largest number of subscribers served by FTTH. Korea Telecom suggests that by 2010, its FTTH network will be able to deliver speeds of 50–100 Mb/s to around three-quarters of Korean households. In November 2003, the Japanese Ministry of Information and Communications announced plans to construct a national broadband convergence network that will offer both wireless and wired users connection speeds of up to 50–100 Mb/s. The aim is to complete the network by 2010, although some areas may have access by the end of 2005.

Specific Challenges

Any change in the asymmetry of traffic and the aggregate data rates places different demands on the switched and PON architecture, but in both cases the second generation consumer terminal equipment are likely to remain at “commodity” data rates. Within the PON architecture, a high down-stream data rate requires high performance receivers and data recovery for the consumer, and very high-speed transmitters. This is likely to be a problem when data rates above 10 Gb/s are required, due to fiber dispersion.

Research Summary: Networking Technology Adoption

System Dynamics Modeling of Fiber-to-the-Home

Andjelka Kelic

Industry Environment

Fiber-to-the-home deployments do not require the cutting edge in technology, especially at the customer premise. All of the standards are constructed to deliver far more bandwidth than the consumer can currently use. The systems are designed so that providers can implement upgrades in bandwidth through software without having to swap out components. For transceiver manufacturers this implies that once initial deployment is complete, the replacement driver will be equipment failure as opposed to technology upgrade. The industry will be left with excess capacity from the deployment ramp up.

Social

In current broadband deployments, customer premise equipment has an expected life of five to seven years. This time frame is far shorter than the twenty year standard for long-haul components, yet it is still too long to prevent overcapacity once networks are deployed. Service providers have changed their reliability expectations for equipment deployed at the customer premise to be more in line with that of consumer electronics than of long haul equipment.

Political

Regulators at the federal, state, and local level have an interest in promoting telecommunications technology and ensuring that the services become available to all consumers, regardless of geographical location. When these regulators set policy, they examine the problem from the perspective of the consumer and consumer choice. This results in policies that are designed to benefit consumers from a price and service perspective, and also to assist new entrants in providing competition in the market.

Rarely do telecommunications policies look beyond the consumer and the service providers to the effects on the remaining portions of the supply chain. The optoelectronic components industry is at the opposite end of the supply chain from the consumer and thus subject to consequences of telecommunications regulation.

Recent broadband policies have been designed to promote the rapid expansion of broadband services to the consumer and also to promote facilities based competition. Rapid deployment of broadband, however, translates down the supply chain to a need for large production capacity that gets used in the initial network build, and then sits mostly idle and is used primarily to replace equipment that has failed.

The number of households adopting FTTH and other broadband (cable modem and DSL) under a government mandate that would give all communities that currently do not have access to broadband access to FTTH in three years will increase over the first 90–108 months before leveling off at 11M for FTTH and 17.5M for other broadband.

The corresponding effect that this policy and adoption rate has on transceiver deployment is shown in Figure 5. As shown in the figure, as the household adoption rate increases, so does the transceiver deployment rate. Once household adoption slows, the transceiver deployment rate begins to decline, ultimately falling off to a replacement rate that represents how often the deployed transceivers fail and are replaced. The figure also shows that the development of a standard FTTH transceiver does not solve the growth and decline problem.

Facilities based competition with multiple providers building FTTH networks would perhaps mitigate the problem; however, the networks are costly since facilities-based competitors need to build complete networks in order to compete with incumbents. To date, the majority of facilities-based competition has not been occurring in identical technologies. For example, broadband is currently provided over traditional phone lines (DSL), cable networks (cable modem service), and in some cases wireless networks.

The regulatory viewpoint of watching out for the good of the consumer is not likely to change. The industry needs to explore ways to protect itself from the cyclical nature of the telecommunications industry and prevent situations of overcapacity and excess inventory. Standardization across markets is one of the potential solutions.

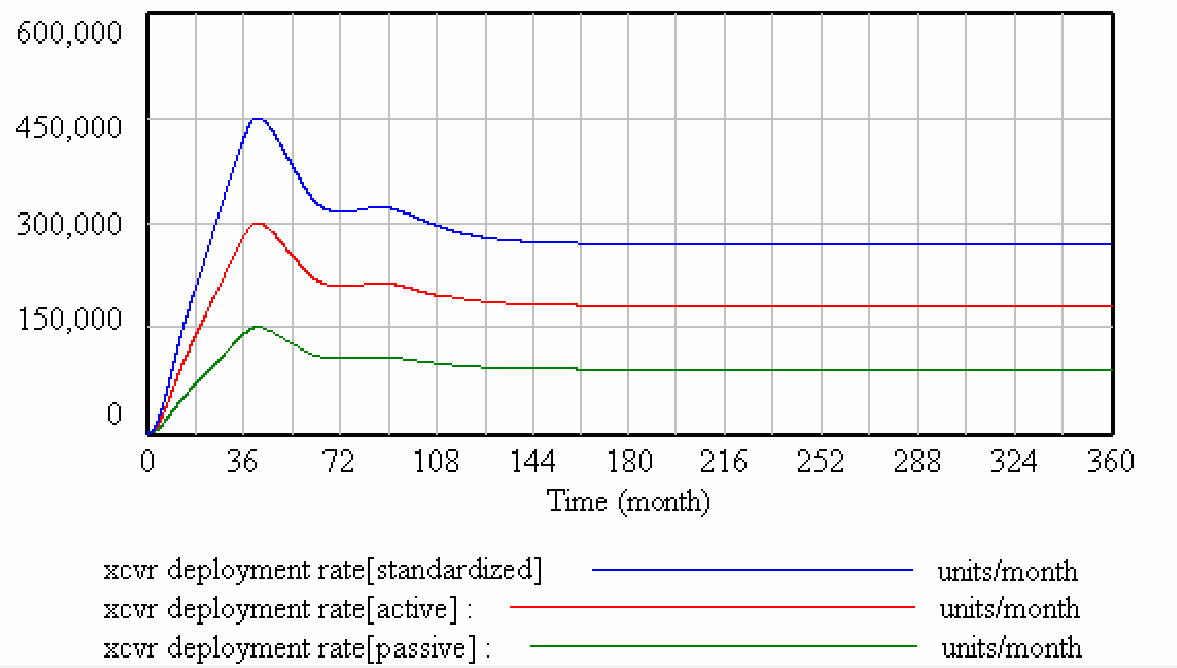


Figure 5. Deployment rate for FTTH standardized transceivers, active transceivers, and passive transceivers.

Free Space Optics

Current

A free space optics (FSO) link consists of two co-located unidirectional links that use narrow divergence laser beams to transmit information, usually using a simple On-Off-Keying scheme. Typical transceivers use 780, 850, or 980 nm sources because they are available at low cost and have high emission power. The major transmission impairment is fog, and this has similar characteristics over a broad range of wavelengths, so that there is no “magic” wavelength under the most severe conditions. There is a modest advantage in moderate fogs at longer wavelengths, and several companies are pursuing this approach [3]. Eye safety regulations are more also relaxed at longer wavelengths, allowing higher transmitter powers. In general, the optoelectronic components used are consumer rather than telecommunications grade, as data rates are typically below 1 Gb/s and solutions are highly cost-constrained. Receivers have quite distinct requirements when compared with traditional fiber designs, especially the need for a large detector area and electronics to work with associated high capacitance.

There is a relatively small market for FSO. In countries with developed infrastructure, these are mostly sold to enterprises for extension of LAN’s, backup links, or capacity augmentation. The telecommunications operator market requires availability impossible to guarantee due to link outage in fog, so there has not been a large take-up of these products by incumbents. In markets such as China, India, and Africa, there is substantial use in operator networks due to the low cost of deployment and the need to be “first to the consumer.” There is also a small and growing market in backhaul from microcell sites in cellular telephony.

Evolution

Data links to trains and other vehicles represent a growing market. Telematics, tolling, and other payment systems have found particular application in Asia, where the secure and proprietary nature of the solutions is seen as an advantage. In addition to a move to higher data rates for point-to-point links, point-to-multipoint systems are seen as the next major evolution. Simple consumer terminals communicate with a complex base station that can support a large number of users with the addition of users at low marginal cost.

Specific Challenges

Fog is the primary impairment, and there are no foreseeable optical solutions to this problem. (The use of radio back-up links may allow a paired solution, which is under investigation by a number of groups). Adaptive optics can be used to improve link budget by focusing the communications beam. Using fiber-fed systems is also desirable, and adaptive systems would likely be required to achieve this at the receiver. Receiver detector area is a key problem, as increasing this leads to more collected power, but the associated capacitance limits the bandwidth. Capacitance-tolerant front ends and low capacitance detectors are therefore significant and quite distinct from most fiber optic communications.

Data Communications: Ethernet

Current

Ethernet and Fiber Channel are the prominent governing standards for data communications. Gigabit Ethernet (GbE) terminations represent a large fraction of the volume associated with photonic components. The ratification of Ethernet standards has been rapid: 100 Mb/s in 1995, 1000 Mb/s in 1998, and 10 Gb/s in 2002—a nominal factor of ten scaling in data rate every 3–4 years. By any measure, this represents substantial progress. Presently, however, there is little discernable activity in higher data rate standards—continuation with the same rate of progress would imply a 100 Gb/s standard in 2006.

Figure 6 shows a set of typical transceivers for Ethernet applications—including SFP, GBIC, XENPAK, and XFP—which apply to various performance criteria. Common to these different packages are optical subassemblies, typically called Transmitter Optical Subassemblies (TOSA) and Receiver Optical Subassemblies (ROSA).

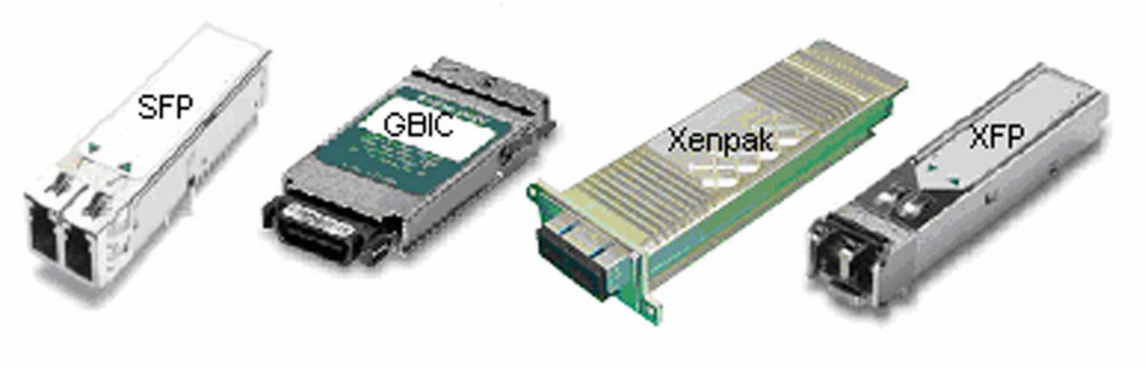


Figure 6. Typical 10-GbE transceiver. Typical TOSA and ROSA.

The cost of these components is falling rapidly: for 10-Gb/s short-reach optical transmission, the cost has been reduced by almost a factor of ten in the past three years. Despite this cost reduction at all solutions, including 1 Gb/s, evidence suggests that single mode fiber is perhaps a few percent of the installed base, and that capacity is most often augmented with a number of GbE multimode fiber or copper links rather than a single 10 Gb link. There exist standards today to drive 10 GbE optically over the installed base of multimode fiber; however, the transmission distances are limited due to inherent physical limitations of the installed fiber. New initiatives are underway to extend the reach, namely by using electronic pre- and post-compensation of the signal to work around the optical challenges.

Evolution

An increase in the line rate for Ethernet data links from the current 10 Gb standard (which by historical scaling trends would jump to 100-Gb/s line rates) will be technically difficult, due to fiber dispersion, and may require some form of CWDM or DWDM wavelength managed solution. The data communications industry has especially demanding packaging density requirements, so a move towards a multi-wavelength and multi-laser solution to reach the next factor of ten in scaling will require that particular attention be paid to the limitations offered by current TOSA and ROSA packages. At the same time, there will be a corresponding challenge on the electrical interface for these new electrical-to-optical transceivers.

Due to the absence of perceived activities addressing the 100-Gb/s node, it can be concluded that the current trends of driving down cost and extending the reach on installed fiber will be important next steps for the data communications-based photonics.

Specific Challenges

Multimode fiber represents most of the installed base in data communications, so that operating at 10 Gb over several hundred meters would represent a significant opportunity. There is work to use electronic dispersion compensation to address this. Operating at rates greater than 10 Gb/s will present significant challenges. Copper-based transmission standards at 1 Gb/s and 10 Gb/s are in existence, so that the use of fiber is not assured.

Data Communications: Fiber Channel

Current

Fiber Channel is used to connect networked storage within machine rooms and over distances of up to several kilometers covering campus areas, as well as the users who wish to access stored information. The optoelectronic parameters of Fiber Channel are similar to those of Ethernet implementation, but the protocols are distinct in that data must always be delivered to the storage device without retransmission.

Standards exist at 1, 2, 4, and 10 Gb/s. There is compatibility to 4 Gb/s, but the newer 10-Gb/s standard operates on single rather than multimode fiber. Conversations with a SAN vendor indicate this will lead to this being a little-used standard. Several manufacturers make transceivers that can either supply GbE or Gigabit Fiber Channel. Similar devices exist at 10 Gb/s, indicating that there is scope to converge standards and create adaptive transceivers.

Evolution

Work by the fiber channel community appears to broaden its application, rather than increase the data rates available at present. Avionics applications are a current area of interest, where the basic integrity of the network is advantageous for critical applications. It seems likely that in the future, a standard that uses multimode fiber at 10 Gb/s or between 4 and 10 Gb/s will be required in order to provide a steady “evolutionary path.” Discussions with SAN manufacturers also indicate this is the case.

Specific Challenges

At present, increases in the data rate of the SAN generally are not reflected in an increase in system performance. This is due to bottlenecks in the electronic backplanes that connect the disk drives and to the evolution of the drives themselves. In this case, the increased signal processing used to improve storage density slows the rate of increase in drive transfer rates. The nature of a SAN network also requires that it operate at approximately the same data rate in all its parts, so any upgrading is limited by the slowest part of the network. The challenge is therefore to translate an increase in data rate to a corresponding increase in storage network performance.

Short-Range Interconnect

Automotive

There is much activity in low-cost interconnect for automotive applications, where reducing wiring harness weight and complexity are of interest. The Media Oriented Systems Transport (MOST) protocol operates up to 25 Mb/s and is designed to use either optical or copper physical layers [4]. Flexray is a drive-by-wire protocol that can use the same physical layer but is designed for safety critical applications [4]. There is also work on an automotive firewire standard for DVD (IDB1394) and other in-car entertainment [4]. One additional motivation for using optical harnesses in automotive applications is to eliminate susceptibility to ESD and EM interference in mission-critical sensors. This application uses visible sources and plastic optical fiber (POF), and is extremely sensitive to cost and system reliability. There is a highly competitive copper alternative at lower speeds.

Evolution

The current available data capacity of the MOST bus is thought to be sufficient in the near future, so the major evolution is likely to be more extensive use of the bus for safety and other sensor information. There is significant interest in communications to and from cars for download of entertainment material from storage in the home, formation of ad-hoc networks with other vehicles, and other applications. (An ISO standard for extra-vehicle communications that incorporates both RF and free space optical links exists [5]). The link to other vehicles can increase demand for bandwidth within the car, but this will probably be relatively modest.

Specific Challenges

The major challenges in this area are the need for extremely robust and low-cost components. Discussions with automobile manufacturers indicate that this has proven to be a problem with early optical implementations and that copper is still a highly competitive alternative.

Consumer

Digital imaging, both still and video, is likely to create new markets for low-cost optical interconnect, both free space and guided wave. The bandwidth to connect consumer devices, such as DVD players and displays, is rapidly increasing. While compression is used for storing and transmitting information such as images, this creates delay, and there is often a need for a high-bandwidth link between the playback device that performs the decompression and the display. Optical digital video interface (DVI) requires a 2.4-Gb/s data rate for transmission of modest video resolution.

There is therefore a need for low-cost and high bandwidth interconnect. Plastic optical fiber (POF) that uses visible sources is attracting significant interest for this, although achieving the performance required for transmitting uncompressed information is challenging. At present, commercial free space interconnect is restricted to Infrared Data Association (IrDA) links, which operate at data rates of 115 Kb/s to 4 Mb/s [6]. Secure payment and “point-and-pay” systems are of increasing interest, with the Infrared Financial Messaging (IrFM) standard being adopted by major manufacturers and credit card operators. In this case, a short-distance optical link with “intrinsic” security from eavesdropping is attractive. At the same time, standards for 100 Mb/s “IrDA type” connections are under development and will find increasing use for low latency transfer of digital content, especially to highly portable devices such as cell phones.

Evolution

The decrease in memory cost and the increase in the resolution of digital images will place increasing demands on playback devices and displays, as well as on the interconnect between them. The move to higher definition display standards will have a similar effect, so that the cost-performance ratio requirements will continue to increase. A similar increase will be seen in free space links, where the potentially lower power consumption when compared with the RF alternative is attractive.

Specific Challenges

A typical bandwidth-distance product for POF is 4–10 MHz-km; more sophisticated perfluorinated graded index POF offers a bandwidth-distance product of 300 MHz-km at longer wavelengths (850 nm). For short-range interconnects and short-span Ethernet, modern POF is attractive. Low-cost sources and detectors that offer high bandwidth represent a significant challenge, however.

The evolution of the IrDA standards is equally challenging, both due to the optoelectronic performance required from low-cost devices and the processing power available on portable terminals. The future of both IrDA and fiber-based interconnect will also depend on the take up of competitive radio standards, specifically ultra-wide band (UWB).

Server Interconnect

The standard chassis design of electronic construction consists of cards that are plugged into electronic backplanes. These provide connection between those cards and a route to connections between backplanes in a rack. The growing demand for bandwidth for both card-backplane and backplane-backplane connections represents a substantial opportunity for photonics. As an example, IBM estimates peak demands for 4 Tb/s of capacity at the present time, and 40 Tb/s in 2010 [7].

The limit on current electrical connections is approximately 2 Gb/s/mm^2, with substantial insertion force required to make the connections. Electrical interconnect also requires detailed electrical design, and substantial power consumption both to overcome interconnect loss and to power terminated transmission lines. Meeting EMI constraints will become increasingly difficult.

Current short-distance optical interconnect is largely based on one-dimensional parallel optics approaches. Current commercial products operate up to 48 Gb/s and use 12 fibers at 4 Gb/s per fiber. Figure 7 shows one such example. The MAUI project [8] has demonstrated a 0.5 Tb/s interconnect that used 4 CWDM channels on each fiber of a 12-channel ribbon.

Figure 7. Typical server interconnect transceiver [9].

Evolution

The demand for bandwidth will continue to grow, with an order of magnitude change over five years. This is very challenging. At present one-dimensional parallel optics, in combination with wavelength, is mostly being used as the scaling dimension. The move to two-dimensional optical interconnect with WDM offers the possibility to scale to the required capacities with relatively modest numbers (though still in the hundreds) of optical channels.

Work on spectrally efficient schemes may offer other dimensions (although the power consumption associated with more complex signaling may make this unattractive [8]). There is also interesting preliminary work on modal multiplexing [10], which may allow greater utilization of a single fiber.

Specific Challenges

Parallel links typically have two degrees of scaling: the number of fibers and the link rate. In certain circumstances, wavelength is used to provide another scaling dimension, but using this extensively can be expensive and therefore not suited to low-cost applications.

There is little doubt that the number of connections required will be large; consequently, the reliability of the optoelectronic components will be important and will have to compete with that available from a simple electronic channel. This represents a significant challenge. At the same time, the target cost for such interconnect is $1 per Gb/s.

The capacity available for a single terabit fiber link requires a connector area of 500 mm^2 assuming an electrical connector density of 2 Gb/mm^2. In parallel optical links, the optical density is possibly two orders of magnitude higher than that available electrically. Either electrical I/O will have to scale significantly, or the transceivers will be directly soldered to the board. (Current BGA technology can provide densities of ~90 Gb/mm^2, rising to 3000 Gb/mm^2 in 2015 [11].)

Generic Challenges: Transceiver Fabrication

Within a typical transceiver package (Figure 1) there are optical, optoelectronic, and electronic components, as well as other mechanical spacers that must be aligned and fixed to high tolerance. The complete component is then sealed and tested.

A study into the economics of transceiver manufacturer was undertaken by Fuchs and Kirchain [12]. This study compared the cost of fabrication of (1) a discretely packaged 1550-nm InP DFB laser & discretely packaged electro-absorptive modulator, (2) a discrete 1550-nm InP DFB laser & discrete electro-absorptive modulator within a single package, and (3) a 1550-nm InP DFB laser and electro-absorptive modulator monolithically integrated on a single device. The cost of research and development was not included.

Table 1 shows the top 10 cost drivers for the manufacturing process. In all these cases assembly, packaging, and testing comprised approximately 80–90% of the total cost of the devices.

Table 1. Top 10 cost drivers for study of transceiver economics [12].

	Monolith. Integrated	Discrete Device	Discrete Package
Alignment	1	1	1
Assembly Tests	2	3	2
Device Test	3	4	4
Chip Bond	4	2	3
Fiber Attach	5	6	5
Bench Assembly	6	9	6
Spin-On Resist	7	7	10
Visual Test	8	5	7
Wirebond	9	10	9
Bench Attach	10		8
e-Beam Evaporation		8	

Alignment

Table 1 shows that alignment is a critical costly step in transceiver manufacturer. Figure 8 shows the effect of fiber misalignment on coupling loss between two waveguides, illustrating the order of precision required for source fiber alignment.

Figure 9 shows a comparison of different alignment and assembly techniques [13]. This indicates that at high volumes, robotic alignment of standard parts is the cheapest, provided the capital cost of the machines is serviced by the volume of production. At lower volumes, schemes that use optical benches and other more expensive parts to enable passive alignments provide a good solution. The exact “break-point” requires detailed economic modeling of the type undertaken by Fuchs and Kirchain.

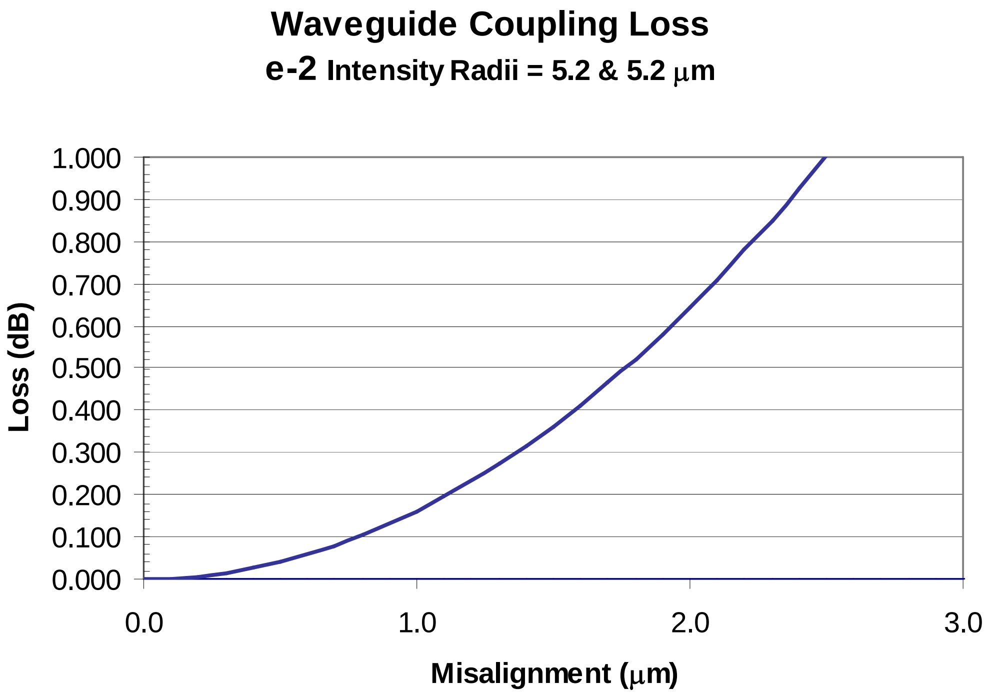


Figure 8. Effect of waveguide misalignment on coupling loss [13].

ALIGNMENT OPTION	Performance Tradeoff?	Added SC Device Complexity?	Relative Alignment Cost at Low Product Volume	Relative Alignment Cos at High Product Volume	
Robotic Active Alignment	No	No	High	Low	Capital utilization (throughput) is key
Robotic Vision Alignment	No	Yes?	Highest	Low	Capital utilization (throughput) is key
Passive Self Alignment	No	Yes	Low	Med.	Process complexity persists at high volume
Lens-Based Expanded-Beam	No	No	Med.	High	Precision alignment of lens. More components
Expanded-Mode Alignment	Yes?	Yes	Med.	Med.	Process complexity persists at high volume
Combined Approach “Avanti”	No	No	Med.	Med.	Distribute robot cost over more products
Integral MEMS	No	Yes?	High	Med.	Process complexity persists at high volume
Optically Generated Coupling	Yes?	No	Low	Med.	Optical connection needed to activate

Figure 9. Comparison of different alignment techniques [13].

Assembly

The problem of improving optoelectronic assembly was summarized as follows [14]:

- Reduce the number of parts
- Reduce the number of processes
- Reduce the number of interfaces

Table 2 shows a typical assembly flow for a transceiver component. Each of these requires detailed design and a high degree of process control, with each company developing custom tools and fixtures to perform these. As yet, there is no accepted “best practice” and standard machinery for each of the required processes. There is a generally accepted view that this would be advantageous, but no consensus as to how this might be achieved.

Table 2. Typical assembly processes [12].

Backend Pre-package	Backend Packaging	Test
Wafer Cleave Bar Cleave HR Coating AR Coating Bench Attach Cooler Assembly Chip Bond Wirebond Burn-in Bench Assembly	Alignment Bake Lidding & Lid Check Package Clean Fiber Attach Sleeve Attach	Incoming Inspection Post-deposition Test Automatic Inspection Plant Transfer Test Set Post Wire Bond Visual Final Chip-on-carrier Visual Assembly Visual Pre-lid Visual Post-ash visual Chip-on-carrier Test Cooler Assembly Test Post-bake Test Temperature Cycle Final Package Test

Packaging

The Telcordia specification for telecommunications components places heavy demands on the performance of transceivers and the quality of manufacture. These are summarized below:

Telcordia GR468-CORE Specifications

- Must have burned-in lasers and receivers in final mounting condition
- Exposed laser, receiver, and fiber surfaces must be in “hermetic” environment
- Must be able to withstand considerable mechanical and thermal shock as mounted
- Must be able to withstand storage at elevated and lowered temperatures (85°C to -40°C) and operation from (85°C to -5°C)
- Must demonstrate reliability in these environments, typically for a design life of 20 years or more.

It seems that these requirements will not be relaxed for telecommunications components, but that the degree of testing is not suited to consumer and computer interconnect. In both interconnect applications, components must be reliable, but testing must be simple for components to meet the required cost.

For low-cost applications, there may be packaging techniques that can be transferred from other industries. Local hermetic sealing is widely used in the automotive industry for MEMS sensors. Figure 10 shows a possible solution for an optoelectronic component.

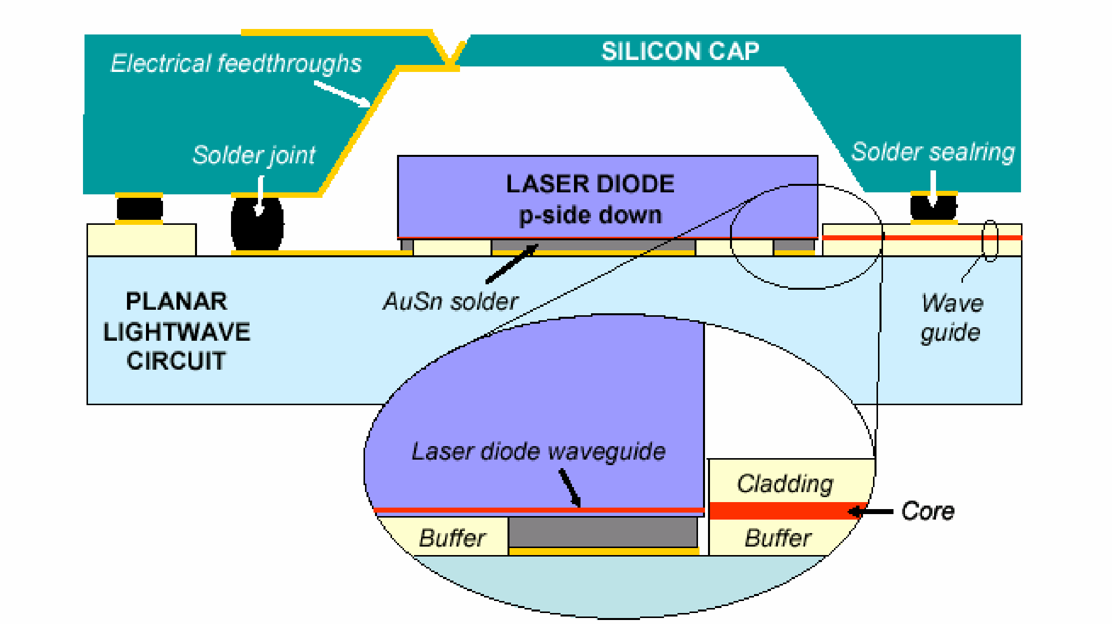


Figure 10. Local hermetic sealing for optics [15].

Functional Test

The Telcordia specifications require the burn-in of lasers and optoelectronic components, but also provide functional tests of completed devices. Each transceiver standard generally has its own testing method. Reconciling these standards with similar specifications is difficult, especially when each has problems of compatibility with its own previous variants. This may be a barrier to the "universal transceiver" concept, in that the cost of meeting all the test conditions may outweigh the benefits of a common production process.

Generic Challenges: Standards and Proliferation

Current

In order to examine the breadth of solutions available, an MIT study [16] examined the number of transceivers (either transmitters or receivers) available, considering typical wavelengths, reach, packaging power, and sensitivity. This identified approximately 580 transceivers, as summarized in Figure 11.

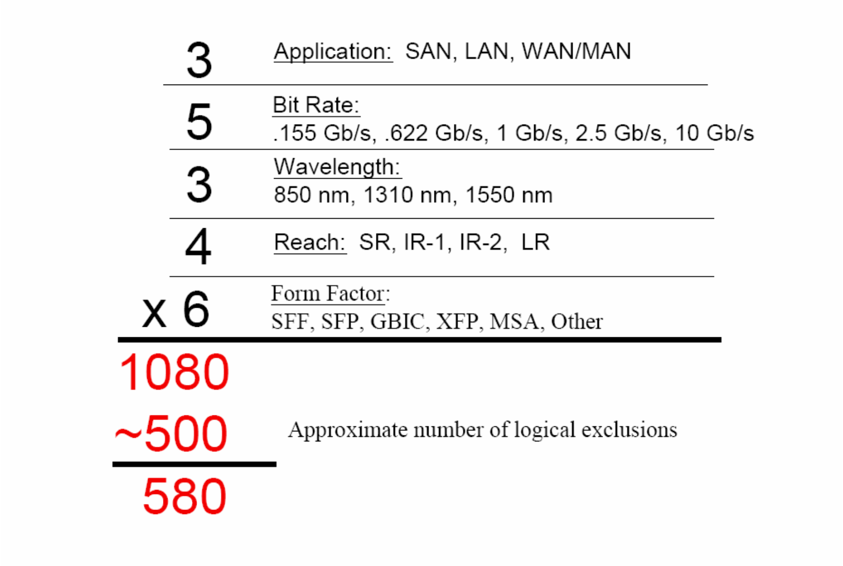


Figure 11. Proliferation of unique numbers of transceivers [16].

Such diversity is a likely consequence of the [then] high demand for each component and the available expenditure for research and development, and possibly a sign of an industry yet to find some common best method of solving a certain problem. Diversity is not necessarily a fundamental disadvantage. In a technical sense, each solution can be specifically optimized for the application, so “capacity” is matched to the demands of the application and not wasted. This cost must be balanced, however, against the gains of volume markets for different applications and the potential for foundry processes that common features offer.

Future Proliferation

There appears to be some stabilization in the rate of generation of new classes of transceivers in data communication, albeit only in certain sectors. As mentioned previously, the ratification of Ethernet standards has been rapid—100 Mb/s in 1995, 1000 Mb/s in 1998, and 10 Gb/s in 2002—with little discernable activity in higher data rate standards. Fiber Channel and Ethernet are distinct in their protocols, but some effort has been made to create transceivers that adapt to both protocols and use the same basic physical layer. In telecommunications, DWDM standards have a well-defined wavelength grid, and requirements for chirp are fixed by fiber and reach.

Within these parameters are a multitude of variants. Multi-Source Agreements (MSAs) have led to common packaging and interface specifications that allow second sourcing for systems suppliers. Such MSAs require substantial technical effort, especially the development of packages such as the XFP design. The cost of these efforts needs to be balanced against the possible revenue from such transceivers.

Conversely, the new deployments in FTTH have standards that create many possible transceivers. Additional analysis suggests that it may be possible to design one or two transceivers that would meet the optoelectronic performance specifications across the various standards, although electronics would be different for each case, with different testing methodologies for each. Even if this reduction were possible, the transceiver required is markedly different from those used for other applications.

Potential Solutions to Proliferation

Organizational solutions to the proliferation of standards are discussed in the Current State of the Industry chapter. In these sections, two technical approaches to the problem are discussed.

A Universal Transceiver

A number of MIT studies have shown that there is some opportunity to reduce the number of standards by considering the basic wavelength, data rate, and link budget requirements, and choosing values that exceed or meet these requirements [16]. A universal transceiver may then consist of an adaptive electronic IC, common O/E and E/O interfaces, and a common package. Functional testing might then be undertaken for all the standards required. In this case, the excess cost must be balanced by the advantage of a standard process and the cost savings this brings about. Figure 12 shows a radical approach to transceiver evolution, where a high level of monolithic integration allows excess functionality at very low cost. In this case it may be that the benefits outweigh the cost of the capacity.

A more pragmatic approach is to use common E/O and O/E interfaces, together with custom electronics (though with a standard interface "format" between optoelectronic and electronic ICs) and perhaps common electrical interfaces of a type governed by an MSA. It seems more likely that this approach will be used, due to the rich diversity of package types, environments, and "legacy" components that must be considered. In all such cases, detailed economic analysis would allow the "best" level of commonality to be determined, and tools to do this are required.

	FTTH	Storage network	Server	LAN
Reach(m)	15000	25	1	1000
Data rate(Gb/s)	1	40	1000	10
Wavelength	1310nm			
Laser	InGaAs/InP	Modulator	InGaAs/InP	
Detector	Ge on Si			

Capabilities of transceiver

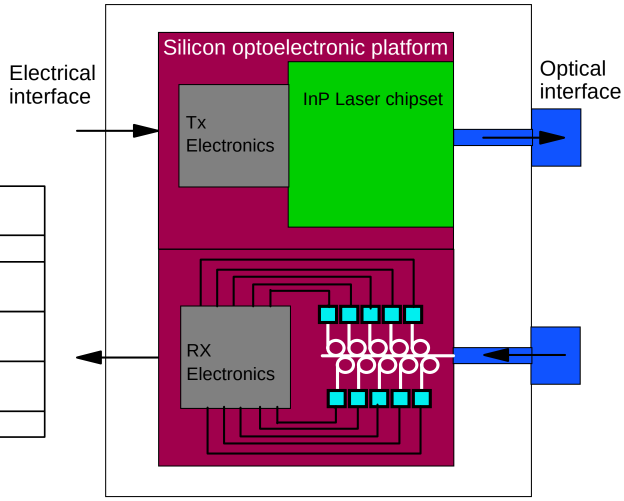


Figure 12. Possible transceiver using silicon photonic platform [16].

Silicon Model

The silicon IC industry is an interesting example to consider: it supports a very rich set of application-specific devices and functions in packages of varying size, form factor, and geometry. In this case, though, there is a “standard” foundry process “inside the package,” standard methods of packaging, and often large markets for each of the products.

Optoelectronics is fundamentally more challenging due to the disparate components and materials that must be used in transceiver manufacture, but some convergence to a common set of processes and techniques is highly desirable. An optoelectronics “fab” would allow proliferation of functional standards, as well as support fab-less start-up companies, larger manufacturers, and the other “actors” of a vibrant industry. In order to create such opto-fabs, there must be not only a sufficient market to support the capital required, but also a convergence of what is considered best practice for the processes of transceiver fabrication.

Process Convergence

There is no shortage of high quality engineered production and assembly processes for transceivers—indeed this is a prerequisite for the production quality devices, and each manufacturer has a particular preference. Devices with the highest performance will likely require hybrid integration solutions, so each materials system can be used to its best effect. The best solution might be seen as an optoelectronic subsystem hybridized with an electronic IC. Monolithic integration might then be limited to parts that can be optimized in each materials system.

Work presented at Roadmap meetings shows that modest volume systems that use passive alignments offer the lowest cost solution for this assembly step. At higher volume, robotic and vision-controlled alignment systems used with simpler parts that do not incorporate passive alignment features can be a cost competitive solution.

Monolithic integration is likely to be used increasingly within the optoelectronic systems; this offers the potential for converging to a standard opto-process. The cost modeling from Fuchs and Kirchain [12] indicates that subsystem integration (using their modulator/laser example) allows lower cost parts (although this does not take into account R&D expenditure). Monolithic integration in system electronics is likely to allow the analogue transimpedance amplifier (TIA) and associated components, as well as digital signal processing, to be combined on a single IC. A single convergent electronic/photonic platform is the subject of the Silicon Optoelectronics chapter. If successful, this may satisfy all but the highest performance requirements.

In all these cases, the decisions that will lead to convergence are largely economic, given that the processes meet the technical requirements. Development of a best-practice route to a transceiver therefore requires a means of comparing alternatives, either using standard decision tools or through research. In all cases, this is likely to require collaboration between manufacturers.

Research Summary: Technology and Policy Drivers for Standardization

Michael Speerschneider

The late 1990s crash was a market reaction to the network and manufacturing overcapacity that engulfed the industry after years of unrealized growth expectations. The analyses in this work suggest that the proliferation of transceiver designs is one of the reasons why the OEM industry has been unable to adequately adjust to changing market conditions. To meet transceiver performance demands across the telecommunications and data communications industries, there are nearly 600 different transceiver product specifications available on the public websites of six major transceiver suppliers (see Figure 11). The research has not addressed the difference in manufacturing processes for each of those products, and it is likely that many of the designs can utilized the same production line. The story is clear, however: there are enough different flavors that the manufacturing capacity is divided among many different production lines and the merging of operations is not straight forward. These results, while striking, do not capture the entire problem as the survey of existing transceivers does not include FTTH transceivers, nor does it cover new and emerging markets—including automotive, personal electronics, and aviation systems—that could provide a significant boost to transceiver volumes in the near future.

The logical solution after realizing the extent of proliferation is that standardization is a potential means by which the OEM industry could be revived. The proliferation of transceiver designs results in a fractured industry that cannot take advantage of economies of scale and manufacturing learning in a way that pushes down costs and allows optical to be more competitive (Figure 13). Standardization can enable OEMs to leverage the volume across various market segments, and within those segments, creating more cost effective manufacturing.

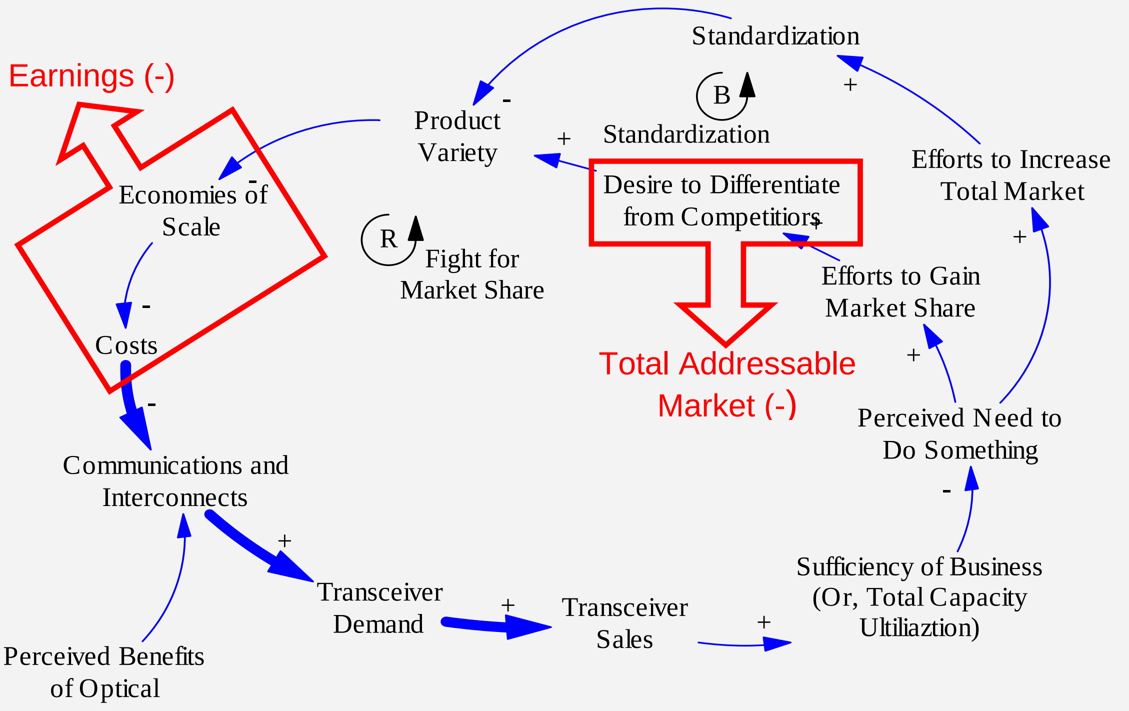


Figure 13. Causal loop diagram for standardization showing “Standardization” balancing loop and “Fight for Market Share” reinforcing loop. Both Earnings and Total Addressable Market decrease as a result. Plus (+) symbols indicate reinforcing loops or directly proportional quantities; minus (-) symbols indicate balancing loops or inversely proportional quantities.

System dynamics modeling was employed to test the assertion that standardization could improve the OEM industry's performance. The following is a summary of the important insights from the exercise.

- Shortening the product lifetime helps the industry by increasing the revenue base as the installed transceivers are replaced more frequently, and by avoiding peak/valley market behavior as each new technology generation closely follows the previous.
- Increasing the R&D investment and/or the R&D productivity can help optical out-compete other communications technologies.
- Standardization leads to orders of magnitude increases in the revenue from the enhanced market penetration spurred by greater concentration of industry resources on the improvement of fewer platforms.
- Continuance of the differentiation policies results in further market stagnation and less resources to improve each platform.
- There will be an initial period in which the revenues for the standardization path are lower than those when continuing with the status quo. This initial weakening of the industry provides a formidable barrier to acceptance.
- Cross-market convergence is important. In the model, each individual segment could be taken as the industry as a whole, with the number of platforms across the segment replaced by the number across the industry.

Transceiver Standardization

Network Hardware – One can argue that variety only adds to the industry's problems and a standard should be developed. Standardization within market segments and across segments can provide strong leverage for the performance/cost improvement learning curve. A key issue is the function partitioning in a standard transceiver. The standard should provide rules that allow manufacturers to seamlessly insert their products into any application, and allow enough synergies that enable volume manufacturing that significantly lowers costs.

Data Management – As the transceiver becomes standardized, competition will move from providing the lowest-cost network to providing higher reliability and superior services. Data management methods directly impact the quality of reliability and services, and therefore standardization of the transceiver should not have minimal affect of the type of management that is used. The integrated circuitry of the standard transceiver should be compatible with any protocols that are developed for any segment. This suggests simplification of the transceiver driver circuits.

Network Architecture – The standard transceiver should be robust enough to be impartial to topology; no particular architecture will favor the transceiver. The decision on topology will be made by network providers as they consider bandwidth demands and the power requirements and the available power sources for the network.

Overcapacity – There are two potential solutions to fill the overcapacity of the OEM industry in the medium to long term. First, overseas demand for FTTH and other optical networks is still strong. Entering into agreements with overseas network provides in need of components could provide the volume guarantees needed to justify investment in automation techniques. The second way to increase capacity utilization is to learn from the IrDA case study and secure volumes without an identified market. For example, a transceiver installed in every TV, stereo, and speaker system would provide volumes and promote the development of ways to use the potential bandwidth, even if it is not used initially. The key to this strategy is low-cost devices that can only be realized through standardization. The second strategy obviously needs cooperation with personal electronic or other industry manufacturers. These measures offer an example to an opportunity for OEMs to tackle the lack of demand in the industry instead of simply working to reduce costs and hoping for demand to pick up.

Industry Cooperation – It is vitally important that the industry come together to formulate the standard. The CTR is a good start to the level of cooperation that is needed; however, to achieve universal buy-in to the path laid by the Roadmap, the work and conclusions of the CTR should be subjected to industry-wide review whenever possible. The other component of cooperation concerns changing the cultural norms of the OEM industry and the providers. The past industry environment put a premium on specialization and optimization. It will take a paradigm shift in corporate expectations to accept a device that may not be optimal for the desired network in exchange for a more viable components industry.

Regulation – Not only must the standard transceiver be somehow codified into a federal regulation, but fair competition in the market also must be provided by regulators. This fair competition largely rests on control over the infrastructure. Based on other networked industries (national highway system, utilities, etc.), there are two types of network control. As in the national highway system, all lines could be controlled and maintained by the federal government. Networks also could be shared by all users. This is common in the utilities markets today, where network providers are forced to sell capacity indiscriminately to all potential users. Finally, the networks could be private and only available to the network owner, as was the case in the early days of the railroad, and is now the model that allows Verizon to begin a FTTH roll out. The biggest fear here is that the network owners would provide their own services and effectively block all other service providers, creating a deficiency in consumer welfare[1].

Standardization – Standardization is essential. The development of that standard is critical and general guidelines should be formulated as soon as possible. MSAs and other efforts to form a standard by the market force of participating OEMs are not adequate: true convergence and industry wide acceptance needs to be achieved. The purpose of the standards will be to begin to reverse the “death spiral” trends. Essentially, the “Gaining Market Share” reinforcing loop should be made extremely weak, leaving the standardization loop as the stronger path (see Figure 13).

Obsolescence – The standard should be made flexible enough to allow significant year-to-year improvement, resulting in shorter product lifetimes. To achieve obsolescence the transceivers need to be cheap enough for network providers to justify frequent upgrades, and network pluggable to allow cheap and easy replacement with minimal network down time and to avoid the cost of a “truck roll[2].”

Incentives – The model has shown that OEMs may be adverse to standardization due to the initial weakening of the industry and lack of a guarantee that standardization will even bring the market back to original levels. To combat these fears, incentive programs should be implemented to help the OEMs through the initial period[3]. Incentives should be careful not to prop up firms that should be acquired by larger firms, or that should simply fail, while at the same time encouraging the industry as a whole to follow the standardization path. The involvement of federal regulators and industry consortiums need work together to work out the incentive structure that could in clued tax relief, subsidies, or capital expenditure grants.

Next Steps

An oversight organization that has the power and respect to influence the industry and the manufacturers should be formed. This organization will be more far-reaching than the CTR, and will not be a purely governmental entity. It is certainly a challenge to develop such an organization, but it is essential. Other industries have managed to organize in appropriate ways, with various levels of sophistication, including the railroad industry and, more recently, the semiconductor industry.

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[1] For a further discussion of this, and other private control issues, see Owen, Bruce. *Assigning Broadband Rights.* Regulation, the Cato Review of Business and Government. Summer 2004, Vol. 27, No. 2

[2] Current non-pluggable solutions require the network provider to send a technician and a truck to the site to upgrade and/or repair the transceiver box. “Truck roll” refers to the deployment of the truck to the location.

[3] Perhaps an incentive program similar to PV in Japan would be appropriate. In that case, the Japanese government covered 50% of installation costs to encourage sales. The revenues for those sales were used for further R&D that improved performance, thus making the products more attractive to consumers. The subsidy is being slowly eliminated as the industry grows.

New Applications

Table 3. Transceiver characteristics in potential new markets.

	Volume	**Cost Requirements**	**Optoelectronic Performance**	**Comment**
FTTH	High	Low	Modest	Significant market for traditional transceiver manufacturers through very complex component
"Digital Home" Interconnect	High	Very low	Low	Possible opportunity for new integrated platforms
Automotive	High	Very low	Low	High reliability required at low cost
Free Space Optics	Low	Low	Low	Not suited to telecoms transceiver manufacturers
Server Interconnect	High	Low	Very high	Rapidly growing market—extremely difficult technical requirements
IrDA Links	Very high	Very low	Low	Not suited to telecoms transceiver manufacturers

The ideal new market would offer reasonable margins, high volume, and a short replacement cycle to ensure ongoing revenue. Table 3 shows a very simple summary of significant non-telecom and datacom markets. FSO and IrDA links do not represent good opportunities for growth, for different reasons. FSO systems use commodity components, and some of the technical requirements are distinct from fiber transceivers. IrDA is an extremely cost-sensitive application with a very simple fabrication process so it is not well-matched to the capabilities of transceiver manufacturers.

FTTH offers a significant opportunity and is well-matched to the capabilities of manufacturers, although the complexity of the transmission scheme means that there is little similarity with other transceivers. Consumer interconnect and automotive interconnect both offer high volumes and initially require relatively modest optoelectronic performance. These might act as initial drivers for newer materials platforms, where monolithic integration of devices with relatively low performance allows manufacture at the very low costs required.

The most technically challenging is server interconnect because the combination of reliability, cost, density, and capacity will be very difficult to meet. This is likely to be a key driver for "platform" optoelectronics processes. Optical interconnect will become "closer to the processing" in electronic systems, which will not only increase the market size, but also create more aggressive performance requirements, thus driving platform development.

Building a Platform: Infrared Data Association

John Petrilla and Lionel Kimerling

The universal platform for air link optical datacom is the IrDA. This transceiver platform has evolved to a low-cost solution for computer peripherals, PDAs, and cell phones. The IrDA development history highlights the key elements of platform building:

1. Minimize functionality
2. Employ commodity components
3. Utilize an accepted packaging solution
4. Have volume expectations high enough for investment in automation

This path may be generic and relevant to establishing a direction for standardization and cost reduction. It is interesting that while standardization triggered cost reduction, it also followed a series of fitness tests of survival. The major lesson is that new technology does not lead to high-volume applications. Design capability, manufacturing infrastructure, and market adoption for a standard platform require low risk to justify investment.

Functionality – The basic platform evolved to an LED, a photodetector, and a preamp. The silicon integrated circuits for the driver and receiver were commodity chips that only became more costly with custom integration. Furthermore, integration limited the universality (*e.g.* bit rate) required for volume production.

Commodity components – Components must be compatible not only in their functions, but also in their packages. Available, trailing-edge technology parts were used. A range of vendors/developers were present for all parts. Yields were already high and no new investment was required.

Accepted packaging solution – Redesign of the assembly process for a new, non-standard platform was not possible; surface mount technology was used. The transfer molding package process was well-accepted.

High volume – Investment in automation was the key to low-cost assembly. High-volume sales provided for investment that shortened development time and manufacturing ramp-up. The IrDA market began in 1995 with no major driver. Laptops drove the early market as a value feature, but the capability was rarely used. This occurred because design was the gating step and was independent of the user. The function worked best when offered by a vertically integrated vendor, such as HP.

At a higher level there are common threads to standardization. Initially, each vendor desired to establish a standard about their proprietary position. The standard emerged incrementally with fast-followers adopting the best new technology, and with design emphasizing retrofit capability. The "killer app," corrosion-protected ports for cell phone and PDA programming, followed as well.

Specific success factors include:

1. The air link had no legacy infrastructure
2. The air link required no alignment beyond die-attach
3. The architectural solution had minimal design impact on systems
4. The total addressable market was 1–10 million parts

Conclusions

There is a rich diversity of applications for transceivers, which will continue to grow as new applications are driven by the needs of computing and imaging systems. The cost pressures and the need for reliable, low-cost manufacture will be difficult to meet. There is little doubt that opto-fabs will be a feature of the industry in the future, along with the all the attendant benefits seen in the silicon electronics industry. The path from the current situation to this desired outcome is unclear, however.

In the near term, technical solutions for most applications are available and are implemented using a wide variety of assembly techniques. A largely economic comparison of these techniques represents a possible first step toward convergence. Identification of what is best practice would allow standard processes and techniques to be defined. The adoption of this smaller set of solutions (whether process or function) will lead to higher volumes for each and therefore to some economies of scale and the development of a more integrated manufacturing infrastructure.

The development of a roadmap requires that it be economically sustainable at each point in its evolution. Therefore, the main recommendation from this work is the development of a set of tools, or a research framework, that allows the many technical solutions to be compared on an economic basis, so that a consensus can be reached on how to build a next generation transceiver. Furthermore, in the future this technique should be used, taking into account available R&D spending, to assist in determining the path to an opto-fab model of production.

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