DATACENTER & TELECOM

Contents

EXECUTIVE SUMMARY

Introduction:

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. 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. This has significantly changed the types of technologies, products, specifications, and subsequently important issues such as reliability and quality assurance within the photonic components space. These forces in general are transforming the data center architectures to a higher level of integration of photonics components.

Current 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, has to be upgraded. Today, fiber-optic networks are a combination of long, medium and short optical interconnects that range from approximately 3 meters 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 or photonic integrated circuits. The summary photonics market in 2019 reached a value of approximately $26B and is forecasted to grow to approximately $80B by 2030 (Source: Oculi llc (2020)). This figure includes both discrete and PIC photonic components and includes the addition of new PIC based technologies such as polymer photonics and dielectric photonics (silicon nitride, etc).

Within the summary photonics components market, three major segments exist: Telecom core/metro, telecom access, and datacom. The growth of the telecom core/metro and datacom segments are forecasted 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. PIC applications, i.e. those applications that include integrated photonics are forecasted to approach half of the photonics components market by 2030.

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 forecasted to grow to 66% of the total photonics market by 2030 which is a significant part of the components business in fiber communications. The datacom industry today are gearing up for 400Gbps and 800Gbps systems using 30-50GHz analog bandwidth photonic devices. Customers are expecting data rates to continue to move quickly beyond 400 Gbps and on to 800 Gbps and 1600 Gbps during the next decade. Some companies mention 3200Gbps today as part of their roadmap planning.

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 30-50 GHz analogue optical bandwidth, but 80-100+ GHz (typically for most optical communication systems, 40 GHz analogue bandwidth roughly corresponds to approximately 50 Gbps NRZ using standing coding techniques; while 80 GHz analogue bandwidth corresponds to approximately 100 Gbps NRZ).

Further, as is topical today, PAM4[1] encoding is popular today and this technique effectively doubles the data rate, so for example, 80 GHz analogue bandwidth can produce not only 100 Gbps NRZ, but also 200 Gbaud using PAM4. At the same time, these new optoelectronic devices must be very small, and operate with very low voltage to keep power consumption low. Today's roadmaps are expressing desire, but at the same time doubts, about getting beyond 50 GHz from a commercial standpoint.

Main challenge:
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. Achieving this rapid growth places increasing demands on improving the performance and decreasing the cost of their next generation of equipment. Thermal and power management of the system continue to be major challenges for data centers. 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 market.

Photonic packaging technology must increase at a rapid rate to achieve the new performance requirements. Today, there is a strong movement towards co-packaging and on-board optics. These technologies need to be able to support faster photonic devices such as 80 GHz modulators that can operate 100 Gbps NRZ or 200 Gbaud PAM-4. Today, one technology close to meeting these speed metrics with low power consumption are polymer modulators.[2] There are other modulators that are being developed with both high speed and low power potential that include: slot modulators, plasmonic slot modulators, silicon based GeSi EAMs, micro-rings, and thin-film lithium niobate.

Needs:

Data centers need faster optical devices (such as 80+ GHz components), higher integration levels, higher reliability, lower power consumption, a higher degree of scalable economics that address $/Gbps metrics, and smaller more miniaturized foot-print platforms. Co-packaged solutions with hybrid integration between different technologies

Needs 2025
- Device speed increased (bandwidths EO S21 of 80 GHz (eg polymer modulator) in PIC platform
- Drive voltage at 1V so that drivers can be eliminated
- Co packaging of electronics and photonics
- Hybrid integration with InP lasers with Si photonics

Needs 2030
- Device speed increased (bandwidths EO S21 to 120 GHz+ (eg polymer modulator) in PIC platform
- Laser operation uncooled to >100 ^{o}C
- Reduced power consumption (50% reduction)
- Integration of photonics and electronics

[1] https://www.edn.com/the-fundamentals-of-pam4/
[2] https://www.lightwavelogic.com/presentation/polymer-modulators-with-50ghz-performance-for-power-consumption-reduction-at-400-800-and-1600-gbaud-aggregated-datarates/

are required. The integration of electronics, photonics and packaging is an important need that the industry is addressing today. The industry will explore this in more intensity over the next decade.

Needs > 2040

- Device speed increased (bandwidths EO S21 to 200 GHz+ (eg polymer modulator) in PIC platform
- Laser operation uncooled to >150 ºC
- Hollow core fibre with loss < 0.2 dB/km
- Low noise integrated optical amplifiers with NF <5 dB
- Uncooled coherent laser with better than 2 GHz stability

MARKET POTENTIAL

Introduction

The main areas of growth in Datacenters and Telecom will be to support the increasing internet traffic of 26% CAGR as a result of the growth in cloud computing, video streaming, and includes increasing mobile data traffic, requiring increases in fronthaul and backhaul network capacity. As datacenters evolve from single megacenter 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.[3] 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 in the iNEMI roadmap have accelerated over the past decade. The number of devices connected to the data center has increased dramatically leading to the concept of the IoT. This second product emulator for the IPSR roadmap focuses on the integrated photonic needs and opportunities for billions of proposed IoT device adaptations, from appliances to HVAC, medical devices and factory automation.

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. This change is driven by the IoT that has quickly increased the number of devices that are interconnected and increasing data-center applications; thus, 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.

These integrated electrical-photonic systems are aggregated in data centers that are the infrastructure that serves cloud computing. Data centers supporting the cloud currently make up the fastest growing segment of the Data Center landscape.

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 in order 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 100 Gbps, and increase to 400 Gbps, and even 800 Gbps, on-board-on-chip photonics will be required.

The above energy limiting factors in addition to efficiency, latency, and the growth of data transmission, place a challenge on the processing power needed to perform any data analytics. A trend is starting to be observed where instead of adding general-purpose cores to a chip and enabling those cores to support additional threads, perhaps it is more efficient to employ specialty cores to do specific tasks. The use of GPUs and FPGAs allow quick turn-around time to quickly adopt more compute and energy efficient algorithms while special ASIC cores are developed to address specific computational tasks. As the big-data era matures and 7 and 5 nm silicon nodes are developed, the packaging components to interconnect these components will also evolve. The challenge is to keep the momentum of scaling performance with cost, as the price of designing using 10 nm (or less) silicon nodes is becoming higher.

Datacom/telecom and ICT

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 and this graph is shown below in Figure 1(source: Cisco VNI). In Figure 1, 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.

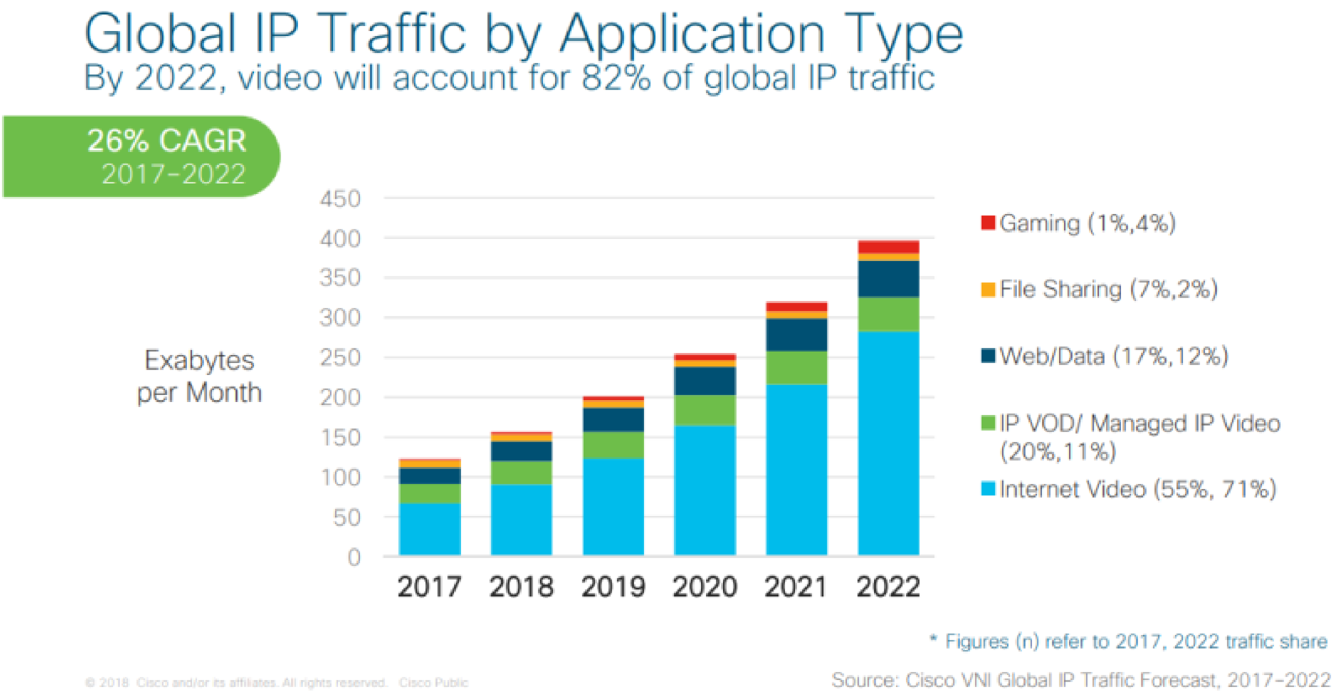

Figure 1. Rapid increase in data traffic measured in Exabytes (Source: Cisco VNI 2020).

The datacom and telecom market in general

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, 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 photonics market has been reviewed in 2019, and is shown in Figure 2. This market has reached a value of $26B in 2019 (Source: Oculi llc.). The summary photonics market is forecast to grow approximately $80B by 2030 at a 17% CAGR (2020-2030); this figure includes both discrete and PIC photonic components and includes the addition of new PIC based technologies such as polymer photonics, dielectric photonics (silicon nitride etc.), as well as other new hybrid technologies.

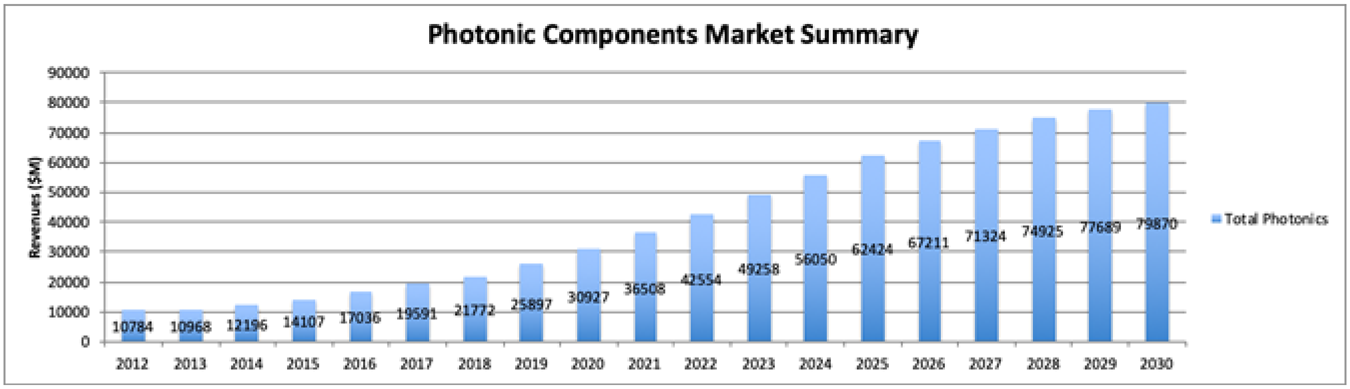

Figure 2. The summary photonics components market forecast for the next decade (Source: Oculi llc 2020).

Within the summary photonics components market, three major segments exist: Telecom core/metro, telecom access, and datacom. The telecom core/metro segment is forecast to grow to $33B by 2030 with a 13% CAGR (2020-2030) and the datacom segment is forecast to grow to $35B by 2030 with 22% CAGR (2020-2030). As can be seen from Figure 3, the growth of the telecom core/metro and datacom segments is very strong over the next decade and provide the engine for growth in the summary photonics components market.

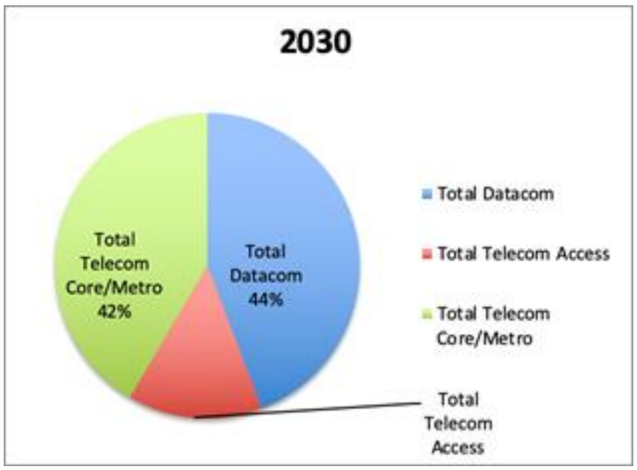

Figure 3. The key segments of the photonics components market showing datacom, telecom access, and telcom core/metro. (Source: Oculi llc 2020).

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 is the trend to integrate photonics components in PICs is beginning to accelerate. The trend is driven by applications that require smaller photonic component solutions, lower power consumption, high data rates, longer interconnect lengths and an improved economics in terms of $/Gbps. PIC applications, i.e. those applications that include integrated photonics are forecasted to grow to approximately $41B by 2030 with a strong 29% CAGR (2020-2030).

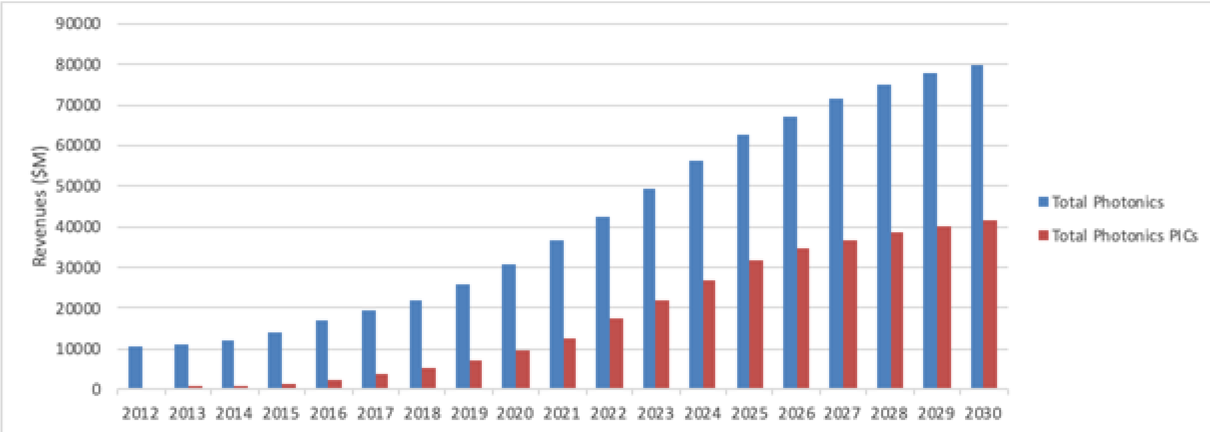

Figure 4. Comparison of the total market size of photonic components and of Photonic Integrated Circuits (PICs) (Source: Oculi llc 2020).

These technologies include InP which is the current incumbent technology, GaAs (with strong growth in areas such as structured light (and the application of GaAs VCSEL arrays) for mobile phones), and other newer integrated technology solutions such as SiP (silicon photonics), polymer photonics, and dielectric (nitride) photonics. The forecast of $41B is approximately 52% of the total photonics components market by 2030, which represents a huge acceleration for PIC based technologies over the next decade. This also means that while PIC based technologies are worth ~9 B$ today with a small segment of the photonics components market, PIC based technologies become a dominating technology by 2030 as shown in Figure 4.

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. While the summary photonic components market is expected to reach $80B by 2030, the photonics transceivers sub-segment is forecasted to grow to $53B by this time. This represents that transceiver revenues will accelerate towards 66% of the total photonics market by 2030 as shown in Figure 5.

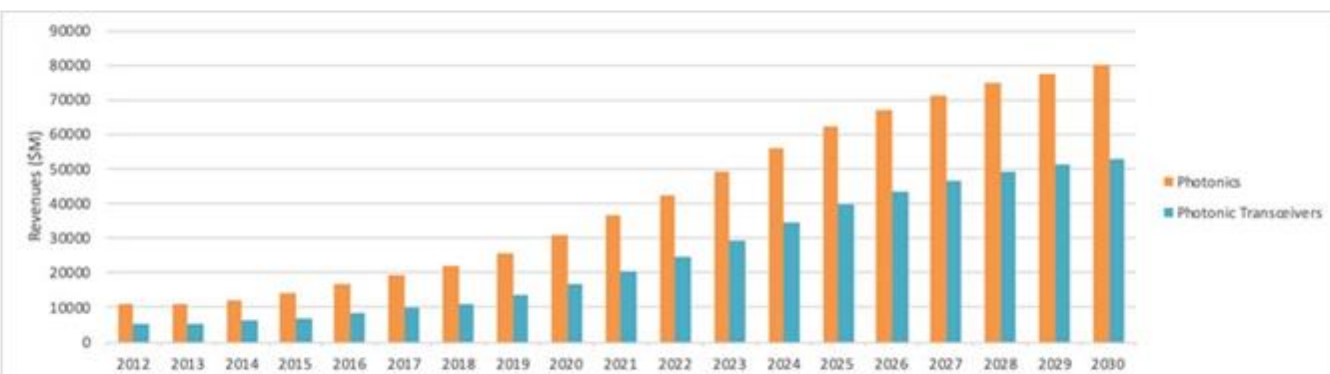

Figure 5. The relative market value of transceivers to the total market of photonic components (Source: Oculi llc 2020).

Within the photonics transceiver market segment there are two main drivers: Ethernet-datacom based transceivers and DWDM based transceivers. Both these segments are forecasted to reach a total of $48B by 2030. In Figure 6 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 the 100G node and the 400G node. The total Ethernet-datacom market is forecasted to reach $28B by 2030 with a healthy 27% CAGR (2020-2030). The

100G segment is forecasted to reach $12B while the newer 400G segment to $7B. By the end of the decade, revenues from both 800G and 1600G are expected to grow quickly.

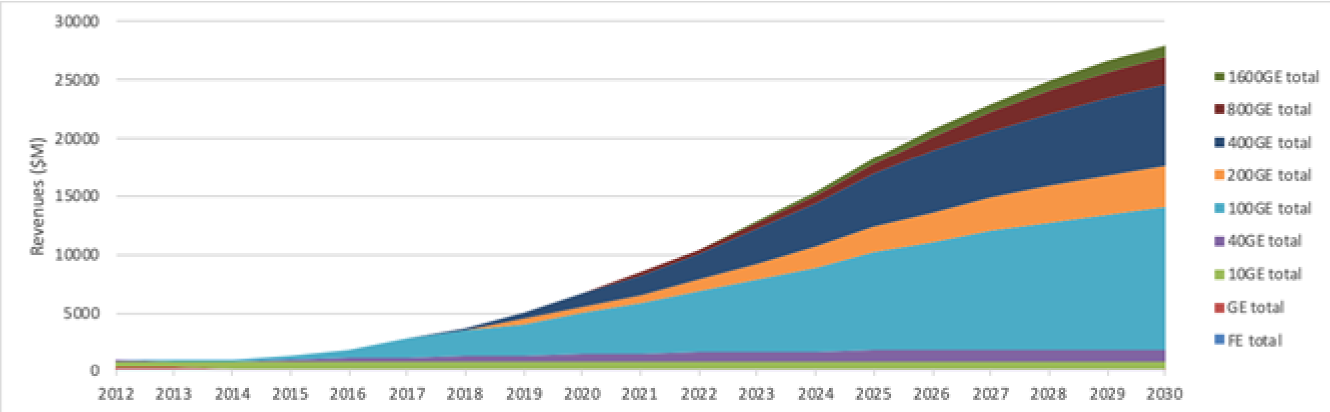

Figure 6. Forecast of Ethernet-datacom transceivers by data rate to 2030 (Source: Oculi llc 2020).

In Figure 7 the forecast of DWDM transceivers are shown by data rate for the next decade. As data rates keep increasing on a yearly basis for both Ethernet-datacom as well as DWDM transceivers, it can be seen that the main drivers in DWDM will be the 100G node and the 400G node. The total DWDM market is forecasted to reach $20B by 2030 with 27% CAGR (2020-2030). The 100G segment is forecasted to reach $6B while the 400G segment to $7B. By the end of the decade, revenues from both 800G and 1600G are expected to grow quickly in DWDM transceivers.

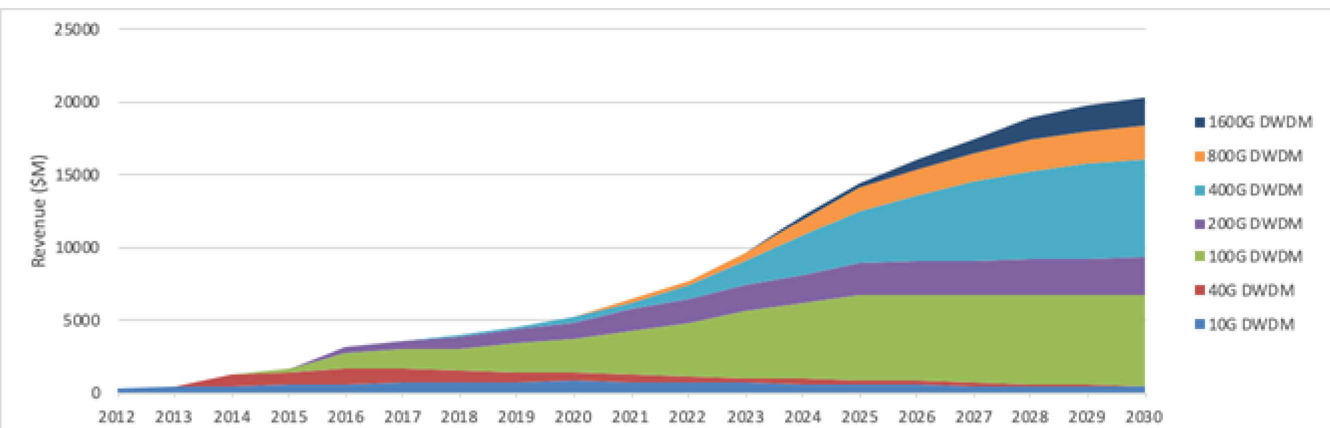

Figure 7. Forecast of DWDM transceivers by data rate to 2030 (Source: Oculi llc 2020).

It is expected over the forecast period 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.

What is more interesting in the forecasts is that by about 2023-25 PIC transceivers will surpass discrete photonic component transceivers from a revenue point of view as shown in Figure 8. This means that the trend to integrate photonics components inside a transceiver is accelerating quickly, driven by the customer interest for smaller, denser and higher performance metrics of transceivers. In Figure 8 PIC based transceivers are expected to reach $27B by 2030 and PIC based technologies are expected to lead this segment by the end of the decade.

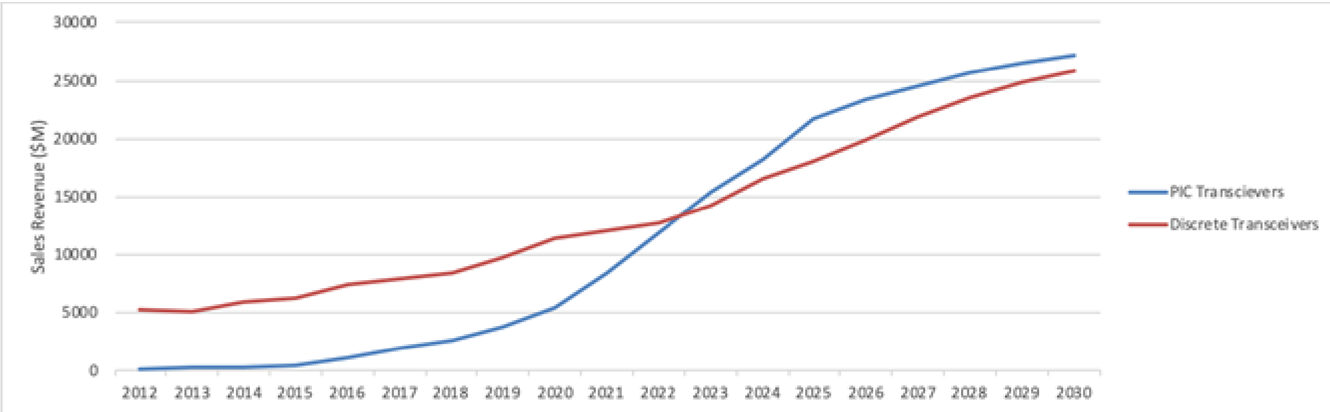

Figure 8. The relative value of PICs used in transceivers as compared to discrete photonic components (Source: Oculi llc 2020).

APPLICATIONS

As compared to the previous paragraphs, a more specific 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)
- Fibre 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 shown in Figure 12 in case of the use of discrete photonic components and PIC based technologies. The CATV market segment is composed of a number of 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 can be seen that the total market forecast for CATV and Radio reaches a peak of about $2.1B by 2030 and is fairly constant over the next decade. PIC technologies are slower to penetrate this market, and grow beyond the year 2020 to about $200M by 2025 and remain roughly at this level to 2030.

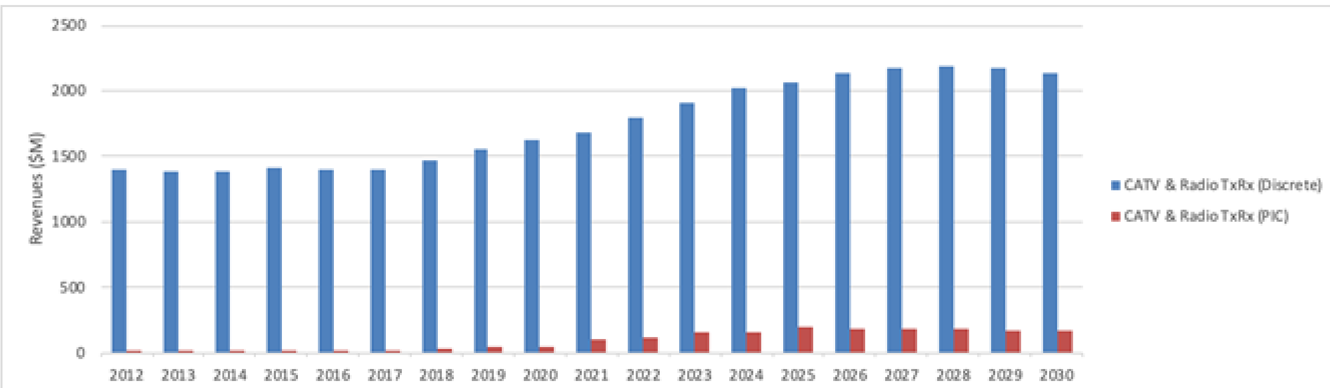

Figure 9. Market development of CATV and Radio TxRx using PICs and discrete components (Source: Oculi llc 2020)

The market potential development for the CATV and Radio segments of the market are shown in Figure 10. It can be seen that these market segments growth is moderate over the next decade with CATV slightly declining to $360M by 2030 and Radio similarly to $1950M by 2030.

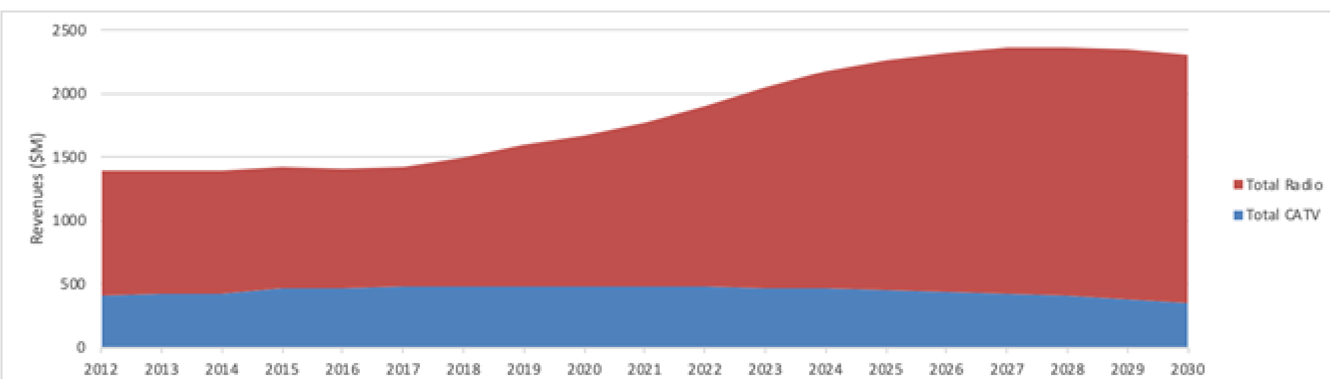

Figure 10. Market development of TxRx devices for Radio and CATV (Source: Oculi llc 2020)

RF ANALOG APPLICATIONS

About the technology

MicroWave Photonics (MWP) is an inter-disciplinary field that bridges photonics and microwave electronics. It aims to apply photonic solutions to microwave applications in order 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.

Possible functions of microwave photonics.
Several functionalities are envisioned in the optical domain as reported below.

1. Microwave signal generation
   a. High purity microwave carrier generation
   b. Arbitrary waveform generation
   c. Terahertz signal generation

2. Microwave signal distribution
   a. Analog photonic link
   b. Radio over fiber
   c. Antenna remoting

3. Microwave signal processing:
   a. Photonic analog to digital conversion
   b. Photonic beamformer
   c. Filtering, up and down-conversion

4. Microwave signal measurement:
   a. Instantaneous frequency and phase measurement

Applications for MWP
Applications for MWP include Analog photonic links, RF transceiver for communication and radar (for defense, automotive, space and other applications), beamformer for 5G and satellite communications, switch matrix for continuous route/switch/stream video signals. All these applications require lasers with a *high optical power* (P_i), *efficient detectors* (responsivity, r_{PD}) and *efficient* (a low V_π) *and small, sensitive modulators* in *waveguides having a low propagation loss* (α) to result in a low-loss optical link (L_m)

At present MWP solutions can replace the existing bulky, static, bandwidth-limited RF-electronics solutions (beamformers, transceivers and switches) and provide scalable, compact, tunable, small alternatives with low power consumption. Large passive switches and tunable matrices (including NAND-networks or photonics-based neural networks) have been manufactured in MEMS technology at TRL 6, but also in the lab (TRL4) in silicon photonics (AIST) or silicon nitride (UPV, LioniX International, SATRAX) at 1550 nm (C-Band) Telecom/Datacom applications. A dualband (flexible in the range 2-18GHz) RF transceiver on silicon-based chip with size of 5x5 mm^2 has been realized at TRL 4 (CNIT).

Currently established is a chip size of 80x80 mm^2 for a 36x144 OBFN chip (1.2 mm^2 per switch & phase shift building-block). High volume production is restricted to stepper field size (22x22mm^2) or scanner field size (26x33 mm^2). Bare-die integration would be beneficial. Criteria for a high performance photonic link (or any other MWP function similar) are

- Laser
  a) High power laser (> 50 mW)
  b) High power gain (> 100 mW)
  c) Small linewidth (< 10 kHz)
- Modulator
  a) High speed (> 40 GHz)
  b) Sensitive ($V\pi$ < 1 V)
  c) Low insertion loss

- Detectors
  a) High speed (> 40 GHz)
  b) Responsivity (> 0.7 A/W)
- Very low RF crosstalk (< -70 dB)

ACTIVE OPTICAL CABLE (AOC)

Market developments

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.

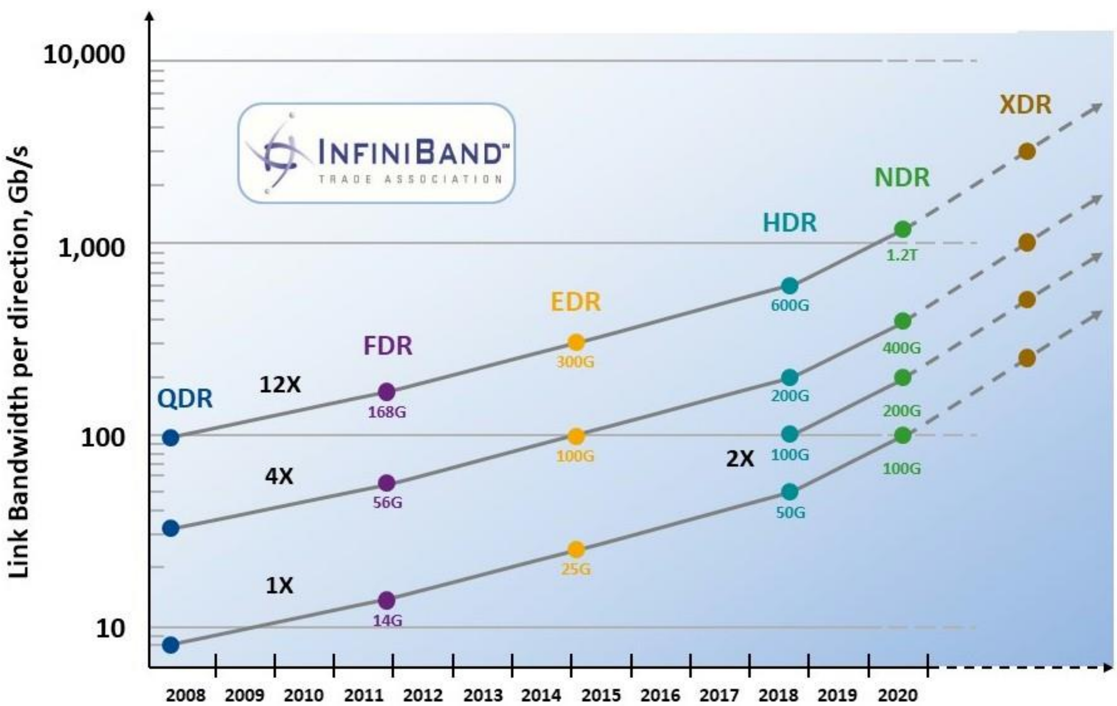

Figure 11. Market demands wrt. data rates for Active Optical Cables (Source: Infiniband Trade Association)

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 11.

The graph also shows the increasing data rates of EDR, HDR and NDR. Typically, 4 lanes are used for the optical interconnect so for example, with FDR systems the combined data rate is 56 Gbps (4 x 14 Gbps). CXP engines are 12 lane solutions that are multimode optical interconnects. Data rates for CXP range from 1 Gbps to 12.5 Gbps per lane, and recent engines in the market-place have been marketed as 120G solutions (10Gbps with 12 optical lanes). The type of laser utilized for EDR, HDR, NDR and associated AOC applications is the VCSEL. Advanced designs are capable of 56 GBaud, and over the next decade, it is expected that the performance of the VCSEL will achieve 100 GBaud with the assistance of electronic control and monitoring as the analog optical 3dB bandwidths of VCSELs are leveling off around 30-40GHz. There is a potential to increase VCSEL optical bandwidths further towards 70GHz, however, this will require advanced quantum-level designs, and this is currently in the academic research stage today. VCSELs utilized in multi-channel solutions for the AOC market are considered PICs as more than one photonic device is arrayed on a single semiconductor chip.

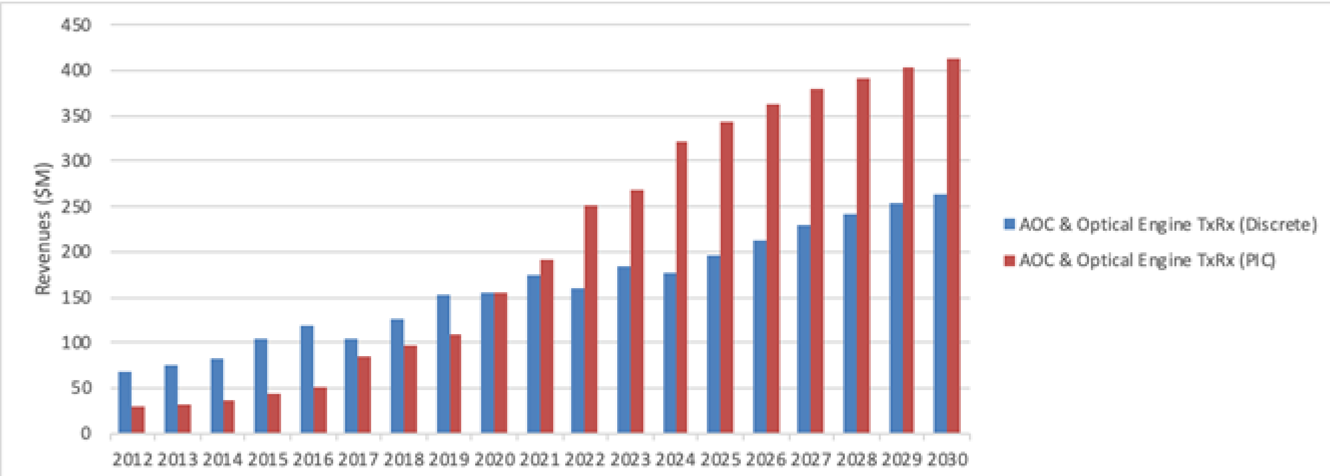

Figure 12. Market potential of Active Optical Cables using either integrated photonics or discrete components (Source: Oculi llc 2020)

Even though this segment is dominated by short wavelength technologies, over the forecast period to 2025 there is the potential for longer wavelength solutions (1310 nm, 1550 nm) to penetrate the market, especially as the cost of short distance single mode fiber transceivers fall, driven in part by the huge volumes by the datacenter applications. While datacenter applications are advocating cost metrics of €1/Gbps @ 400 Gbps, it is quite probable that the high-speed computing applications that utilized AOC technology may find it cost effective to implement longer wavelength designs.

The market potential for AOC is shown in Figure 12 between the use of discrete photonic components and PIC based technologies. The substrate for AOC emitters is GaAs and VCSEL diode lasers are used to generate optical signals into the multimode fiber interconnect links. It can be seen that the total market forecast for AOC reaches approximately $650M by 2030 dominated by PIC based technologies which surpass discrete based technologies by 2022. PIC based technologies experience a CAGR growth (2020-2030) of 20% by 2030. The market potential for the Infiniband segments of the market is shown in Figure 13. It can be seen that these market segments remain fairly constant over the next decade with the exception of the 4x EDR data rate which grows significantly out to 2030 and reaching $500M market size.

Cost development

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.

Operating environmental considerations

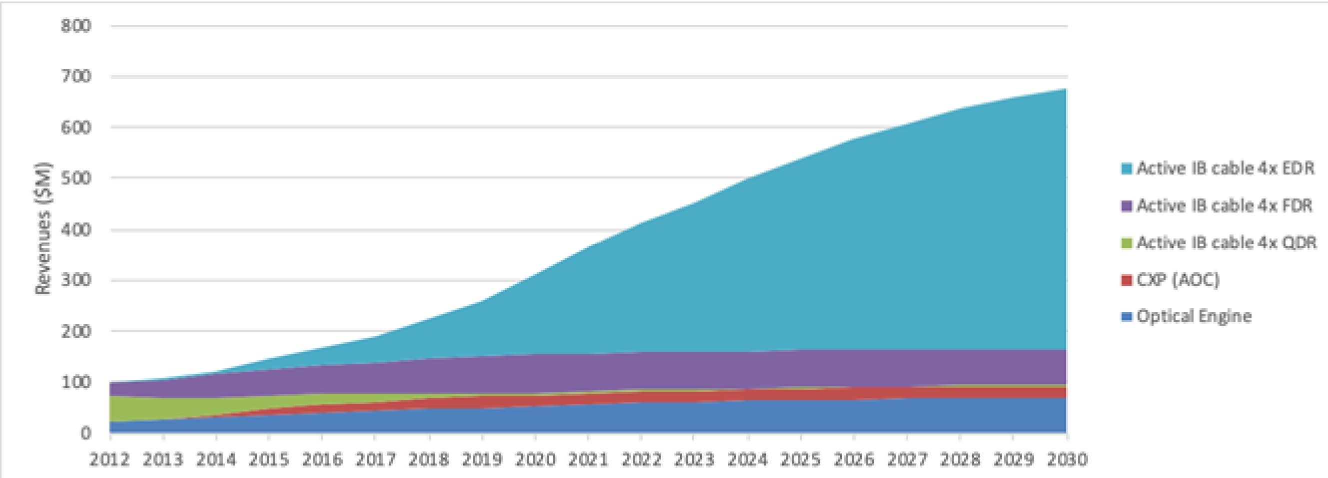

Figure 13. Market development of the Infiniband segments forecasted up to 2030 (Source: Oculi llc 2020).

The typical environment for both CXP engineers for AOC and Infiniband products are consumer, high-performance computing, and datacenter type applications. These applications require more compliant environmental reliability and quality assurance specifications compared to typical telecommunications specifications.

For example, AOC environments may typically require working temperature specifications of 0°C to 100°C operation, while in telecommunications, the temperature ranges may certainly exceed those ranges with considerably higher lifetimes and reliability requirements such as Telcordia CR-468 amongst others.

Table 1. Functional requirements AOC

AOC	[unit]	2025	2030	2040
Annual revenue	[M€/year]	1000	2000	3000
Cost price (100Gb/s)	[€/unit]	95	56	30
Energy consumption	[W]	3	1	0.5
Wavelength range	[nm]	850	850&980 and O, Cand L band	850&980and O, C and L band
Reliability	[%]	3yrs+	3yrs+	3yrs+
Footprint	[mm²]	QSFP+/28	OSFP	OSFP+
Output power	[W]			
Life cycle	[years]	2-4	2-5	2-5
Bandwidth	[Gbps]	100	200	4000
Swap time	[seconds]	<60	<60	<60
Medium	[material]	Optical	Optical	Optical

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. AOC cables have a number of datacom applications that have slightly more flexible specifications compared to standard telecommunications products, and this keeps the pricing of the AOC cables reasonably competitive today. Once the specifications trend towards telecommunications, there is a concern that the high performance (100 Gbps or above) data rates may demand tighter technical specifications which may adversely affect the bill of materials and increase the €/Gbps metrics. When baud rates go up to 50 Gbaud and beyond the MMF transmission distance reduce to below 50 m. Like transceiver trends in datacenters, it is expected that higher speed AOC will be implemented using SMF fiber and longer wavelengths when bit rates get to 200 Gbps and above.

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. Currently, AOC cables utilize VCSEL laser diode technology and these devices have been shown to perform to 56 Gbps, which is adequate for present day products. It is not clear at this time if the VCSEL could be increased to data rates of 100 Gbps or beyond over the next decade, and this may be a challenge for the industry. Adding more optical lanes is one solution, but does increase footprint and size of the AOC product solution.

FIBRE TO THE X (FTTX)

Market developments

The FTTX market segment is composed of a number of fiber optic components utilized for Fibre to the home (FTTH), fibre 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.

The market potential for Fibre to the X (FTTX) is shown in Figure 14 for discrete photonic component solutions and PIC based technologies. It is shown that the total market forecast for FTTX declines from $2.5B in 2012 to about $1.2B by 2018 but regains speed and grows to approximately $11B by 2030. Part of the growth is due to an advancement in photonics technology, and especially PIC based technologies as can be seen in the graph of Figure 14. PIC technologies penetrate this market reasonably quickly from about the year 2020 and are forecasted to grow to $3B by 2030 indicating that many of the transceiver designs will contain integrated photonics technology in PON based networks. PIC based technologies experience a strong CAGR growth (2020-2030) of 48% by 2030.

The market potential for the FTTX photonic component segments of the market are shown below for point to point transceivers, PON splitters, PON OLT transceivers, and PON ONT transceivers. It can be seen that these market segments undulate with a dip and a rebound over the next decade and regain market size and presence with forecasted revenue reaching $9B by 2030.

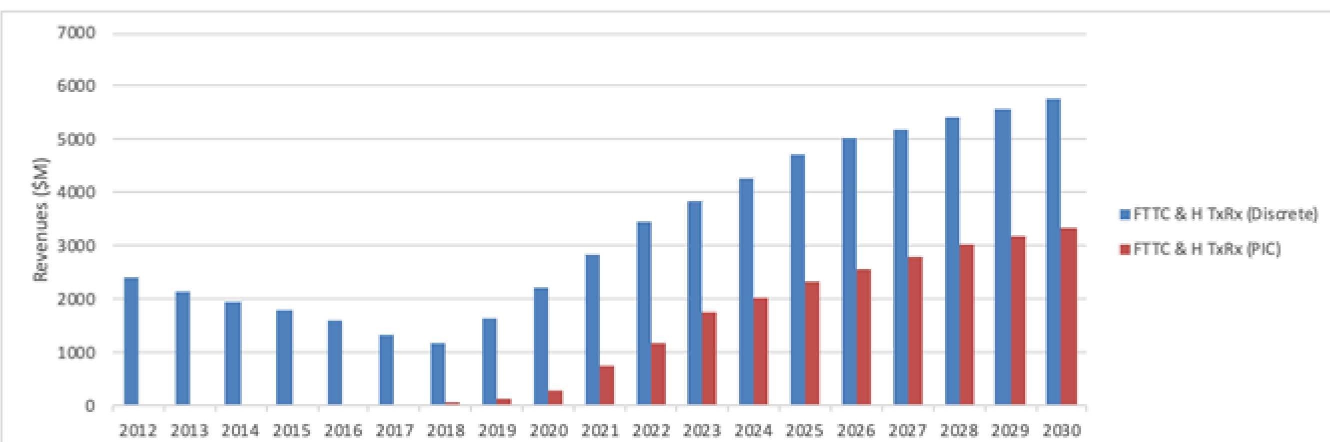

Figure 14. Market potential of Fiber to the X (FTTX) using either integrated photonics or discrete components (Source: Oculi llc 2020).

Some remarks concerning the FTTH (Fiber to the Home) market segment. The most important driver for the requirements within the FTTH-segment will be the need for bandwidth of internet users. This need can be pretty well predicted based on existing trends which have been persistent for quite some time now (see e.g. https://www.nngroup.com/articles/law-of-bandwidth/).

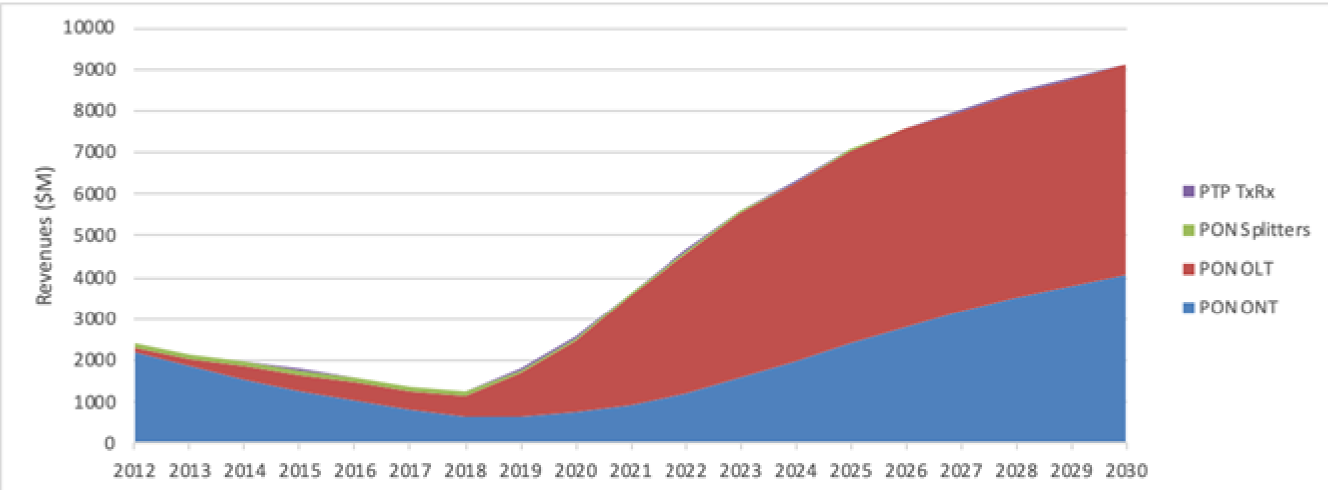

Figure 15. Market potential for the FTTX photonic component segments (Source: Oculi llc 2020)

Table 2. Functional requirements FTTX

FTTX	[unit]	2025	2030	2040
Annual revenue	[€/year]	7B	10B	12B
Cost price	[€/unit]	80%	65%	50%
Energy consumption	[W]	1	0.7	0.5
Wavelength range	[nm]	1200-1600		
Footprint	[mm²]	SFP-like		
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 standardisation, 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.

Of course, it is unlikely that characteristics like costs and power consumption will be reduced at the same time as a next step in maximum transmission rate is defined. In practice, the bandwidth will increase gradually, while the cost price will decrease slowly since to remain cost competitive in comparison to copper technologies, it is expected that the evolution in cost price reduction at the transceiver level will continue.

It is expected that the wavelength operating window (roughly between 1200 and 1600 nm) for this application is not likely to change in order to be able to keep using the existing single-mode-fiber infrastructure. Of course, adaptations of individual components are likely to become necessary, e.g. the tunability of transceivers within a part of the wavelength range and a reduction of the line width when the amount of simultaneously used wavelengths increases. Since optical transmission is already applied in the metro/long haul networks which provide a larger transmission rate than in FTTH, we can use IEEE and ITU standards as predictions for FTTH-specifications. From these standards the expectations about applied wavelengths and tunability aspects can be derived. With respect to footprint, the SFP formfactor which is currently used for the transceiver will likely suffice in the near future as well, although reduction in dimensions is appreciated but not considered to be of critical importance. Reduction of costs is considered to be of larger importance.

5G FRONT-HAUL AND BACK-HAUL

A 5G network will look as in Figure 16 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.

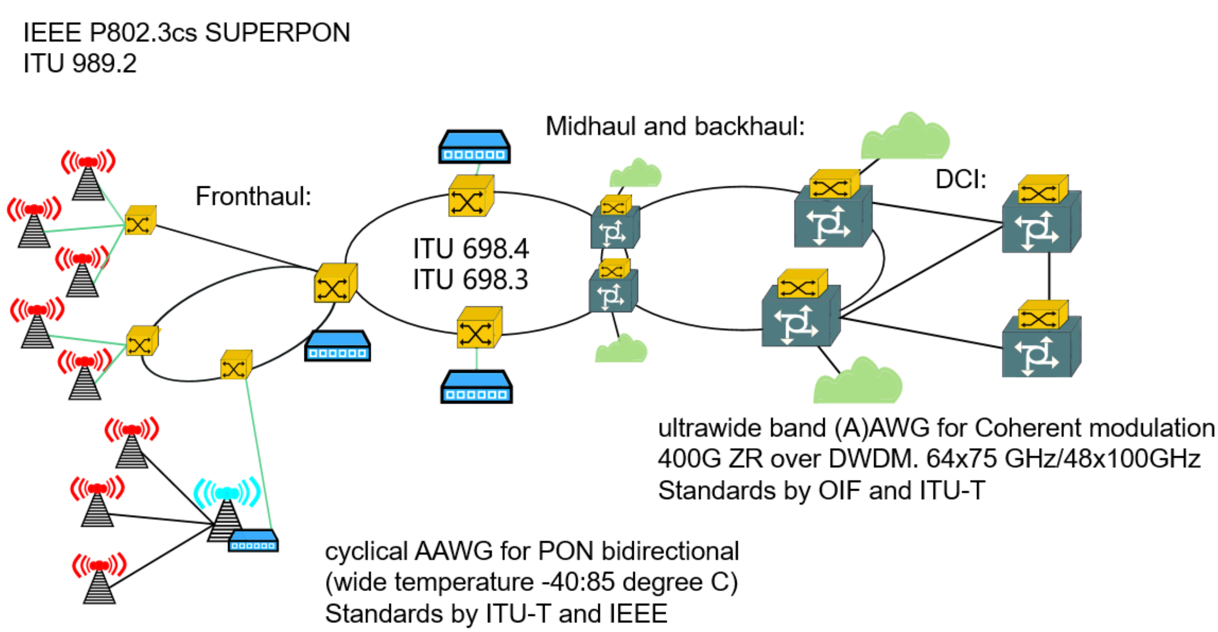

Figure 16. 5G network layout

It can be generally assumed that bandwidth requirements increase when the signal accumulates from the end user, through the aggregation network into the core towards the datacenters. For this reason different transceiver technologies need to be developed depending on where we are in the 5G network. For the ONU on the access side the main technological development will be in the development of a cost-effective tunable laser. In the backhaul coherent modules will be used on ITU grid of 100 GHz or 75 GHz spacing for 400 Gbps transceivers and will cover the C-band. In the future higher bandwidth coherent transceiver will use a wider spectrum and will require an increase in channel spacing. Hence the capacity of the trunk will not increase unless more efficient modulation schemes are developed that have more bits per GHz.

About the technology

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 or long haul modules will be designed.

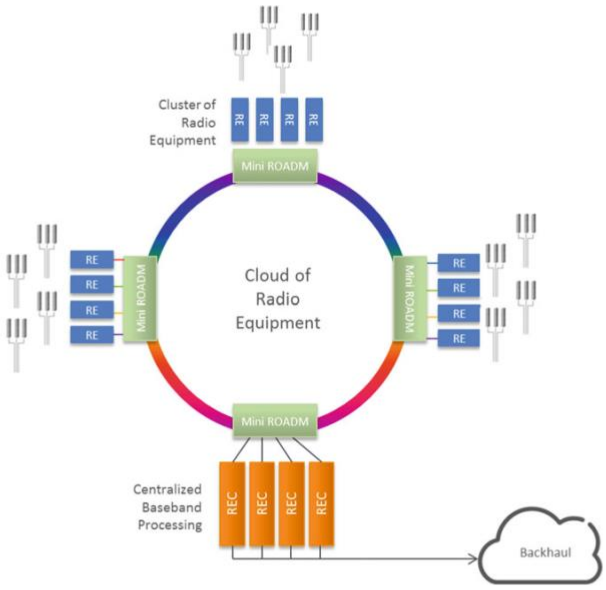

Figure 17 ring front-haul network

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

Figure 17 illustrates a possible fronthaul scenario in which a pool of REC devices communicates with a cloud of RE devices, distributed over a geographical area of a few kilometers, through a wavelength division multiplexed (WDM) ring network ensuring high bandwidth, transparency, high scalability, and simplification in cabling arrangement and installation.

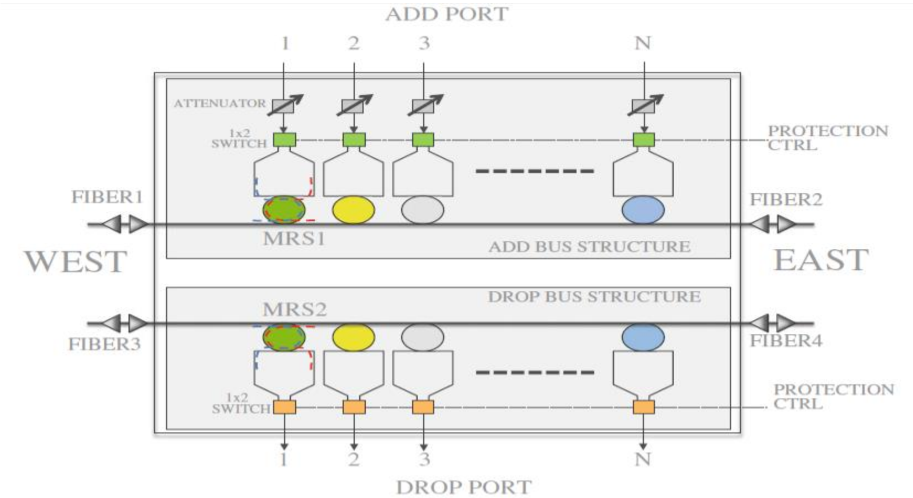

Figure 18. Mini-ROADM device

Silicon photonics is most suitable for large-scale integrated switching devices due to its characteristics of easy integration with control electronics, high miniaturization, mass producibility, potential high yield, and low cost due to the use of a well-established CMOS production infrastructure.

An example of a new integrated switching device is the Mini-ROADM, a photonic integrated device realized in silicon photonics technology and able to perform the MUX/DEMUX of all WDM channels and ADD/DROP local channels. The picture of the Mini-ROADM is shown in Figure 18. The photonic switching element here used is based on micro-ring resonators switch (MRS) able to add/drop (by configuring the 1x2 integrated optical switch) the selected wavelengths to/from the bus in both network directions (West and East).

Commercial outlook

At the moment, countries like South Korea, China and Japan have all announced their 5G installation plan. China will be a main driver for this. After missing out on 3G and 4G opportunities, China has made the installation of 5G one of their top-priorities. Aiming to showcase the 5G technology during the 2022 Winter Olympics, investment by China alone will exceed 1.5Trillion RMB or 200Billion USD for the next 5 years (source EY).

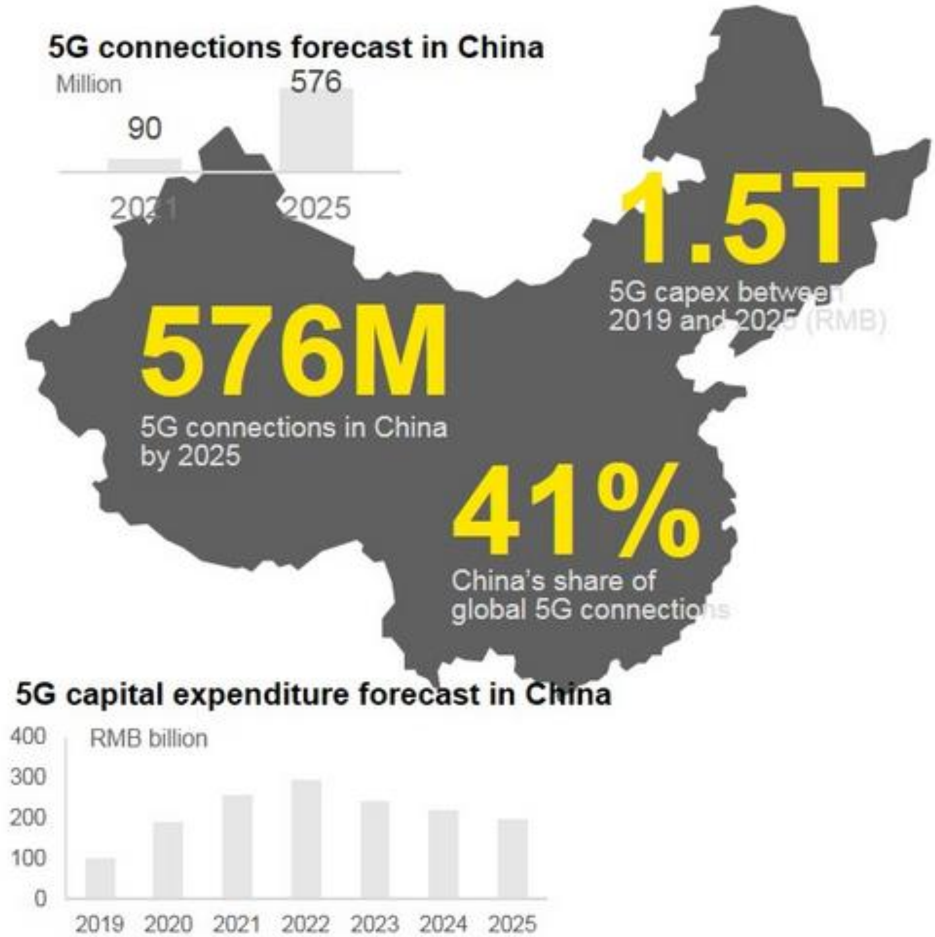

Figure 19 5G Connections and Expenditure forecast in China

Table 3. Functional requirements pluggable module transceiver 5G front-haul and back-haul

5G front-haul and back-haul	[unit]	2025	2030	2040
Annual revenue (including system equipment infrastructure)	[€/year]	100B	200B	400B
Annual revenue optoelectronics components	[€/year]	5B	7.5B	10B
Cost price	[€/unit]	300 for 10K units	200 for 10K units	50 for 10K units
Energy consumption	[W]	5	3	1
Wavelength range	[nm]	C-band		
Footprint	[cm²]	500	20	10
Output power	[W]	1	1	1
Life cycle	[years]	25	25	25

Bandwidth	[Bps]	100G	400G	1000G

*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 100 Gbps and beyond, the bandwidth density and the energy efficiency must also increase.

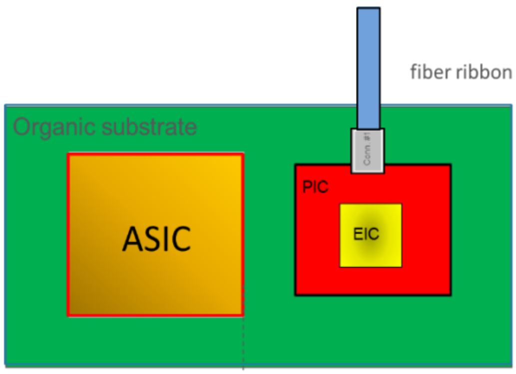

Figure20. Optical Multi-Chip Module (OMCM).

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 a large number of parallel connections, like in the COBO-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.

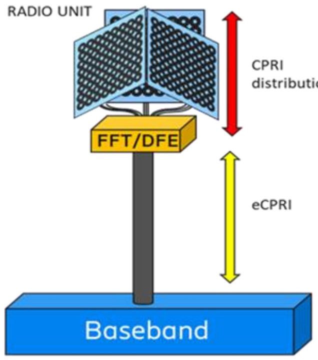

Figure 21.
high-band radio over fibre interface

In future radio systems, high band digital unit DUs will be implemented with a high number of antenna ports and they will operate with larger radio bandwidths up to 1 GHz. The high-band radio over fibre interface (CPRI distribution) are shown in Figure 21. In this scenario it will be necessary to increase the processing capacity of digital ASICs, both in the DU and in the central unit CU sub-systems, and exchange more data, leading to an increase of the bandwidth of both board-to-board and chip-to-chip interconnect.

Current Radio equipment makes an extensive use of electrical interconnects up to 25Gbps for intra-board communication, the electrical interconnects become the bottleneck due frequency dependent channel loss that prevents, at very high data rate, to extend the electrical link to more than few centimeters through PCB copper lines and reach the radio frequency integrated circuits (RFIC) distributed across the antenna. Additionally, the increase of processing function in the radio unit would increase the power consumption and consequent heat dissipation issues.

Therefore, the development of a new type of optical interconnect is the key for future Radio systems. Moreover future Radio Unit at millimeter wave frequencies due to the small size of the antenna elements, the high number of antenna elements and the large radio bandwidth (up to 1 GHz) will require OMCM technology with low energy efficiency, high throughput in the range 10-20 Tbps, a target cost < 0.1 €/Gbps and a PIC with bandwidth density > 50 Gbps/mm^2 including fiber coupling.

Table 4. Functional requirements co-packaged optics

Co-packaged optics (single transceiver)	[unit]	2025	2030	2040
Annual revenue	[€/year]	<1B	3-5B	10-15B
Cost price	[€/Gbps]	0.1	0.05	0.01
Energy efficiency	[pJ/bit]	20	5	1
Wavelength range	[nm]	1300-1600	1300-1600	1300-1600
Bandwidth density	[Gbps/mm²]	100	500	1000
Life cycle	[years]	5	5	5
Aggregate throughput	[THz]	12.8	25-52	100+
Swap time	[seconds]	n.a.	n.a.	n.a.

OPTICAL WIRELESS (LI-FI)

About the technology

Optical wireless communications can broadly be divided into a) LiFi (light fidelity), b) visible light communications (VLC), c) free space optical (FSO) communications and d) optical camera communications (OCC):

a) **LiFi** is a high speed wireless access technology that uses the optical spectrum to serve mobile devices indoors and outdoors. The optical spectrum is used in both link directions, uplink and downlink. Because in most cases, illumination is not required in an uplink scenario, infrared is the preferred spectrum in this case. Notice that LiFi does not necessarily require a line-of-sight (LoS) link. LiFi is currently being standardized as a new IEEE 802.11 standard with the reference 'bb'. It harnesses the huge and unlicensed optical spectrum which is about 2600 times larger than the entire radio frequency spectrum. LiFi has unique advantages over radio frequency (RF) technology in that it is inherently more secure as the radiation of light can be much easier controlled than RF radiation. For example, light does not propagate through opaque objects. Therefore, most walls block light signals which enhances physical layer security and at the same time reduces interference. LiFi has already been adopted in the defence sector as a secure wireless networking technology. Moreover, LiFi is a technology that can also be used in intrinsically safe environments such as nuclear power plants and chemical plants because it does not involve an antenna which could spark explosions. Lastly, it can be used underwater to extend wireless networks to subsea level.

b) **VLC** is high-speed bi-directional point-to-point wireless communication primarily for indoor and outdoor use cases. VLC assumes the strong presence of a LoS link. It primarily connects two static points and can therefore be classified as a fixed wireless solution for backhaul communication, wireless interconnects in datacentres and also for short range board-to-board communication. Like LiFi, VLC extends to the infrared spectrum.

c) **FSO** is a high-speed bi-directional point-to-point wireless communications technology primarily for outdoor use cases. It covers distances from hundreds of meters to tens of kilometers. FSO extends to satellite to ground communication and satellite-to-satellite communication. In the future, this technology may also be used to build mesh networks between planes, and for plane-to-satellite and plane-to-ground communication.

d) **OCC** is one-directional optical wireless communication to CMOS camera sensors embedded into consumer devices. The CMOS sensors act as a data detector. This technology is adopted for positioning and localization services. It also enables broadcasting of short message such as weblinks.

Commercial Outlook

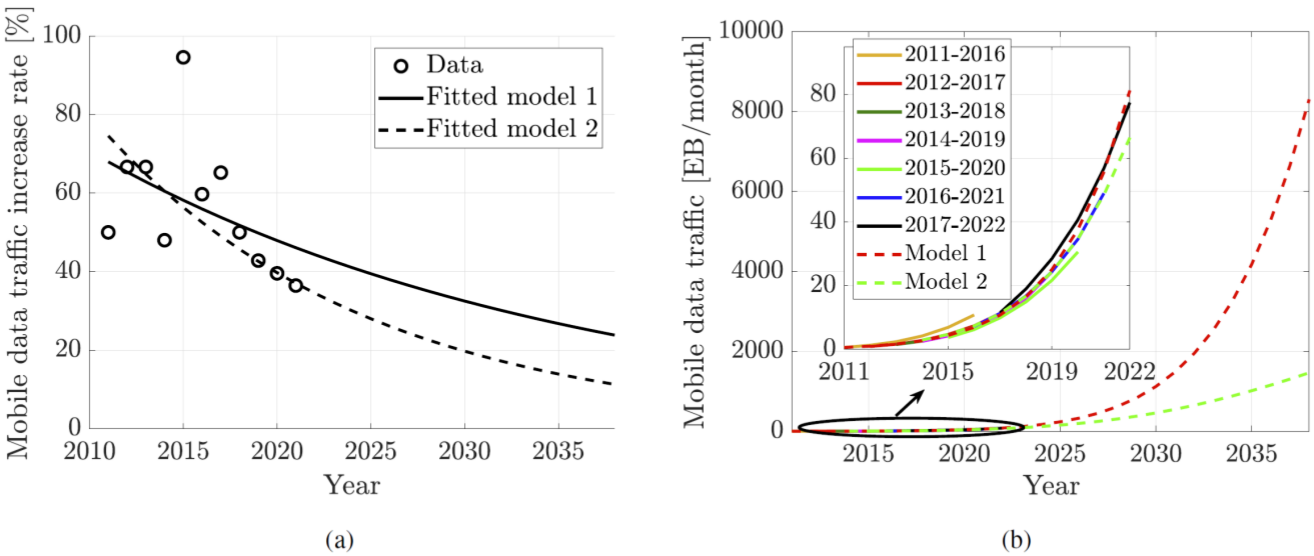

Figure 22: (a) Compound annual growth rate (CAGR) of mobile data traffic and two models (model 1 and model 2) developed from actual data; (b) predicted mobile data traffic based on the developed models and tested against actual and forecast mobile data traffic.(Harald Haas)

The total addressable market of optical wireless communications spans across a large number of sectors such as defence, 5G and 6G, IoT, healthcare, transport and datacentres. Data rates of up to 1 terabit per second (Tbps) for point-to-point wireless communication have already been demonstrated in research labs. It can, therefore, be expected that Tbps wireless networking with light will be commercially available within the next 10 – 15 years. This will drive new markets such as those in datacentres. It is forecast that within the next 10 to 15 years, the annual mobile data traffic will grow from currently about 50 – 70 exabyte per year to 1000 to 4000 exabyte in 2035 (see Figure 22). This is an average increase of about times 40 (with a predicted maximum of 80) compared to the current mobile data traffic. Therefore, optical wireless communications will take a central role in 6G as there is a clear need for new spectrum to serve this demand. In 15 years' time, optical wireless technologies could carry 80% of mobile data traffic due to the rapid expansion envisaged in data traffic and lack of availability of RF spectrum. Optical wireless communication technologies will serve both new access networks as well as the increasing demand for ultra-high speed backhaul communication. The latter is due to increasing network densification. Crucially, ultra-high speed backhaul communications is considered a key enabler to be able to continue to scale datacenters.

Technology requirements

The requirements for optical wireless technologies will be met using a range of semiconductor technologies such as GaN LEDs, GaAs VCSELs, Si photonics and InP devices.

Table 5: LiFi / VLC components for mobile and fixed wireless (backhaul)

LiFi / VLC components	[unit]	2025	2030	2040
Annual revenue	[€/year]	1.5 Bn	22 Bn	300 Bn
Unit price	[€/unit]	30	10	3
Energy consumption	[W]	3	1	0.5
Wavelength range	[nm]	300 – 1000		
Footprint	[mm²]	25- 1000		
Output power	[W]	0.005 - 500		

Life cycle	[years]	1-5		
Bandwidth	[Bps]	100 Gbps	1 Tbps	10 Tbps
Speed	[m/s]	3	50	100

UNDERSEA AND LONG HAUL PHOTONIC COMPONENTS

Market developments

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 a number of 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.).

It is shown in Figure 23 that the total market forecast for amplifiers and pumps declines from a peak of $1.4B in 2019 to about $0.8B by 2030. Part of the decline is 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 will penetrate this market very quickly from about the year 2020 and grow to $0.9B and keep that share to 2030 indicating that a large part of the photonics based solutions will contain integrated photonics technology in long haul based networks. PIC based technologies are expected to experience a very strong CAGR growth of 37% by 2030. 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.

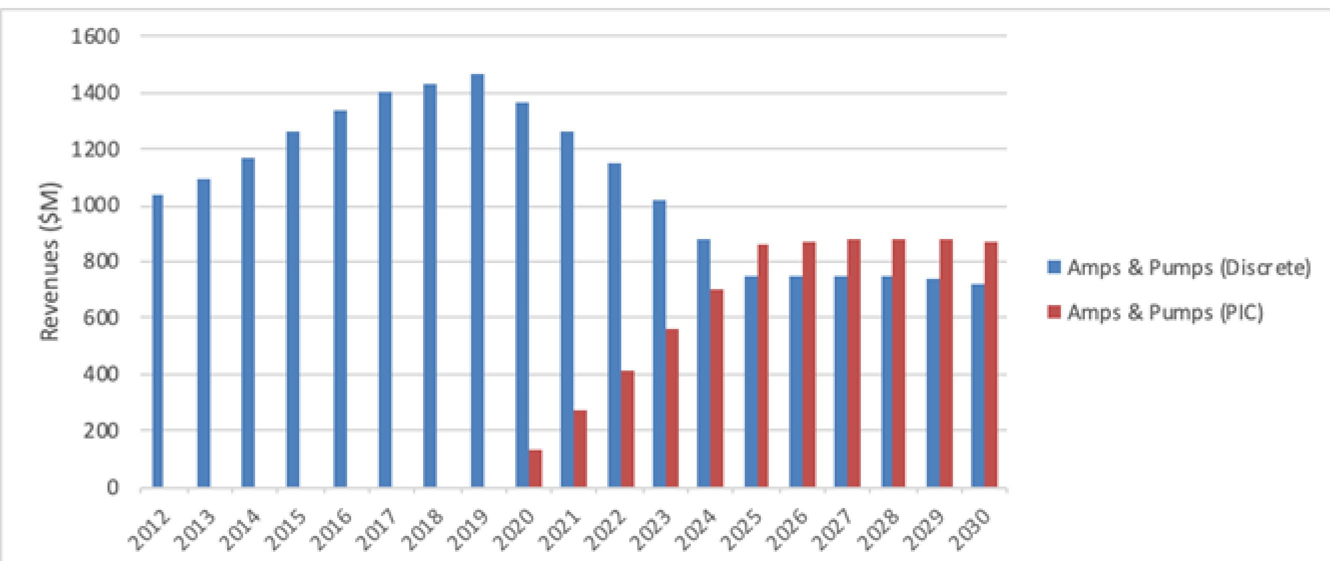

Figure 23. Market potential for long haul components (Source: Oculi llc 2020)

METRO AND OPTICAL TRANSPORT

As network traffic continues to grow (doubling approximately every 2 years[4]), efforts are focused on increasing the bandwidth of the existing fibre infrastructure through more efficient use of the spectrum available. Generally, higher modulation speeds and new modulation formats are favoured 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 >80 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 ºC 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. This is effectively taking a standard telecommunication transceiver module for >100km reach, stripping out many of the high cost components, maintaining the coherent functionality, and significantly reduce the cost structure. Companies are designing low cost DSP chips for this market, and this is expected to continue well into the next decade. Datacenter operators have need for high volumes of 10-100 km interconnect reach links as they evolve their architectures from simply inside a datacenter to distributed datacenters across a metro environment. The drive for low-cost coherent is just beginning, and the designs of low-cost coherent modules will evolve quickly in the next few years as vendors, suppliers, and standards organizations debate what features will be not only necessary for this link, but at what reduced cost can it be implemented in a datacenter volume scenario.

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

[4] See Figure 1 in this document that conveys the increase in traffic levels on the internet.

- Increased reliability
- Packaging (simplicity/cost)

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

- Modulator bandwidth of >120 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:

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 6. 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 the 2013 iNEMI Roadmap, 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 fiberlength.

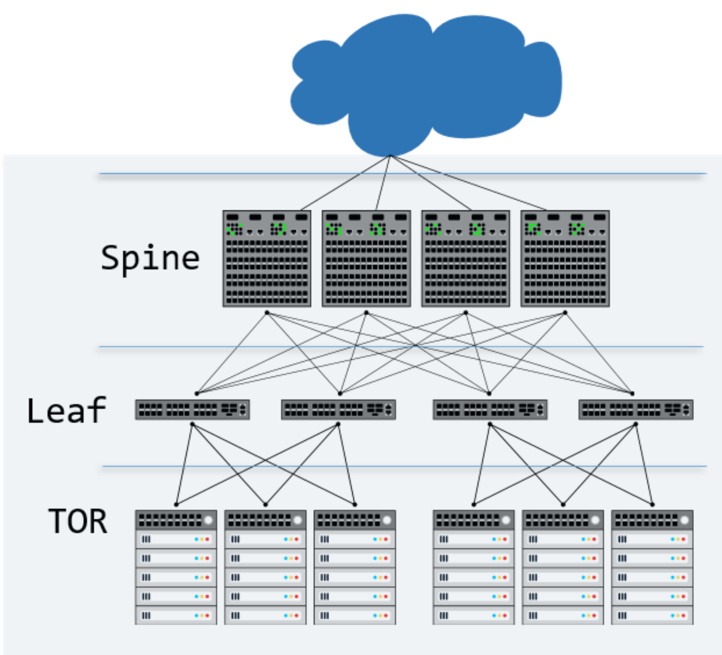

Figure 24. Data center communications architecture

In Figure 24 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 Gb/s and as it connects over longer distances, like kilometers or more, it favours 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 Gbs 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 and above.

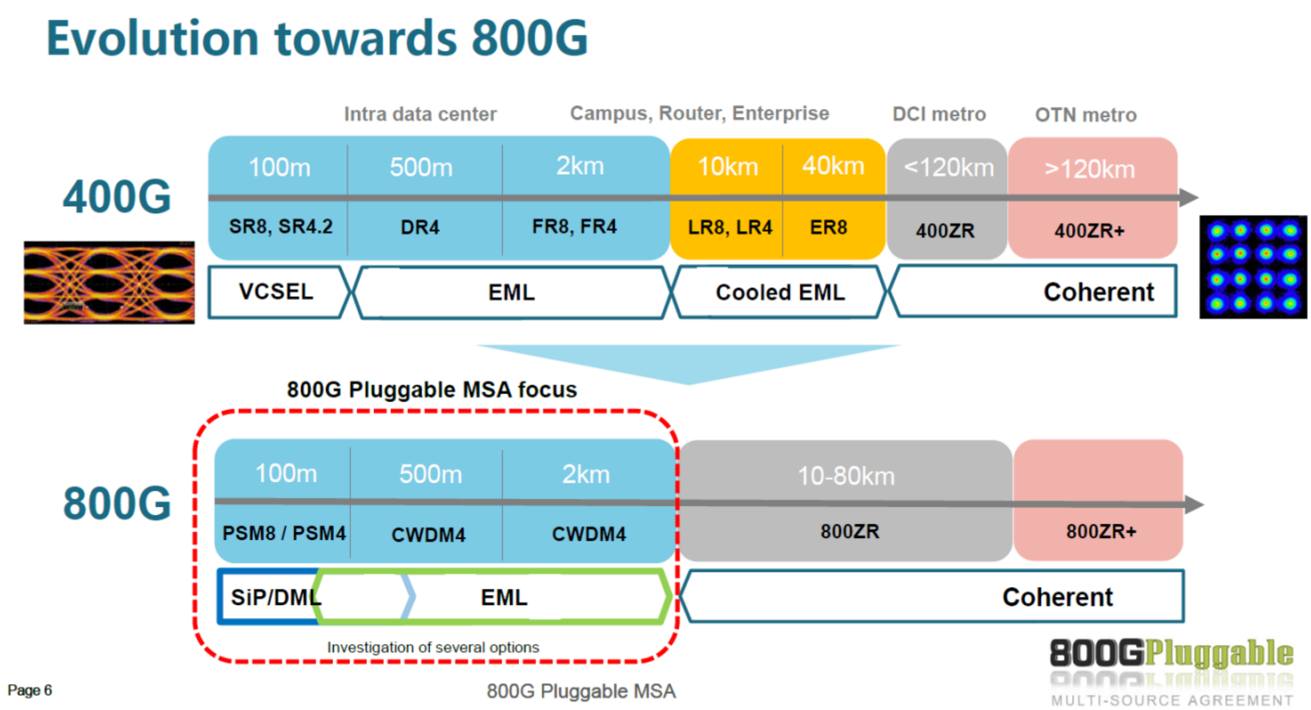

Figure 25. Evolution towards 800G in the datacenter

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 70 GHz which translate to 100 Gbps using NRZ, and 200 Gbps using PAM-4 signaling will be necessary over the next decade. Presently, only a few InP modulator chips can perform at 60 and 70 GHz analog bandwidths, while new and novel modulators in polymers have demonstrated analog bandwidths at 70 GHz and 100 GHz. 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

A presentation at the 2015 Emerging Green Conference[5] argues that IoT and Data Center 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
  Reuse 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. With the increase in mobile electronics, a new

[5] The 2015 iNEMI Technology Roadmaps have been used as a primary source particularly the High End System Product Emulator.

set of technology becomes available but at a much different scale of size and bandwidth than needed for Data Centers.

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 and Package-on-Package 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 Gb/s 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. First, 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.

Table 7. Functional requirements for Datacenter and HPC optical components

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

Overview of datacom drivers in comparison to the Photonic technology platforms:

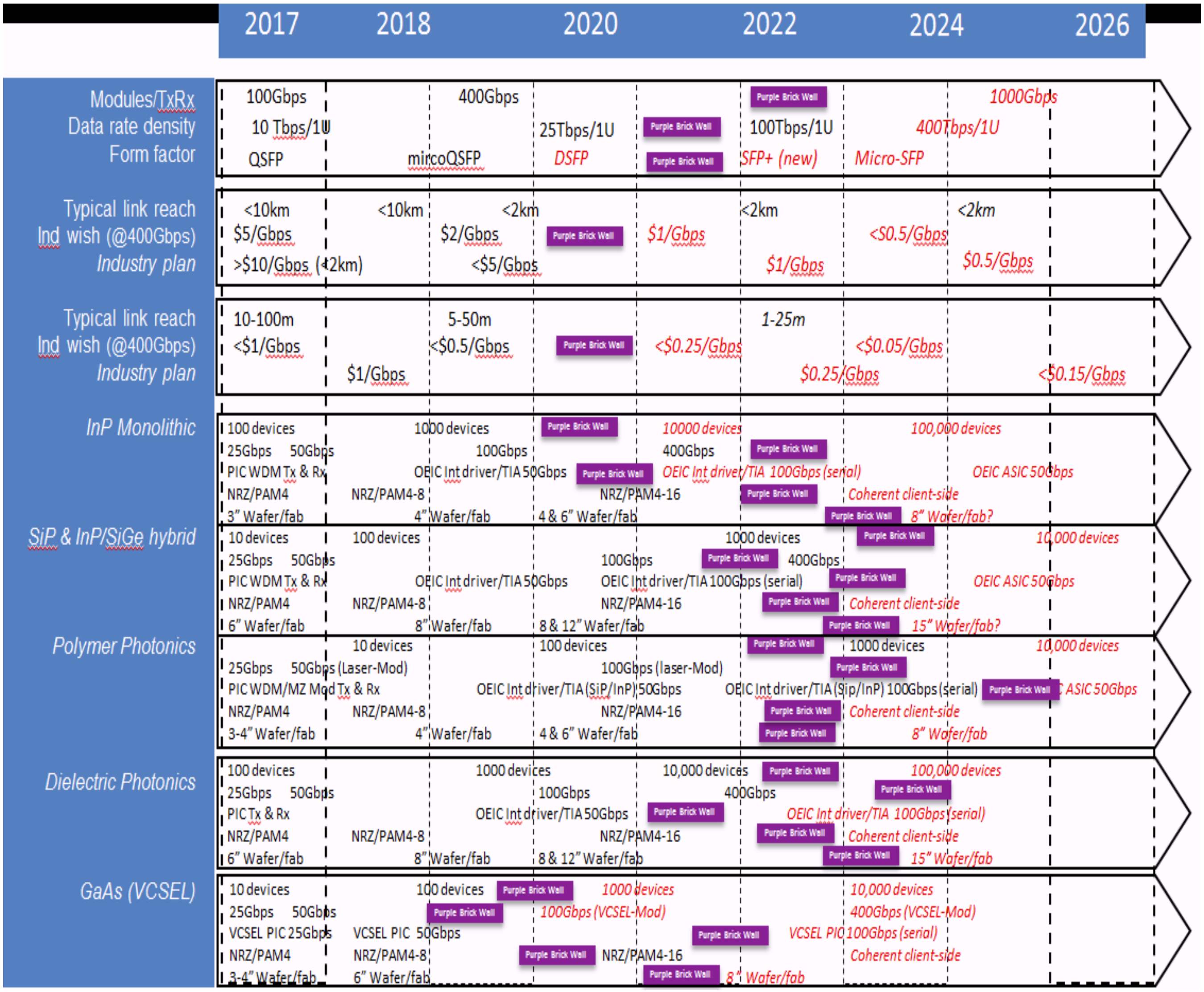

Figure 26. Overview of datacom drivers in relationship to photonic integrated chip technologies. Source: Light Wave Logic & PhotonDelta

PRIORITIZED DEVELOPMENT & IMPLEMENTATION NEEDS (< 5 YEARS RESULT)

Critical Milestones		
CM1	Higher speed modulation >120 Gbaud, <1 V operation (70 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 °C to 85 °C uncooled (0 °C to 70 °C in datacenter/datacom)	
CM6	Packaging (simplicity/cost)	
CM7	Non-hermetic packaging and chip scale packaging	
CM8	High responsivity high speed detector (>100 Gb/s)	
CM9	Lower power consumption (50% reduction)	

PRIORITIZED RESEARCH NEEDS (> 5 YEARS RESULT)

Critical Milestones		
CM10	High operating temperature laser (>150 ºC)	
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 ºC uncooled	
CM17	Uncooled laser for coherent with better than 2 GHz stability	

GAPS AND SHOWSTOPPERS

Laser materials for efficient operation at temperatures >150 ºC
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 eg 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)

- 80+ GHz optical bandwidth photonic devices (e.g. E/O polymer-based, thin film Lithium Niobate, SiGe 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.

CONTRIBUTORS

Michael Lebby, Lightwave Logic - chair
Richard Pitwon, Resolute Photonics - chair
Michael Robertson, Huawei Technologies R&D UK Ltd. - chair
Bob Pfahl, IPSR/iNEMI
Dale Becker, IBM,
Chuck Richardson, iNEMI,
Amit Agrawal, Cisco
Keith Newman, Hewlett-Packard
Russell H. Lewis, HP
Sherwin Kahn, Alcatel-Lucent
Debendra Malik, Intel
Paul van Dijk, LioniX International
Alberto Bianchi, Ericsson
Fabio Cavaliere, Ericsson
Peter Maat, Astron
Boudewijn Docter, EFFECT Photonics
Henk Bulthuis, Broadex Technologies UK Ltd.
Mike Wale, UCL & Technical University of Eindhoven
Nestor Coronado, Value loops
Maarten van Egmond, Genexis
Timo Aalto, VTT
Shangjian Zhang, University of electronic science and technology of China
Erwin Vergeest, Finisar
Stephane Barnebe, CEA LETI
Zhaohan Liu, VTEC
Hans Hilgenkamp, University of Twente
Edwin de Jong, NIBC
Eric Mounier, Yolé developpement
Hann-Huei Tsai, NARLabs
Jeroen Duis, PHIX
Sylwester Latkowski, Technical University of Eindhoven & PITC
Tobias Gnausch, Jenoptic
Martin Korst, Fraunhofer
Frank Shepherd, NRC
Jinzhong Yu, Chinese academy of Science
Rogier Verberk, TNO
Andre Richter, VPI Photonics
Bert-Jan Offrein, IBM
Ruth Houbertz, Multiphoton Optics
Martin Moehrle, Fraunhofer Heinrich-Hertz Institute
Zhiyong Li, Chinese academy of sciences
Huub Ambrosius, Technical University of Eindhoven
Lionel C. Kimerling, Massachusetts Institute of Technology
Makoto Okano, AIST

Arnan Mitchell, RMIT University
Koji Yamada, AIST
David Marpaung, University of Twente
Jan Mink, VTEC
Willem Vos, University of Twente
Harald Haas, The University of Edinburgh

REFERENCES AND ACKNOWLEDGEMENTS

1. The 2015 iNEMI Technology Roadmaps have been used as a primary source particularly the High End System Product Emulator.
2. The data for Market Forecasts and Situational Analysis, where not otherwise stated, has been provided by IHS Technology.
3. Pfahl, R.C., Jr. “Roadmap of future high volume electronic products and their environmental impact,” Emerging Green USA 2015, Portland OR.
4. Source: OSA Industry Development Associates (OIDA) Roadmap Report: Photonics for Disaggregated Data Centers (2015)

APPENDIX

Gain definition of an RF photonic link

Gain definition of an RF photonic link (a photonic circuit where RF signals propagate on an optical carrier) is the rationale for these applications as depicted in Figure A1, including a Mach Zehnder Modulator, continuous wave laser (usually around 1550 nm (C-Band, a wavelength that has good a propagation distance through fiber or waveguides)) and a photodetector.

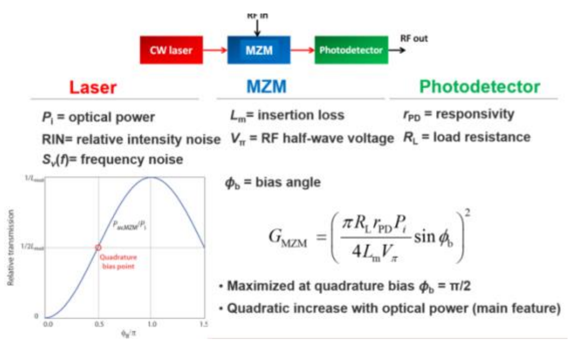

Figure A1. MWP rationale

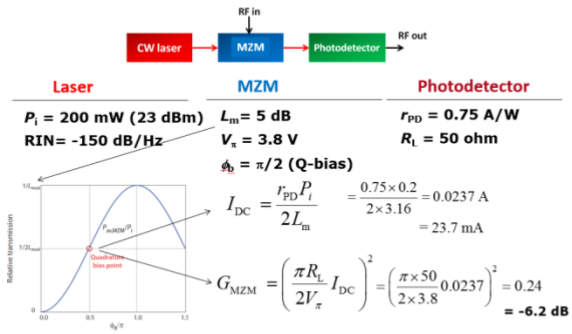

Figure A2. Typical values of individual components in a photonic link

Figure A2 shows an example for typical values of the individual components. Currently the typical values of a link gain as function of aimed laser current and what is partially achieved are present in Figure A3.

Noise

Moreover, frequency noise, thermal and shot noise should be evaluated against relative intensity noise (RIN) and higher-order interference (a challenge for high-bandwidth applications) should be evaluated to define the spurious free dynamic range (SFDR) of the photonic Link. The following noise contributions need to be considered:

- Thermal noise: $S_{th} = kTB$ (= -174 dBm + 10 log B @ 290k)
- Shot noise (proportional to optical power (P_{opt})): $S_{shot} = 2qI_{av}BR_L$
- Relative intensity noise (RIN) (proportional to (P_{opt})^2): $S_{RIN} = 10^{\frac{RIN}{10}} I_{av}^2 BR_L$

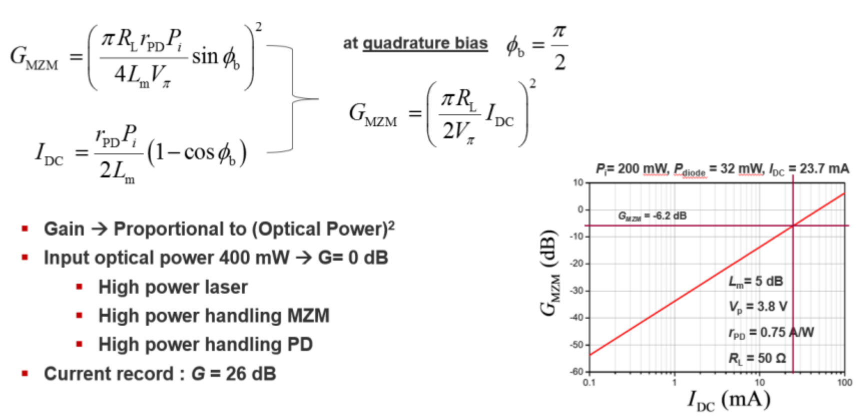

Figure A3. Typical overall numbers for a photonic link

Where:

- B = noise bandwidth

- k = Boltzmann constant (1.38·10-23)
- T = temperature
- q = electron charge
- r_{PD} = photodetector responsivity (A/W)
- I_{av} = average photocurrent
- P_{av}= average received optical power
- R_L = load resistance (50 ohm)

The average received optical power is proportional to the photodetector responsivity and average photocurrent:

- $P_{av} = I_{av}/r_{PD}$