DATACENTER AND TELECOM

EXECUTIVE SUMMARY

MARKET PLATFORM:
The data explosion generated by the growth in social networks and digital entertainment, cloud-computing, and IoT are radically driving the growth of data centers and the need for high bandwidth, low-latency, low power consumption fiber-based communications. Since, 2022 this growth has accelerated to unprecedented levels due to that rapid adoption of AI in general and Generative AI in particular. This has changed the dynamics of the market to the point that telecommunication companies are not driving next-generation technology platforms and metrics, but the datacom (amongst other segments), the datacenter industry (Web 2.0) social media companies (such as Google, Facebook, Microsoft, Amazon etc.) are. These forces in general are transforming the data center architectures to a higher level of integration of photonics components.

CURRENT MARKET PLATFORM STATUS:
Internet traffic is one of the important metrics that is being used to show activity in telecommunications as well as data communications (which includes datacenters and high-performance computing). Internet Protocol (IP) traffic has typically been used to gauge the amount of data that is being transferred through the internet. To accommodate the strong growth in Internet data traffic, the fiber-optic infrastructure that allows data to be communicated between network nodes and within datacenters, must be upgraded. Photonic components are used to build the fiber-optic infrastructure; they comprise devices like laser diodes, photodetectors, multipliers, modulators, and transceivers. These are known as discrete components, while a mix of these components that are integrated or connected on a single substrate (such as silicon, InP or GaAs) are known as PICs or photonic integrated circuits.

Three major segments exist in the datacom and telecom market: Telecom core/metro, telecom access, and datacom. While this report will continue to use the phrase “datacom”, it is important to point out interchangeably using the phrase “datacenter” would be acceptable given the dominance of this sub-sector in driving revenue and innovation in this segment. The growth of the telecom core/metro and datacom segments are expected to experience very strong growth over the next decade. One of the key metrics that is needed for any market analysis is how the market for photonics components will grow over the next decade from a PIC perspective. This is important since the trend to integrate photonics components in PICs is beginning to accelerate. This trend is driven by applications that require smaller photonic component solutions, lower power consumption, high data rates, hybrid packaging, longer interconnect lengths, and scaled economics in terms of $/Gbps.

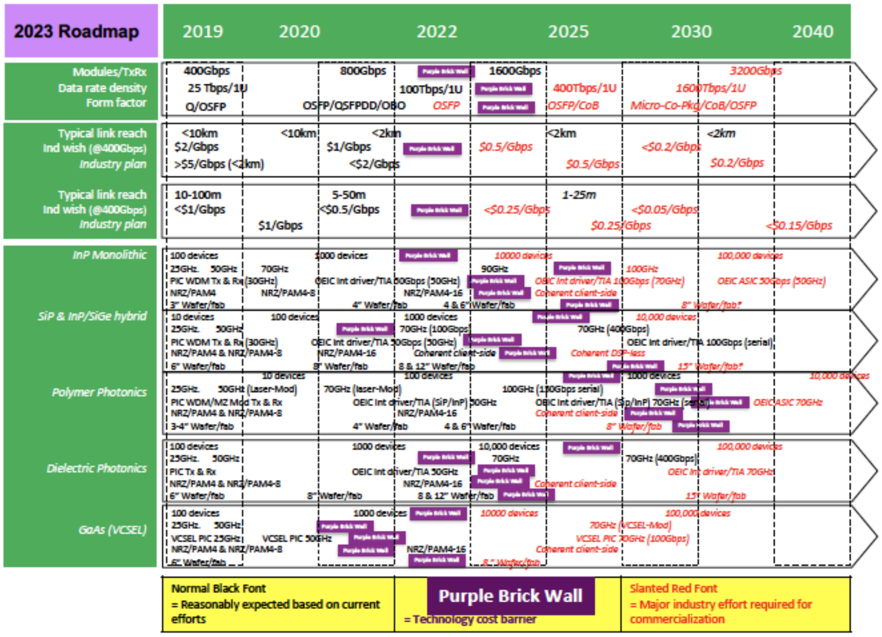
While the rise of PIC based technologies is exciting, equally exciting in the photonics component market is the increase of the market for transceivers. Transceivers are small boxes at the end of each fiber-optic link that comprise photonics components and PIC components. The photonics transceivers sub-segment is expected to grow to quickly over the next decade from the rapidly ramping the deployment of 800Gbps systems using 60-80GHz bandwidth photonic devices. Within 5 years, 1600Gbps and 3200Gbps are expected.

The obvious yet most difficult next move is to revisit increasing the optoelectronic device speed, and those speeds in particular that are driven not from 60-80 GHz analogue optical bandwidth, but beyond 100+ GHz (typically for most optical communication systems, 40 GHz analogue bandwidth roughly corresponds to approximately 50 Gbaud NRZ using standing coding techniques (and 100Gbps PAM4); while 70 GHz analogue bandwidth corresponds to ~100 Gbaud NRZ, and 200Gbps PAM4. Subsequently, 100GHz analogue bandwidth corresponds to ~150 Gbaud NRZ, and 300Gbps PAM4, which is commonly referred to as 300G per lane.

Further, as is topical today, PAM4[1] encoding is popular today and this technique effectively doubles the data rate, so for example, 250 GHz analogue bandwidth can produce not only ~300 Gbaud NRZ, but also 600 Gbps using PAM4 (which is a lane rate of 600G, 3X today's lane rate of 200G). At the same time, these new optoelectronic devices must be very small, and operate with very low voltage to keep power consumption low.

PURPLE BRICK WALL

The transceiver/modules roadmap that displays the purple brick walls is shown below in Figure 1 and Figure 2. The first figure shows the individual line purple brick walls for each technology segment. The following figure shows the purple brick wall areas that require focus to addesss the challenges to achieve the metrics laid out in the transceiver/module roadmap.



Sources: LWLG, Photon Delta, IPSR (2023)

Figure 1: Transceiver/module roadmap showing purple brick walls for technologies that will drive transceiver design (Sources: LWLG, IPSR, PhotonDelta)

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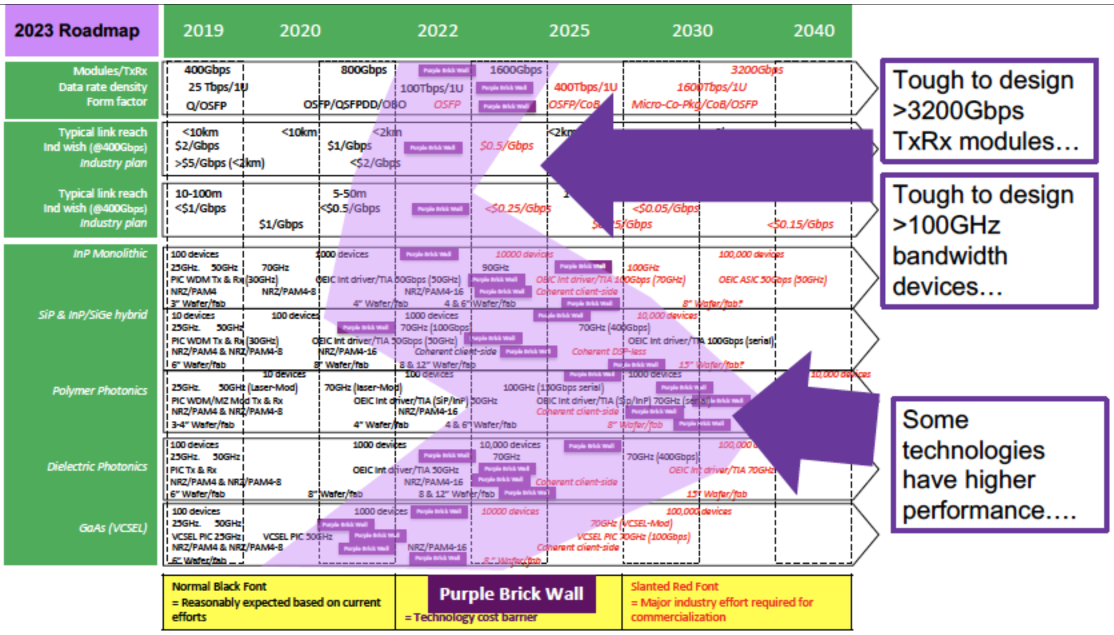
[1] https://www.edn.com/the-fundamentals-of-pam4/



Sources: LWLG, Photon Delta, IPSR (2023)

Figure 2: Transceiver/module roadmap showing the key challenges identified by the purple brick walls for technologies that will drive transceiver design (Sources: LWLG, IPSR, PhotonDelta)

Table 1. Purple brick wall barriers – critical needs for transceivers/modules

Purple Brick Wall	Description
Product vehicle	>3.2Tbps and 6.4Tbps optical transceiver using multichannels
Form factor	Higher density and smaller form factor than OSFP today
Lasers	High operating temp (>150C); wavelength stable, uncooled 1310nm
Low noise integrated opt amplifiers	Noise factors for optical amplifiers <5dB
High speed, low power modulators	>100GHz 3dB bandwidth (EO); 1Volt or less for direct drive from CMOS
Waveguide loss	Low loss in visible wavelengths <0.01dB/cm
Temperature of operation	0-85C uncooled
Power consumption of TxRx	<1Tbps/10W
Full PIC implementation	Includes both Active and passive integrated components on PIC platform

MAIN ROADMAP CHALLENGE:

The main roadmap challenge for the communications industry is to plan future data line rates that exceed 200G and extend towards 300G and 400G. These line rates are needed to achieve pluggable transceiver and/or co-packaged transceiver aggregate data rates of 400Gbps, 800Gbps, 1600Gbps (or 1.6Tbps), 3200Gbps, 6400Gbps and beyond. While companies are looking to complete the designs for 200G line rates in 2023-2025 timeframe, they are also looking how to extend the data rates and line rates further[2]. Interest in line rates of 300G and 400G are still at an early stage, however, active electro-optic polymers offer modulator device demonstrations today that achieve these goals[3].

Several vendors are looking at how to address 200G line rates, and are planning spatial multiplexing (adding fibers), wavelength division multiplexing, (adding wavelengths in a single fiber), encoding with more complex symbols per bit

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[2] Arista presentation from OFC 2022 for OSFP pluggable optical transceivers

[3] [3]https://www.lightwavelogic.com/presentation/polymer-modulators-with-50ghz-performance-for-power-consumption-reduction-at-400- 800-and-1600-gbaud-aggregated-datarates

(PAM, QAM etc), designing optical and electrical devices for higher bandwidth, lower voltage (power), and smaller footprint (size) as part of a PIC platform. These higher performance drivers are being accelerated by data hungry customers such as data centers, high performance computing, and shorter reach telecommunications.

MARKET POTENTIAL

The main areas of growth in Datacenters and Telecom will be to support the increasing internet traffic of 50% CAGR primarily because of the growth of Generative-AI, “G-AI”, applications but all as a result of additional growth in cloud computing, video streaming, mobile data traffic and the general expectation by consumers to have higher connectivity options. This growth will also require limited increases in fronthaul and backhaul network capacity. As datacenters evolve from single, core megacenter locations to clusters of small datacenters, disaggregation is taking place requiring growth of high-capacity links between the smaller datacenters. Integrated photonics is of great interest as an enabling technology for disaggregation. Disaggregation promises improved efficiency and data capacity for the data center but is limited by the cost and performance of the links. Latency requirements, in particular, impose hard limits on distances over which certain resources can be disaggregated.

The trends identified by Bloomberg and other analysts noting the explosive growth of G-AI, as well as trends noted in the IPSR roadmap have accelerated over the past decade. While the IPSR roadmap primarily focuses on the number of devices connected to the data center that could lead to the adoption of billions of IoT devices for appliances as diverse as HVAC, medical instruments and factory automation, Bloomberg and others focus on the need to accommodate increasingly complex photonic devices that will be widely deployed in either edge or core datacenters.

The massive amount of data from these fast-growing elements are unstructured and the demand for analytics and fast movement of data is also accelerating. In addition, the importance of security has been repeatedly highlighted with multiple high-profile situations gathering world-wide attention.

The Data Center of today is seeing a transformation from independent computing, storage and networking systems to integrated system units. As noted above, this change is driven by the twin demands of comples G-AI focused devices and mass quantity IoT devices. These devices will increase the number of devices that are interconnected thereby increasing the amount of data that is transmitted, sorted, analyzed and distributed.

Issues involving processors, storage, networking and switching fabrics and their future trend toward increased integration are all driving the packaging requirements for data centers. The physical entities that constrain or direct development of packaging for these subsystems are the thermal, electrical, photonic and mechanical metrics that define the system characteristics.

Thermal and power management of the system continue to be major challenges for Data Centers. A key component of the total cost of ownership is the cost of the energy to power the high-end equipment and, in some locations, the amount of energy that can be delivered to a data center is at the limits of what the utilities can deliver. Thus integrated silicon photonic systems must equal or better electronic systems in terms of cost, energy use, and performance if they are to achieve widespread utilization in the data centers.

To achieve reduced energy use, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is creating standards where the temperature and humidity can be higher than has been traditionally required for high-end equipment. In doing so, there is less energy required to cool the data center. Therefore, there is a need for better thermal technologies within these systems to maintain acceptable junction temperatures. Further, ASHRAE recommends that server inlet temperatures be between 18 and 27 degrees Celsius (64.4 to 80.6 degrees Fahrenheit), with relative humidity anywhere between 20 and 80 percent.

Likewise, the active power management of the components that make up a system to maximize the power- performance of the system is also a desirable capability. More efficient power conversion will also continue to be developed including voltage regulation close to the loads (such as in microprocessors) that significantly cut the power distribution losses within the system.

However, the biggest challenge is moving the data with minimal latency. The bandwidth requirements have resulted in the off-die data rates continuing to increase even as the processor clock frequencies have stagnated. This change has been enabled by low-power transmitter and receiver designs with continually advancing sophistication in the equalization techniques. The total amount of power for these interfaces is constrained by the amount of energy available as stated above. The parallelization of interconnects is limited by the expectation that the price of the interconnection will also be approximately constant. This results in the current trend of quickly increasing data rates per physical channel.

Packaging technology must increase at a rapid rate to achieve the new performance requirements. As breakpoints are reached, lower loss laminates, smoother copper, higher bandwidth connectors are required. Development of these components in high-volume manufacturing with cost-competitive materials and processes is ongoing.

Optical interconnects are becoming more widely used with VCSEL data rates reaching 50 Gbps and silicon photonics becoming commercially viable. The need for increasing bandwidth to move the data as well as the growing size of data centers defining the distance the high bandwidth interconnect must travel is creating more need for optical communication. At this time 3 meters has the potential to be the breakpoint between copper cables and optical fibers but this is expected to fall to 2 m and 1 m over the next decade. As aggregated data rates surpass 400 Gbps, and increase to 800 Gbps, and even 1600 Gbps, on-board-on-chip photonics will be required.

Internet traffic is one of the important metrics that is being used to show activity in telecommunications (which include trends in end-user connectivity) as well as data communications (which includes datacenters and high-performance computing). Internet Protocol (IP) traffic has typically been used to gauge the amount of data that is being transferred through the internet and this graph is shown below in Figure 3(source: Cisco VNI). In Figure 3, global IP traffic is forecasted to approach 400 exabytes per month by 2022.

The metric is Exabytes per month. An Exabyte is 10^{18} bytes, which is 1000 Petabytes, or a million Terabytes or a billion Gigabytes of data. The graph shows a strong growth of 26% CAGR (2017-2022), the majority of the traffic is being driven by internet video, and is very fast approaching the metric of Zettabytes per month, which is 10^{21} bytes, of data per month. Some estimates are discussing the further metric of Yotta which is 10^{24} bytes of data over the next decade, which is also expected to be driven by internet video but also by emerging web/data, gaming, and, Internet of Things (IoT) devices.

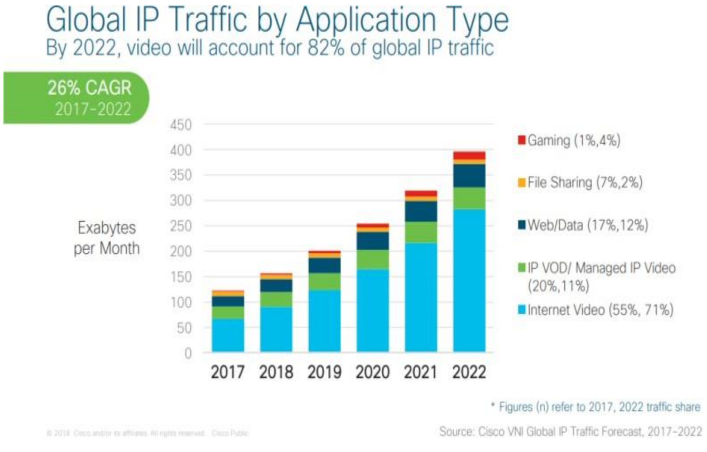


Figure 3. Rapid increase in data traffic measured in Exabytes (Source: Cisco VNI 2020).

As noted above, it also useful to track end user connectivity trends as user expectations will impact IP traffic growth patterns.

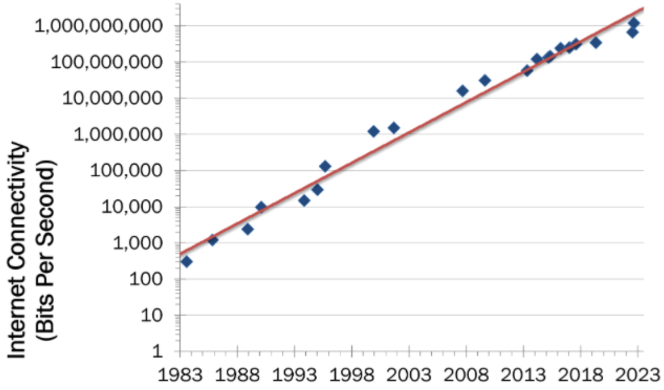


Figure 4: "Nielsen's Law" Internet Connectivity Grows at 50%/yr (Source: Nielsen Norman Group 1/23/23)

However, "traditional" Internet and user traffic data and forecasts are quickly becoming overshadowed by intra and inter data center traffic patterns which are driven by the rapid adoption on G-AI. While publicly available data is limited, secondary evidence of this growth can also be seen by the growth in computing power and high speed = largely photonic enabled component - link sales

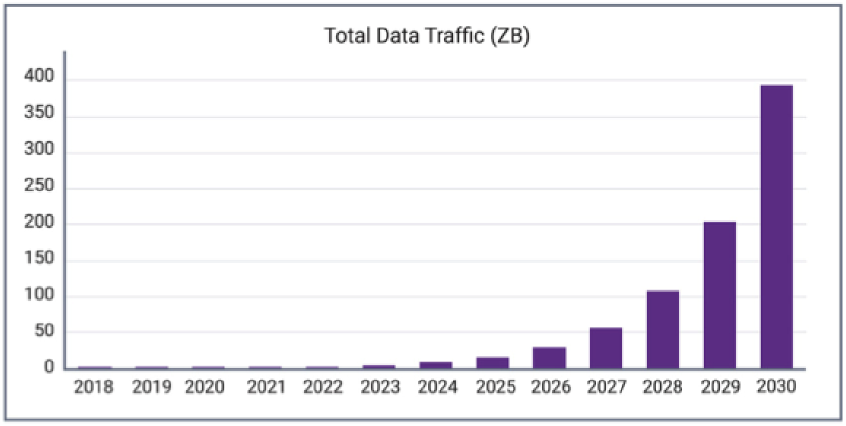


Figure 5: Total Data (center) traffic. Impact of AI on Electronics and Semiconductor Industries", IBS, April 2020.

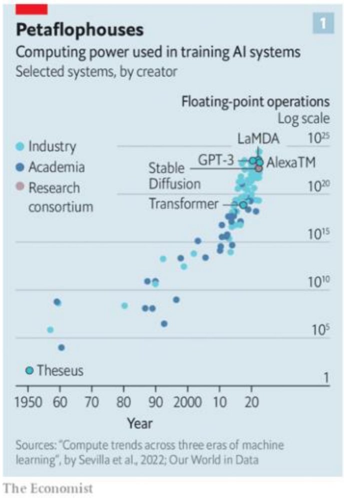


Figure 6: "Who Will Dominate the Generative AI Search Market?", Wally Boston, February 21, 2023

To accommodate the strong growths in data traffic, the fiber-optic infrastructure that allows data to be communicated between network nodes and within datacenters, has to be upgraded. Today, fiber-optic networks are a combination of long, medium and short optical interconnects that range from approximately 3 m to over 1000 km depending on application in the optical network. Photonic components are used to build the fiber-optic infrastructure; they comprise devices like laser diodes, photodetectors, multipliers, modulators and transceivers.

These are known as discrete components, while a mix of these components that are integrated or connected on a single substrate (such as silicon, InP or GaAs) are known as PICs. The summary assessment of the entire photonics-enabled marketplace in 2022 is estimated to be over $2T[4].

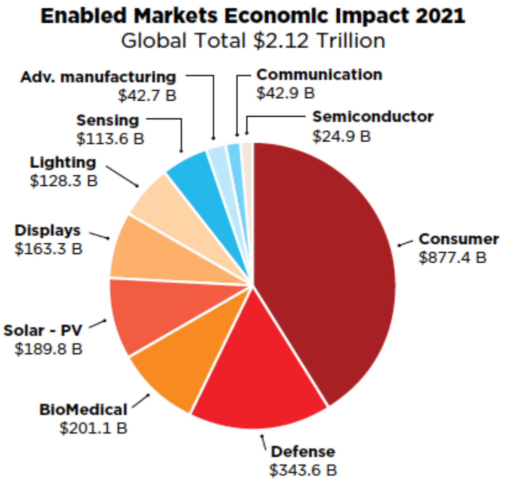
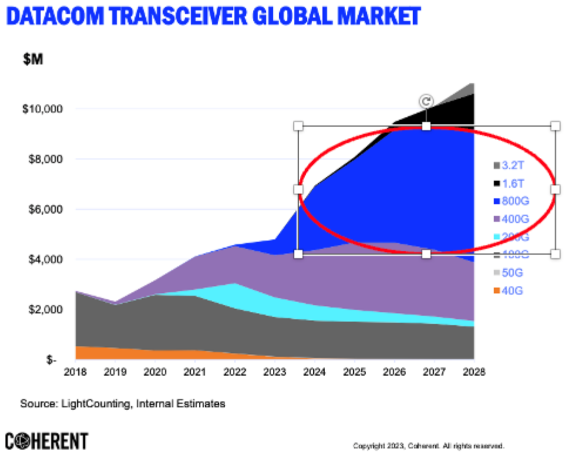


Figure 7. The summary photonics components market forecast for the next decade (Source: SPIE 2022)

In Figure 8 the forecast of Ethernet-datacom transceivers are shown by data rate for the next decade. As data rates keep increasing on a yearly basis, it can be seen that the main drivers will be 800G applications.



Source: LightCounting, Internal Estimates

Figure 8. Forecast of -datacom transceivers by data rate to 2028 (Source: LightCounting/Coherent 2023).

It is expected over the next decade that transceivers will be an excellent platform for the accelerating trends of PICs in both telecom and datacom applications; it is well known that transceiver trends over the past decade have been towards smaller devices i.e. smaller transceiver formats and footprints, with higher densities of photonics components.

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[4] SPIE Optics and Photonics Industry Report, 2022

INDUSTRY NEEDS

The data bandwidth demand is resulting in systems with ever faster interconnect speeds, even as processor speed is staying constant. The size of the data centers creates a challenge for power demand creating an increasing focus on power efficiency of the systems. Data centers have an increasing number of systems residing in an environment of higher temperature and humidity which is also subject to corrosive elements. Despite these challenges, data centers need to reduce their power consumption and operation costs while also managing the total cost of ownership of these systems. It is expected that PIC based technological solutions must achieve not only increased performance, but effective reliability and economic scalability to become competitive in the data center.

Needs 2025

- Device speed increased (modulator bandwidths EO S21 of 100 GHz in PIC platform
- Drive voltage at 1V so that drivers can be eliminated, as well as Linear Drive Optics architectures.
- Co packaging of electronics and photonics, OSFP and QSFP-DD lower power designs
- Hybrid integration with InP lasers with Si photonics

Needs > 2040

- Device speed increased (modulator bandwidths EO S21 to 200 GHz+ in PIC platform
- Laser operation uncooled to >150 ºC
- Reduced power consumption (80% reduction), with architectures such as Linear Drive Optics
- Integration of photonics and electronics
- Uncooled coherent laser with better than 2 GHz stability

Needs 2030

- Device speed increased (modulator bandwidths EO S21 to 150 GHz+ in PIC platform
- Laser operation uncooled to >100 ºC
- Reduced power consumption (50% reduction), with architectures such as Linear Drive Optics
- Integration of photonics and electronics

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APPENDIX

APPLICATIONS

As compared to the overview above, a more specific technical sub-division of the market for photonic components can be given. In this section a more detailed overview is given of the following applications:

- CATV and Radio
- RF Analog applications
- Active optical cable (AOC)
- Fiber to the X (FTTX) (X=curb, building, home, cabinet etc.)
- 5G front and back-haul
- Optical wireless (Li-Fi)
- Undersea and long-haul systems
- Metro and optical transport
- Datacenters and High-performance computing

CATV AND RADIO

Market Potential

The revenues development for CATV and Radio TxRx devices is expected to be in the magnitude of $2B by the end of the decade (2030). The CATV market segment is composed of several fiber optic components utilized for CATV networks. These can be categorized as CATV amplifiers, CATV laser diodes and receiver photodetectors, and CATV passive photonic components. For Radio, there are 4 main data rates speeds for the photonic components and those are 3 Gbps, 6 Gbps, 10 Gbps, and 25 Gbps. These photonic parts are segmented in a number of distance categories that include <40 km, <10/15 km, <2 km, and <300 m. It is expected that PIC technologies are slower to penetrate this market as it is price sensitive compared to traditional data-communications and telecommunication market segments.

RF ANALOG APPLICATIONS

MicroWave Photonics (MWP) is an inter-disciplinary field that bridges photonics and microwave electronics. It aims to apply photonic solutions to microwave applications to achieve superior performance in terms of frequency agility, bandwidth, insertion loss, dynamic range, efficiency, size, weight, power and EMI robustness. MWP serves as an enabling technology in a wide variety of applications such as GHz and THz signal generation and distribution, high-speed wireless communication networks and radar systems.

ACTIVE OPTICAL CABLE (AOC)

An active optical cable is a short distance interconnect that connects racks and switches typically inside a datacenter or in a high-performance computing environment. The fiber-optic cable is multimode and is limited to a distance of a few 100s of meters depending on the specifications and optical link budget designed. The key for AOC cables is that the transceiver is designed to be part of the connector so that the optics is completely hidden to the user. In a typical AOC cable, each end of the interconnect cable has embedded transceivers where the output of each end is not a fiber optic connector but electrical connectors. The design of AOC is meant to bring down the $/Gbps metric so that markets such as datacenters, high-performance computing, PC and consumer markets can be reached at a competitive pricing. AOCs are designed to fit into existing network infrastructures by interfacing to systems via a wide range of standard MSA connectors including CXP and QSFP+. The electrically connectorized cable ends are electrically compliant with InfiniBand, Fibre Channel, SAS 3.0 and 2.1, and other consumer protocol applications.

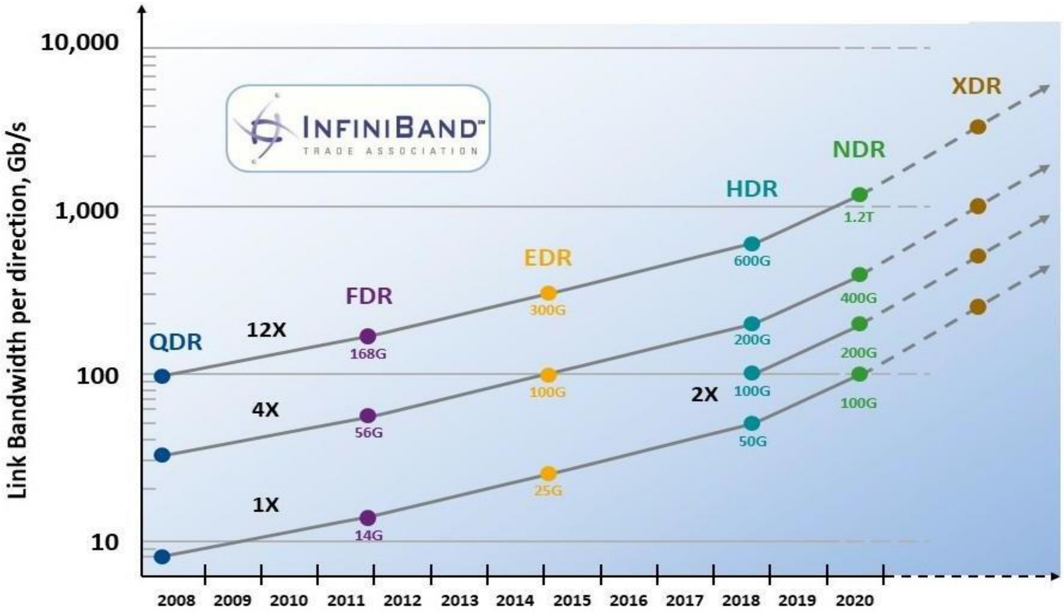

Figure 9. Market demands wrt data rates for Active Optical Cables (Source: Infiniband Trade Association)

Infiniband has been one of the most successful protocols for AOC cables and a graph of the increasing data rates from the Infiniband trade association is shown in Figure 9.

The typical cost for CXP and Infiniband products have been steadily decreasing each year since introduction. Average price erosion is around 10% per annum. That being said the average selling price (ASP) of AOC CXP engines are range from €1-2/Gbps for slow speed (1 to 5 Gbps) CXP to €2-5/Gbps for high speed (10 to 12.5 Gbps) CXP engines depending on volumes.

The key challenges for AOC technology over the next decade will be to continue to increase the data rates towards 400 Gbps while keeping the size or footprint, power consumption and reliability performance similar to that of today's product set.

The goal by the industry is to design higher performance AOC solutions that bring the €/Gbps to under €1/Gbps at 400 Gbps, and closer to €0.50/Gbps at 400 Gbps over the next decade.

FIBER TO THE X (FTTX)

Market development

The FTTX market segment is composed of several fiber optic components utilized for Fiber to the home (FTTH), fiber to the curb (FTTC), fiber to the local box in the street (FTTX) based networks. The photonic component in these segments can be categorized as Passive Optical Network (PON), ONT (Optical Network Transceiver), PON OLT (Optical Line Transceiver) and PON components such as optical splitters. The data rates for the PON transceivers typically are 2.5 GPON, XG-PON1, XGS-PON, NG-PON2, 1G-EPON, 10/1 EPON, 10/10 EPON transceiver modules.

Table 2. Functional requirements FTTX

FTTX	[unit]	2025	2030	2040
Annual revenue	[€/year]	7B	10B	20B
Cost price	[€/unit]	80%	65%	40%

Energy consumption	[W]	1	0.7	0.3
Wavelength range	[nm]	1200-1600		
Footprint	[mm²]	SFP-like and chip scale packaging modules		
Output power	[dBm]	3-10		
Life cycle	[years]	3-7		
Bandwidth	[bps]	10G	50-100G	200G-1T
Swap time	[seconds]	n.a		

The trend is visible towards higher bandwidth devices; soon the 1 Gbps date rate will not be adequate anymore, especially to ‘power users’. It is expected that within a period of about 5 years, a data rate of 5G is required, with a continuously upgoing trend. It must be noted that in standardization, in general ‘jumps’ in the maximum data rates are defined, e.g. from 100 Mbps through 1 Gbps to 10 Gbps.

Despite the larger bandwidth which will be attained, the power consumption of FTTH-solutions is subject to a downward pressure, not only required by the consumers but particularly due to regulatory forces. This is true for the entire FTTH-solution as a whole and particularly for the transceiver devices. When the output power is increased, energy consumption and non-linearities in the devices will increase as well. For this reason, the output power budget for the application is of greater importance; e.g. when a more sensitive receiver is used, the output power can be reduced thereby reducing power consumption and heat dissipation.

5G FRONT-HAUL AND BACK-HAUL

A 5G network will look as in Figure 10 below. The main difference between existing mobile networks and 5G network is the low latency and high bandwidth requirement for the end user in a 5G network. This means that the passive power splitter that is currently used in the field, to distribute the signal to the end user, or remote antenna unit, can no longer be used. Either a lot of cabling, using parallel fiber is deployed or a wavelength splitter can be used as the ODN (Optical Distribution Unit) in the passive optical network on the fronthaul. This multi wavelength or WDM-PON scenario for 5G has been supported by various standardization bodies, like IEEE, and ITU-T. Relevant standards are SuperPON (IEEE P802.3cs) NGPON2 ITU 989.2 standard and Metro WDM-PON in ITU 689.3 and 689.4. The WDM-PON works with coloured transceivers, which makes the logistics complicated. Ideally every end user has the same transceiver unit which can be achieved by employing a tunable laser that can select any wavelength of the typical 20 wavelength channels for upstream traffic.

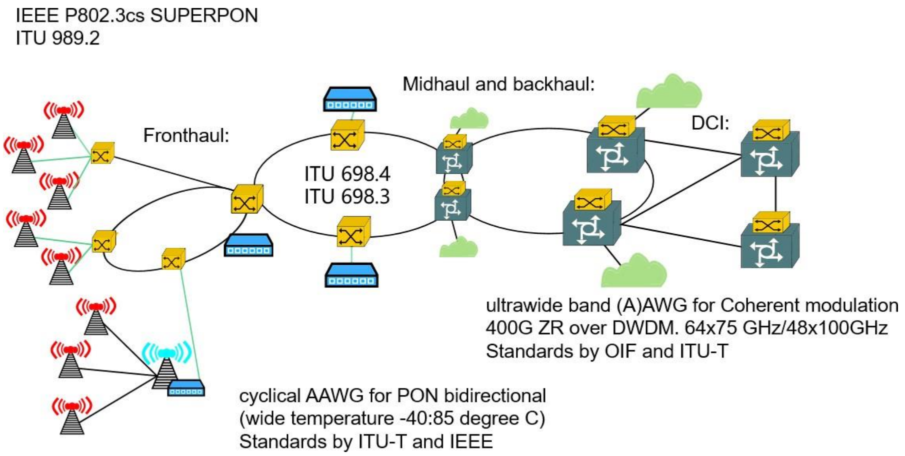

Figure 10. 5G architectural network layout

At present optical switches are based on Wavelength Selective switches (WSS) which are based on 3D MEMS in free space optics that are costly and bulky devices. In the future, new type of photonic devices of a much lower cost, a higher level of device miniaturization as compared to the current optical metro /long-haul modules will be designed.

In fronthaul, centralization of baseband processing is emerging to secure performance, flexibility, and scalability of RAN. A centralized pool of baseband processing devices, the radio equipment controllers (RECs), may serve several distributed radio equipment (RE) aggregated in clusters optimizing the use of computational resources and enabling a significant energy saving.

Starting in 2023, Google has been deploying “OCS” or “Optical Circuit Systems” in datacenters. OCS could find applicability in other parts of the network including RAN networks.

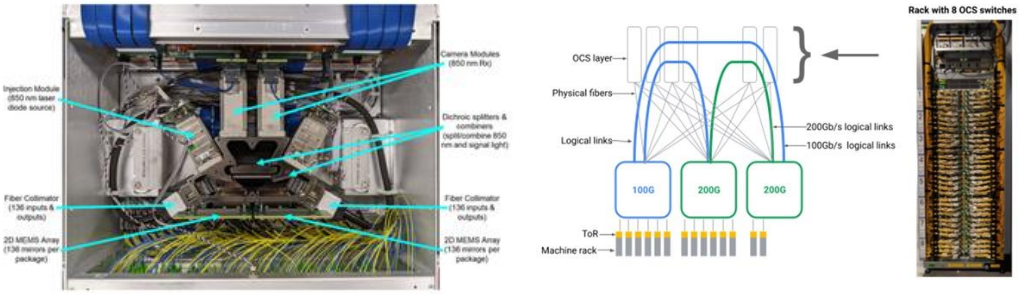

Figure 11. Google OCS Solution.

OPTICAL INTERCONNECTS

At present the optical interconnects are implemented by a number of low channel count optical pluggable modules or board mounted optical engines. Next generation Digital ASIC for 5G and data center systems will have a much-increased processing capacity reaching tens of terabit/sec in a single unit. To achieve that the signal data rate increases from the currently used 25 Gbps to 400 Gbps and beyond, the bandwidth density and the energy efficiency must also increase.

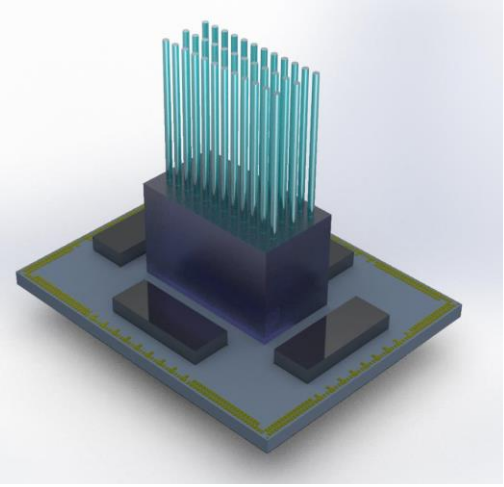

Figure 12. 16 x 112 Gbps full-duplex 4xDR4 HDI/O chiplet with in-house Silicon Photonics, Equalizing Driver, TIA (Nubis Communications 2023)

In such conditions, a new ASIC optical interconnect technology is needed based on co-packaging digital ASICs with multi-channel optical transceivers in the same multi-chip substrate to form an optical multi-chip module (OMCM). OMCMs may well be classed as co-packaged units that are part of a photonics integrated circuit (PIC) platform over the next decade.

These OMCM modules will include a high processing capacity electronic ASIC and a high scale integration silicon photonics interposer as part of a photonics integrated circuit (PIC) platform, and will comprise of a bank of high-speed optical transceivers. The analog electronic integrated chip (EIC) to drive the optical transceivers is 3D integrated on top of the photonic interposer (see Figure 20).

This can be particularly beneficial in the situation where one encounters many parallel connections, like in the OBO-switch in datacenter where a single Tomahawk BCM56980 is supported to deliver 12.8TBs switching capacity. See https://www.onboardoptics.org/cobo-switch . Or for DWDM-coherent systems when large number of optical lanes are available to be multiplexed on a single fiber. For these and other applications on board optics may emerge as a way of reducing footprint and reducing optical power because you locate the high-speed electronics as close to the actives (lasers and detectors) as possible, avoiding all kinds of signal degradation that require further electronics for recovering the integrity of the signal.

UNDERSEA AND LONG-HAUL PHOTONIC COMPONENTS

The market potential for long haul components that are utilized in undersea networks is shown below between the use of discrete photonic components and PIC based technologies. The undersea and long-haul market segment is composed of several fiber optic components utilized for these applications. The photonic component in these segments can be categorized as RGM passives which include isolators, gain flatting filters, power monitors, C and L band amplifiers where the types include EDFA and Raman, pumps (980nm, 1420nm, and 1480nm), dispersion compensators, dynamic gain equalizing filters, passive amplifiers that include filters, WEDs, power monitors etc.).

The expectation for amplifiers and pumps is to achieve a market magnitude of around $1B by the end of the decade (2030). There is an expectation that there will be a decline in the reduction of cost and ASP of photonic component parts over the next decade, in part due to an advancement in photonics technology, especially the penetration of PIC based technologies in this type of applications. PIC technologies are expected to penetrate this market very quickly from about the year 2024 and grow quickly so that a large part of the photonics-based solutions will contain integrated photonics technology in long haul based networks. PICs for this market will tend to become hybrid solutions, and are expected to be not only a InP PIC, or a SiPh PIC but a combination of the two. The trend over the next decade in this segment of the market will be high performance, as the optical components will be in situations where replacement is difficult. While InP and silicon components today are being utilized in a discrete format, hybrid PIC solutions are anticipated with InP sources, coupled to passive integrated components in materials such as silicon, dielectric and even polymers as they mature to become additive to InP and SiPh technology platforms.

METRO AND OPTICAL TRANSPORT

As network traffic continues to grow (doubling approximately every 2 years), efforts are focused on increasing the bandwidth of the existing fiber infrastructure through more efficient use of the spectrum available. Generally, higher modulation speeds and new modulation formats are favored over WDM, as in WDM systems extra components such as multiplexers and wavelength lockers are required introducing extra cost. Increasing bitrate also carries a cost as higher speed electronic driver technology is required as is co-integration of electronics and photonics to reduce RF loss and crosstalk at bitrates in excess of 100 Gbps. Innovation using new materials and physical effects are also required for optical modulation >100 GHz as conventional technologies struggle to achieve these speeds. Photonic integration particularly hybrid integration will be required to deliver these devices in compact form at low cost with low power consumption.

Photonic integration has had a chequered history. For simple FTTH transceivers it was found to be more expensive than using individual lasers and detectors in simple packaging. For coherent receivers, however, the requirement for phase stability means that it is well-suited. Because of the high cost of InP material, small devices interconnected with lower cost passive waveguide material are more economical if the interconnection can be simple and efficient.

Another key area to be considered is the thermal compatibility of photonics and electronics. Semiconductor lasers generally need to be cooled to near room temperature to work efficiently, whereas electronics can operate successfully up to 200 ^{o}C and can generate considerable heat. Also, dielectric photonics is less temperature sensitive than III-V material. This has led to one approach to photonic integration of having an "optical power supply (eg a comb laser)" separate from the PIC.

Coherent communications has developed quickly over the past decade and has penetrated many telecommunications fiber optic interconnects and connections. These links tend to be many kilometers in length, especially over 100 km where performance tends to drive acceptance over that of low cost. While cost is becoming more of an issue for 100 km, 400 km, 600 km, >1000 km, and even 10,000 km fiber optic links, electronic DSP chips have alleviated a number of optical design issues and allowed costs to be kept reasonably under control. It is interesting to note that DSP chips are not low-cost, and tend to be one of the most expensive parts of a coherent interconnect link, no matter what the reach is (over 100 km). While this trend has been successful over the past decade, the next decade will have a heavy focus on low-cost coherent for the >10 km fiber optic interconnect reach links. In the range of 10 km to 100 km, which includes classic reach distances of 25 km, 40 km, and 80 km, a number of datacenter operators as well as the telecommunications industry are seeing an interest in 'coherent-lite' product solutions in the market-place.

To satisfy future telecom requirements, PICs will need to focus on addressing the following issues:

- Lower electrical power consumption
- Higher data rates
- Lower cost
- Smaller size
- Increased reliability
- Packaging (simplicity/cost)

To meet future optical systems requirements by 2030, transceivers are predicted to require the following:

- Modulator bandwidth of >150 GHz, low Vpi < 1 V
- New reliable material systems and integration platforms
- Driver-modulator co-design and integration
- Matching detectors with high responsivity (>80% efficient), low dark currents (<10nA) across L and C band
- High optical power (>10mW) narrow linewidth lasers (<100kHz) for multiple bands
- High operating temperature (150°C) lasers
- Temperature stable lasers with respect to temperature
- Integrated polarization rotators, splitters, and isolators > 25-30 dB ER (from all passive components)
- Low noise optical amplifiers with NF< 5 dB (integrated components)
- Small footprint electro-optical packaging (DCO-like)

It is expected that this can be achieved using these platforms:

Table 3. Transceiver requirements expected for 2025 and 2030

2025	InP monolithic integration
	Hybrid combination of silicon and InP
	Wafer bonding for electronics co-integration with photonics
	Non-hermetic sealing of chip scale packages
	Alternative modulator platforms: E/O polymers, thin film $LiNbO_3$ SiGe, etc.
	Flip-chip of electronics and photonics
2030	New material platform for lasers (better temperature performance)
	New TEC materials (integrated microTEC)
	High E/O effect materials eg polymers with temperature stability >200C

Table 4. Functional requirements for Metro and Optical transport

Metro and optical transport	[unit]	2025	2030	2040
Annual revenue	[M€/year]	28000	46000	62000
Cost price (40 channels)	[€/unit]	7000	5000	3500
Cost price/unit/channel	[€/unit/channel]	120	62.5	40
Wavelength range	[nm]	O, S, C and L band		
Reliability/channel	FIT	50	40	30
Life cycle	[years]	15 years		
Bandwidth (per channel)	[Bps]	400G	800G	1600G

CRITICAL (INFRASTRUCTURE) ISSUES

Paradigm Shifts: In previous photonics roadmaps, the move to cloud computing was well publicized and a key component of providing the computing and data services for the nearly always available connectedness to on-line computing capability for both personal and business reasons. As portable electronics is growing quickly, the networking and data center infrastructure must grow to meet the demand. This shift is happening around the globe creating demands on the network bandwidth and the availability of cloud computing and data processing.

These trends are continuing and accelerating in some areas as expected. It is still true that the data center cost and power is being held essentially flat, as the capability must increase to meet the cloud-computing demands. For a computer system, this translates into increasing cost pressure as the system capacity grows, driven by more processor cores per socket, and more data bandwidth to memory. The virtualization and networking integration into the computer system tends to reduce the number of physical devices in a subsystem allowing room for even higher levels of integration. The amount of data being consumed, however, means the number of devices interconnected is increasing rapidly.

TECHNOLOGY NEEDS

The packaging technology development for Data Center is currently driven by a need to process the quickly increasing amounts of data (Big Data) in a heterogeneous distributed environment (the Cloud). The optical links in the datacenter and between datacenters all have high speed transceivers with different characteristics, mainly depending on the fiber-length.

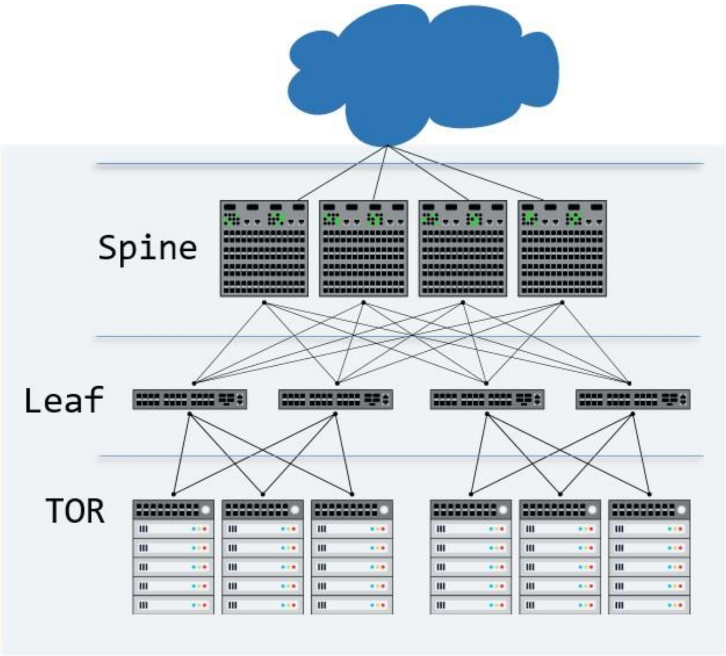

Figure 13. Data center communications architecture

In Figure 13 we can distinguish intra-rack communication, mainly by AOC, intra-building communication, between TOR-leaf switch mainly supported by QSFP transceivers using 4 or 8 wavelength or 4 or 8 parallel fiber. The bulk of the cabling, using SMF fiber is between leaf and spine switch. Here, the signal speed will soon be 800 Gbps and as it connects over longer distances, like kilometers or more, it favors using a single or duplex fiber supporting multiple wavelength as opposed to many parallel fibers. Beyond the spine switch and for DCI (Data center interconnect) transmission will be based on small high speed coherent transceiver modules that can be multiplexed on DWDM grid in the C-band. The 800 Gbps pluggable MSA, Figure 25, has provided some guidance on the next step of speed-upgrades that can be expected. Beyond that even higher speeds require high bandwidth modulation technologies are required to support baud rate of 58 Gbaud and 116 Gbaud, 200Gbaud and above.

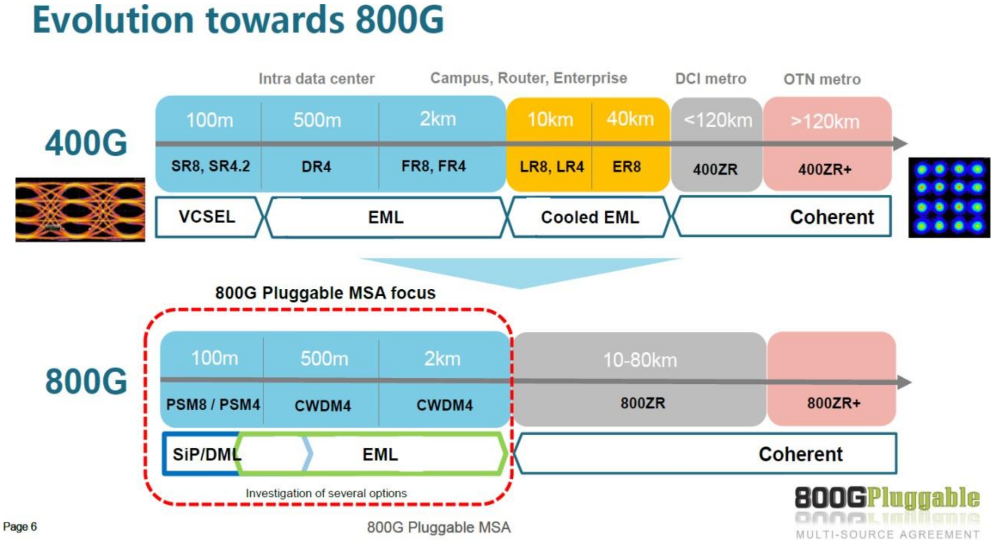

Figure 14. Evolution towards 800G in the datacenter

The attributes of these systems are discussed in the following paragraphs.

Bandwidth

The interconnect bandwidth demand is growing quickly and is expected to keep a steady growth well into the next decade. The bandwidth increase to now has been primarily provided with rapidly increasing bit rates per channel and incrementally increasing channel density. Today, optical devices are being implemented at 400 Gbps, and the forecast over the next decade is for 800 Gbps and 1600 Gbps solutions. As we go to 2030, the challenge of getting enough reach (i.e. sufficient trace lengths) to interconnect two devices while simultaneously overcoming the loss of the trace will create the need for various signaling technologies and there will be a drive to look at alternative packaging schemes such as co-package solutions. Both binary non-return to zero (NRZ) and pulse amplitude modulation (PAM) signaling will be developed with the appropriate equalization and application. Optical communication will become more broadly used as the cost and power of electrical interfaces at 50 GBaud, 100 Gbaud and above will make optical communication more attractive. Optical component devices current exhibit bandwidths of 100 GHz which translate to 150 Gbaud using NRZ, and 300 Gbps using PAM4 signaling will be necessary over the next decade. Presently, only a few InP modulator chips can perform at 60 and 70 GHz analog bandwidths (with significant drive power), while new and novel modulators in polymers have demonstrated analog bandwidths at 100 GHz and over 250GHz with polymer plasmonics. There is an expectation that both InP as well as SiPh baseline integrated photonics platforms may look to alternative materials for the modulator function over the next decade. Silicon photonics is expected to become available in a broader range of applications because of the advantages of cost with silicon processing and packaging in addition to the opportunity to create high-density interconnections.

Power

The challenge of electrical power defines the limits of how components are integrated, that is, the number of cores on a processor chip, the density of interconnect with the trade-off of the signaling options of speed and optical vs. electrical. The footprint and content of rack electronics are constrained, and the availability of power from the utilities is capped in many installations. Therefore, the amount of power each rack and component can consume is constrained. Concern about overall power usage in datacenters becoming a significant proportion of global power consumption (estimates of > 5%) has led to a focus in design of components with higher efficiency and requiring no external cooling. This should form an important part in the design of PICs.

Thermal

The thermal capability, that is, the ability to remove heat from components and also from the frames that make up the system is at the limit of existing capability. Because the cooling of the data center also uses a sizable amount of power, the temperatures in the data center are rising while the chip temperatures must be maintained at a constant limit from generation to generation to maintain reliability at acceptable levels. At the component level, lower thermal resistant interfaces will be developed with advanced technology. The introduction of silicon photonic components will present a new challenge to maintain optical alignment and stability in this environment.

Environment

As more large data centers are established globally, there is a broader range of environmental conditions that are encountered. Corrosive environments are encountered more frequently and the electronics must be able to withstand those elements. To maintain the power used for air handling in the data center, higher temperatures and higher humidity is being allowed by new ASHRAE standards. As packaged components are subjected to more moisture, the loss of interconnections will be increased which must be factored into the designs or materials chosen to minimize the impact.

Latency

Reducing the latency in communications in data centers is a paradigm shift that drives the need for new architectures such as disaggregation and the need to change from disk storage to solid-state storage to reduce latency.

Sustainability

It is expected in the next few years that datacenter product design decisions will align with good environmental practices during the next decade with few exceptions. It further suggests that stakeholders need to develop Sustainability Metrics to quantify the impact of using electronic products to replace energy intensive processes. In terms of end-of-life and recycling potential:

- Data Centers
  Owners will reuse whenever possible because of modularity
  Recycling is economically viable because of large mass in single location
- Internet of Things
  Re-use is possible for certain products in certain countries
  Because individual products are distributed, low mass, extremely heterogeneous, and contain little valuable material they are not economically viable for recycling

ASSEMBLY AND PACKAGING

The new technologies that are becoming available must meet the challenges of the previous section – bandwidth, power, thermal and environmental. Key new processor packaging technologies are being developed with some fundamental changes in the rest of the electronics industry and will impact the technology that can be leveraged. Most recently, office and desktop computing hardware could be used for memory DRAM development, CPU and MPU core development, signaling protocols, and cooling hardware.

The packaging and component technology that will be developed and integrated into Data Centers will be those that successfully developed with acceptable cost and risk of adoption that includes hybrid flexibility for the customer. Thus, the packaging for integrated silicon photonic components must utilize as much common technology as possible from the technology developed during the next decade for conventional electronic packaging. Examples would be chip-scale silicon based hermetic packaging, co-package solutions based on hybrid silicon photonics platforms, and increased density of electrical interconnects through techniques such as flip-chip bumping.

The following paragraphs discuss the packaging technology challenges for both electronics and silicon photonics.

TSV

Through Silicon Vias are enabling 2.5D silicon interposers and 3D chip stacking providing high-density interconnect, and therefore, high bandwidth capability between components. Also, glass interposers may be a factor for some applications with Through Glass Vias (TGV) providing advanced connectivity. Memory modules are already introduced and applications will expand. The introduction of TSV has lagged expectations due to yield and cost issues which still need to be addressed.

Advanced Packaging - SiP and PoP

System-in-Package (SiP) and Package-on-Package (PoP) technologies provide the capability of optimizing cost and function in a package. Integrating voltage regulation and silicon photonics with processor chips or bridge chips will increase. The mobile systems are where the current growth driver in this technology segment originates. However, the Data Center will adopt these advanced package technologies because the increased interconnect pins, greater memory, and additional cores when placed in close proximity enables high-bandwidth interconnection in the existing power envelope. These tradeoffs will make the appropriate technology aspects economically scalable from mobile platforms to Data Centers.

Electrical connectors for packages and cards

Electrical interconnection will continue to be the dominant interconnection for short-reach (< 3m) communications. The developing signaling standards are in discussion to go beyond 50 Gbps per channel. Electrical connectors for printed circuit board and cable communication delivering low insertion loss, flat impedance profiles and minimal crosstalk will maximize the reach of the copper interconnect at an acceptable BER. The rate of adoption of the higher speeds will depend on the ability to equalize the channels in the existing power envelope while the channel cost-performance as measured in $/Gb/s is reduced over time. The cost-performance is strongly impacted by bandwidth density. Use of Photonics signaling reduces many of these concerns and will be particularly effective when single-mode interconnects and cabling are employed. The degree to which embedded waveguides will be used depends on a number of factors, but can be alleviated via on-board fly-over interconnects that use currently developed optical receptacles.

Optical Interconnects

Optical interconnect will be used more broadly. Transceivers and active optical cables (AOC) will be used for in-frame communication, potentially replacing copper interconnects in backplanes or cables when the cost, power and bandwidth tradeoffs justify the switch to optical. Integrating optical devices into packaging (co-packaging) to reduce trace length and, thus, power demand for high-bandwidth interfaces will demand advanced heterogeneous packaging and leverage the SiP and PoP technology components for increasing integration at the package level. Low-cost single-mode optical connectors will be needed to support pluggable electro-optical modules.

Silicon Photonics

The desire for higher levels of integration of optics will favor the adoption of silicon photonics. The system-level cost management, integration density, and power limit trade-offs must be carefully considered as the development of silicon photonics is pursued. The technology selected must leverage the existing silicon technology and infrastructure wherever possible to reduce both risk and cost. The use of silicon photonics will be universal as it will be fully integrated with other attractive, high performance optical technologies such as dielectric photonics and polymer photonics.

Datacentre and HPC	[unit]	2025	2030	2040
Annual revenue	[€/year]	50B	80B	150B
Cost price	[€/unit]	1000	450	200
Energy consumption	[W]	10	4	1
Wavelength range	[nm]	850 (Oband)	O/C band	O/E/S/C/L
Reliability	[%]	99	99.9	99.99
Footprint	[mm²]	2000	1000	600
Output power	[W]	5	10	15
Lifecycle	[years]	3	2.5	2
Bandwidth	[Bps]	800	1600	3200
Swap time	[seconds]	60	30	10
Speed	[material]	Optical	Optical	Optical

Table 5. Functional requirements for Datacenter and HPC optical components

PRIORITIZED DEVELOPMENT & IMPLEMENTATION NEEDS (< 5 YEARS RESULT)

Critical Milestones		
CM1	Higher speed modulation >200 Gbaud, <1 V operation (100 GHz+ analog optical bandwidth)	
CM2	Integration of electronic drivers and photonics	
CM3	Co-packaged photonics and electronics	
CM4	Low cost tunable laser	
CM5	Operation 0 ºC to 85 ºC uncooled (0 ºC to 70 ºC in datacenter/datacom)	
CM6	Packaging (simplicity/cost)	
CM7	Non-hermetic packaging and chip scale packaging	
CM8	High responsivity high speed detector (>200 Gb/s)	
CM9	Lower power consumption (50% reduction)	

Table 6. Prioritize development and implementation needs (critical milestones)

PRIORITIZED RESEARCH NEEDS (> 5 YEARS RESULT)

Critical Milestones		
CM10	High operating temperature laser (>150 °C)	
CM11	Wavelength stable lasers with respect to temperature	
CM12	Low noise integrated optical amplifiers with NF <5 dB	
CM13	Modulators (E/O polymer/SiPh, InP etc) >200 Gbaud	
CM14	Low loss Hollow Core Fibre with wide spectral capability(<0.2 dB/km)	
CM15	Laser, modulator and detector components compatible with hollow core fibre	
CM16	Transceiver operation -40 to +85 °C uncooled	
CM17	Uncooled laser for coherent with better than 2 GHz stability	

Table 7. Prioritized research needs (>5 years result)

GAPS AND SHOWSTOPPERS

Laser materials for efficient operation at temperatures >150 °C
Physical mechanisms to deliver Modulators >200 Gbaud
Low noise amplifiers to cover the whole SMF fibre spectral operating window
Massive increase in Access network capacity will be required to handle 5G backhaul
RF interference and crosstalk as baud rates increase and package sizes decrease
MUX/DEMUX in WDM systems – discrete filters at present – need to move to AWG type for larger channel counts
Narrow bandwidth of grating couplers for WDM applications

RECOMMENDATIONS ON POTENTIAL ALTERNATIVE TECHNOLOGIES

Stable polymer materials for high speed modulators
Efficient laser light sources in alternative materials

CONCLUSIONS

Data Center growth is driven by the rapidly increasing amount of data and the number of devices that are interconnected. This product sector is forecast to have revenues continuing to grow at a CAGR of 26%.

The technology for high-end computing is driven by the quickly increasing number of interconnected devices and the resultant growth of data bandwidth between those devices. Meeting the demands of increased data bandwidth, processing and storage must be done under the constraints of capped available power and the expectation of prices to the user decreasing over time. The attributes that are important are the data bandwidth, power efficiency, thermal management and environmental conditions in which the systems operate. Addressing these challenges will require:

- Advanced silicon integration using stacked silicon with through silicon vias,
- Advanced packaging integration built on the SiP and PoP technologies (already in production use in mobile computing),
- Optical interconnection for increased reach of bandwidth into the data center,
- Silicon photonics to enable integration of optics,
- High-bandwidth connectors,
- Low-loss materials and design features to maximize the reach of electrical interconnect
- Power regulation integration to improve efficiency.
- Dielectric optical devices (such as multiplexors, and demultiplexors)
- 100+ GHz optical bandwidth photonic devices (e.g. E/O polymer-based, thin film Lithium Niobate, BTO, plasmonic (polymer) modulator devices) that are mounted onto silicon photonic platforms.

The increased performance that these enabling technologies will provide must be provided below the cost of existing technology for their adoption by the industry.