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Advancement in Optical Interconnect Technology for High Speed Data Transmission

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ABSTRACT

Optical communication roadmaps have been moved forward 3-4 years by the critical need for remote working during the pandemic. The development of 800 Gb/s and 1.6 Tb/s technologies exceeds original projections with the first co-packaged optical modules anticipated in 2023. Furthermore, advances in quantum computing and quantum communication are creating a demand for new "quantum grade" optical fiber interconnect to support quantum networks and connectivity to quantum photonic integrated circuits. In this paper, we report on the latest advances in optical interconnect required to enable the proliferation of co-packaged optics, quantum networks and quantum photonic integrated circuits.

Keywords: Optical Interconnect, Quantum Communication, Optical Communication, Photonic Integrated Circuits, On-board Optics, Co-packaged Optics

1. INTRODUCTION

The world was plunged into a necessary isolation imposed on global populations during the COVID-19 pandemic. Remote communication services such as teleconferencing, e-learning, online shopping and e-banking, which were considered more of a convenience than a necessity, became the only lifeline for personal life and business operations. We were forced into an unprecedented acceleration of digital technologies unlike anything witnessed in the past 40 years.

Many of the emerging technologies, which involve high speed communications, digitalization of social data, intelligent data processing and network security became the focus of tech companies and governments around the world. Advancement in these technologies has inevitably accelerated the adoption of high speed optics. The proliferation of 200 Gbps and 400 Gbps optics by Internet Content (Cloud) Providers, which was initially scheduled for adoption by late 2022 or early 2023 is already being deployed today. The development of 800 Gb/s and 1.6 Tb/s technologies also exceeds the original projections with the first co-packaged optical modules anticipated in 2023 [1]. Furthermore, advances in quantum computing and quantum communication have been buoyed by huge investments and a nascent technology race between the US, China, and Europe, creating a demand for new "quantum grade" optical fiber interconnect to support quantum networks and connectivity to quantum photonic integrated circuits.

In this paper, we report on the latest advances in optical interconnect required to enable the proliferation of co-packaged optics, quantum networks and quantum photonic integrated circuits. We shall also touch on the potentially challenging operational environment, in which these interconnects would need to operate.

Although the primary function of optical interconnects have remained the same, the technology has been constantly evolving and innovating ever since the discovery of optical fiber as a communication medium by Sir Charles Kao back in the 1970s. Every year, over a billion optical connectors are deployed in various applications around the world, and their growth has been steady as more technologies and industries incorporate optical and photonic components. Today, optical interconnects are used in all forms of industries such as optical telecommunications, medicine, transport (automotive), broadcasting and even in space exploration.

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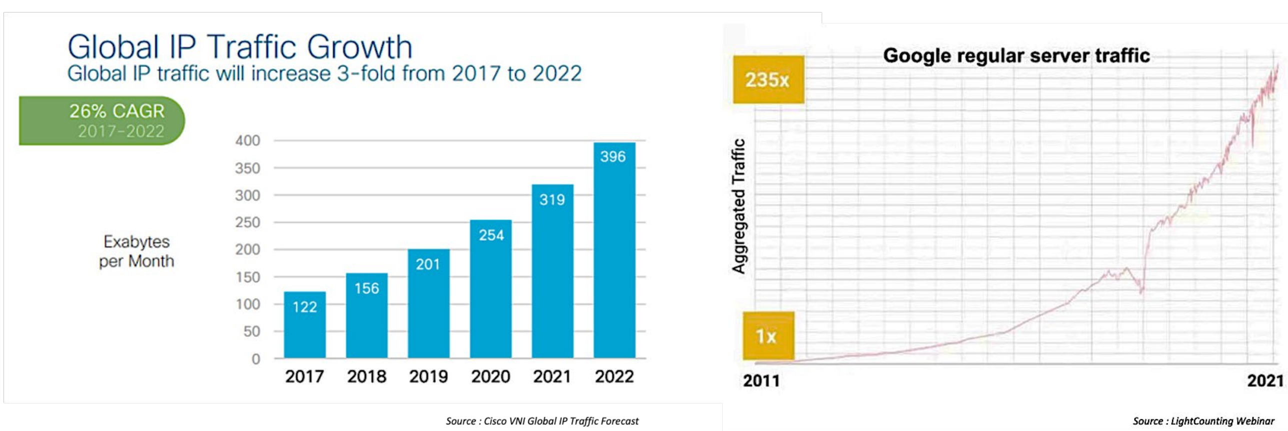
1.1.1 Market drivers Accelerated Adoption of Optical Interconnect

Figure 1: Evolution of Optical Interconnect Technology over the past 20 years

Before the early 2000s, optical fibres were exclusively used in long haul and trunk networks and in most cases a point-to-point architecture. The boom of optical communications to the masses took off in the early to the mid of 2000s with the introduction of Fiber-to-the-Home (FTTH) where telecommunications service providers began to adopt the use of optical fibre to provide broadband services to their consumer and business customers, thus replacing the xDSL offerings which use of traditional copper cables. When the end users are able have access to high-speed broadband, many find new innovative ways to utilise this newfound capability thus accelerated the growth of internet traffic as we can see in Figure 2 below.



(a) (b)

Figure 2: (a) Global IP Traffic Growth from CISCO and (b) Google regular server traffic

Ultra HD videos, user generated content and social media gain popularity and today it has become a part of our daily lives. Nevertheless, as new content is being constantly generated, the storage and management of the corresponding digital data gave birth the next phase of the optical evolution and this time it is happening inside the many data centres that were being built to house servers, switches, and data storage systems. Copper interconnects that were used to connect the servers, switches and storage together are no longer sufficient to provide the speed and reach required to cope with the burgeoning demand of content fuelled by the newfound appetite for content of the customer. These copper interconnects (e.g., UTP cable and RJ45 connectors) had to give way to optical jumpers and interconnects such as the LC and MPO connectors which provided a small footprint and increase fibre counts.

Today we find ourselves at the beginning of another evolutionary phase of optical interconnect technology. As the amount of content and information is generated at an unprecedented rate due to the mass adoption of high-speed broadband (whether wired of wireless), the task of managing and processing the daunting amount of data has been delegated to Cloud services enhanced by artificial intelligence (AI) and machine learning (ML). Nowadays, over 70% of data transmission happens within the data centres (DC), which are data being transferred between the servers and storage via the switches. As such, intra-data centre interconnect has been adopting optical technology to cater to the increase in demand for bandwidth, but also to reduce the power consumption. Optical connectors had to evolve to be smaller in footprint to reduce the overall DC space requirement and to increase channel density on the equipment front panel. In addition, optical interconnect is being used to link components within the active equipment itself (i.e., servers, switches, and storage). On-board optics, optical backplanes, and Photonic Integrated Circuit (PIC) coupling are currently the key drivers for innovation of optical interconnect (Figure 3).

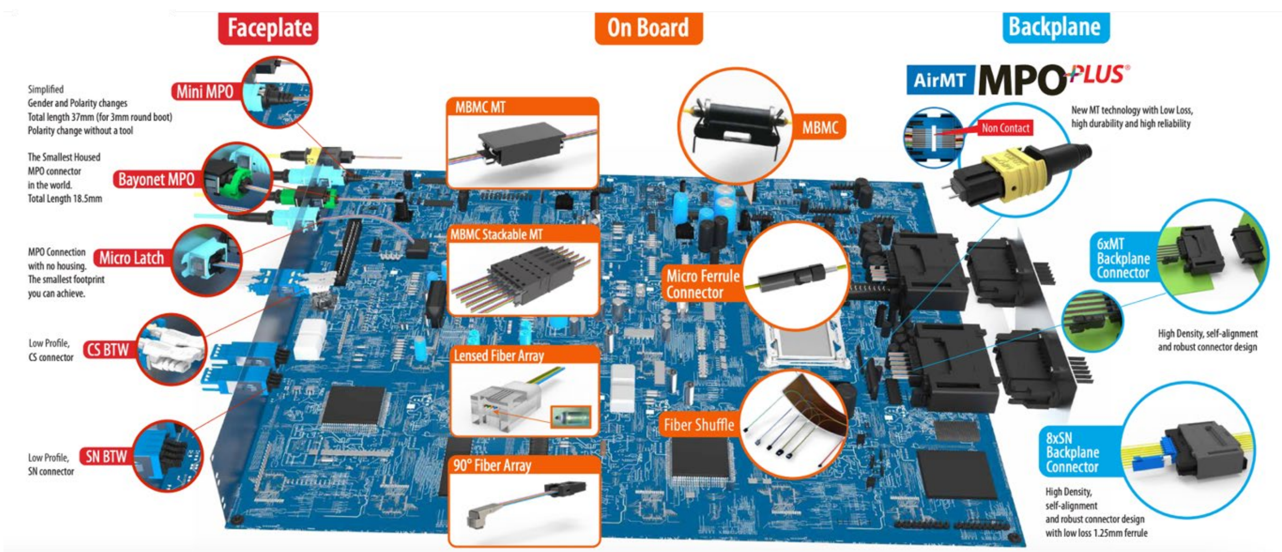


Figure 3: Optical Interconnect for On-Board Optics applications

2. OPTICAL INTERCONNECT FOR HYPERSCALE DATA CENTERS

2.1.1 Hyperscale DC – the epicentre of optical interconnect transformation

Similarly to how telecommunications has driven innovation in optical connectors in the past, the key industry driving innovation in recent years has been the world of Cloud data communications (i.e. hyperscale data centres). The demand for higher network bandwidth in data centers has been increasing significantly with the advent of social media, video streaming and increased number of smartphone users. In order to cater for emergence of next generation application and technology such as 5G, Cloud Services, 4K Videos and the Internet of Things (IoT), data centers around the world are growing in numbers, floor space and bandwidth capacity.

This was most evident in 2016 when data centers around the world started to upgrade their links from 40 Gbps to 100 Gbps links. It was forecasted that from 2016 - 2022, transceiver revenue would increase at a CAGR of 39%, mainly fuelled by new data center builds, expansion and also retrofitting of existing data centers and finally, adoption of enterprise data centers [2]. In fact, transceiver vendors are currently expanding their manufacturing capacity to keep pace with the demand for 100Gbps modules. As the global the migration toward 100 Gbps began, the IEEE released a new standard titled IEEE

802.3.bs-2017 "IEEE Standard for Ethernet Amendment 10: Media Access Control Parameters, Physical Layers and Management Parameters for 200 Gbps and 400 Gbps Operation". The initial target to support capacity growth was to introduce a 400 Gbps solution, but an intermediary 200 Gbps capability was added to support a cost and performance optimized migration path towards 400 Gbps. Nevertheless, the 100 Gbps transceiver alone is expected to continue growing at a CAGR of 53% out of the total transceiver (100G, 200G & 400G) growth of CAGR of 63%. This is due to the fact that 200G & 400G transceivers started to become commercially available from 2019 and are starting now to noticeably reduce the market share of 100 Gbps transceivers [3].

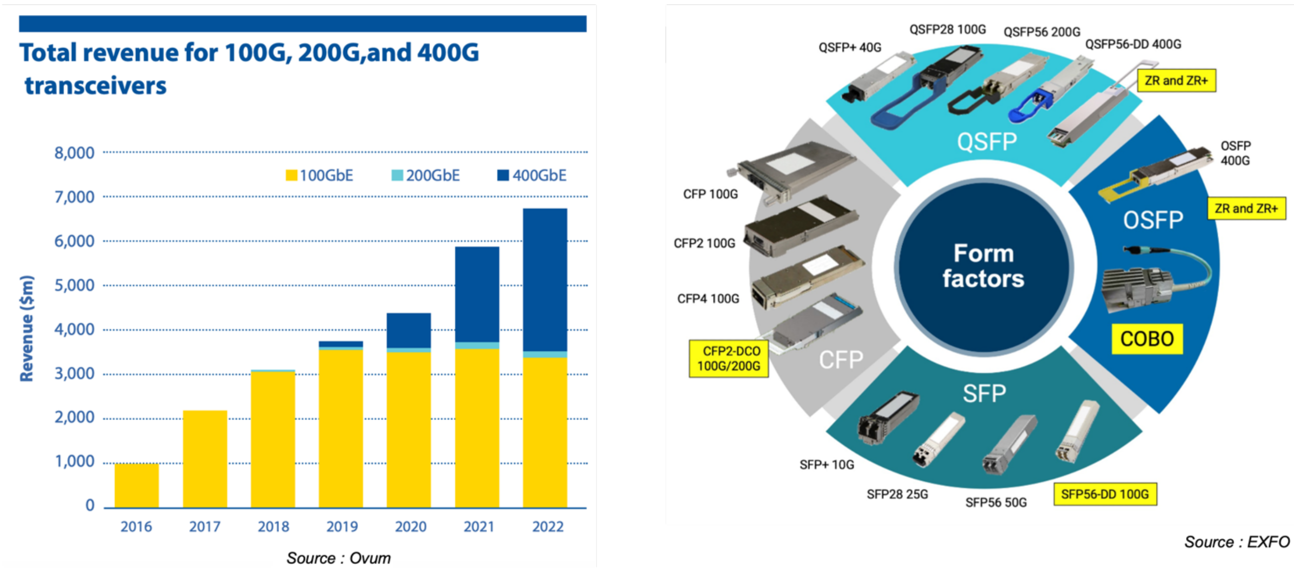


Figure 4: Various Pluggable Transceiver Form Factors for various Bitrate

2.1.2 The birth of Very Small Form Factor (VSFF) Optical Connectors

In early 2016, a group of thirteen industry leaders collaborated in the QSFP-DD Multi Source Agreement (MSA) to develop a high-speed, double-density Quad Small Form Factor Pluggable (QSFP-DD) interface. The QSFP-DD pluggable transceiver was introduced, which had the same QSFP form factor, but included an additional row of electrical contacts to support an eight-lane electrical interface thus allowing backwards compatibility with QSFP modules. Each of the eight lanes of the QSFP-DD can operate up to 25 Gbps NRZ modulation or 50 Gbps PAM4 modulation, thus providing bandwidth of up to 200 Gbps or 400 Gbps aggregate. The backwards compatibility of the QSFP-DD allows for easy adoption of the new module type, scale-up of system and corresponding scale out of the network.

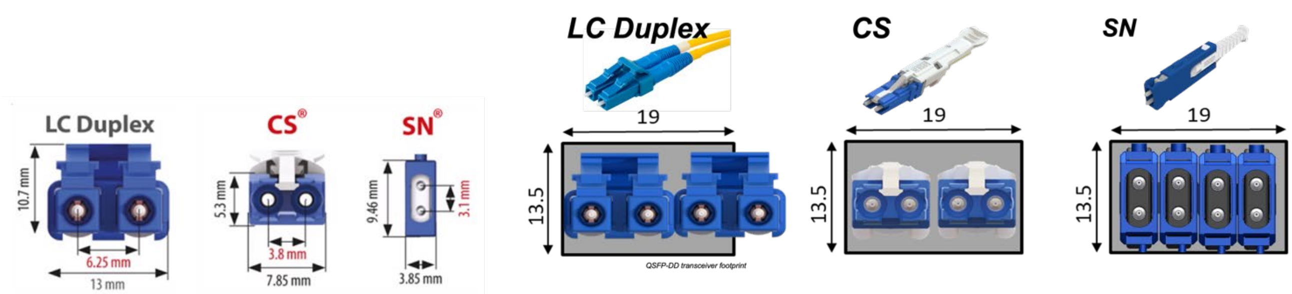


Figure 5: VSFF Connectors designed for QSFP-DD Footprint

LC duplex connectors are currently used for connection in standard QSFP transceiver modules, especially for WDM base duplex modules. Although LC duplex connectors can still be used in QSFP-DD transceiver modules, the transmission bandwidth is either limited to a single WDM engine design either using a 1:4 Mux/DeMux to reach a 200 GbE transmission or a 1:8 Mux/DeMux for 400 GbE. This increases the transceiver cost and cooling requirement on the transceiver. A new connector type was required to double the connectivity to the QSFP-DD while maintaining the same connector footprint. This gave rise to the first new generation of Twin Ferrule Connector, the CS® Connector, standardised as ANSI/TIA-604-19 Type SEN.

The smaller footprint of CS® connectors enables two of them to be fitted to the front interface of a QSFP-DD module, for which LC duplex connectors are too large. This allows for a dual WDM engine design using a 1:4 Mux/DeMux to achieve 2x100GbE transmission or 2x200GbE transmission in a single QSFP-DD transceiver. In addition to QSFP-DD transceivers, the CS connector is also compatible with OSFP and COBO modules.

Nonetheless, innovation has still not slowed down. Networking switch faceplate density is doubling with new product introductions from multiple vendors using the QSFP-DD as a transceiver interface. 128 single lanes (channels) ports or 32 quad lane ports have been the maximum network switch faceplate density in data center switches since 2012. Recently most networking switch ASIC vendors have been able to double the channel count on a single switch ASIC to 256 lanes. Several MSA's (QSFP-DD, OSFP, and SFP-DD) have been created with double-density transceivers to manage the increased bandwidth density while still maintaining a 1RU switch faceplate form factor. With these new double-density transceivers the fiber count has doubled from four lanes to having up to eight fiber pairs. Many of the transceiver implementations have split the eight lanes into two separate quad interfaces to maintain compatibility with the rest of the installed fiber and network switch infrastructure. When one of these new switches are deployed, the immediate need is to increase the number of fiber pair terminations in the same physical space as the current infrastructure in both the rack and the rest of the structured cabling infrastructure.

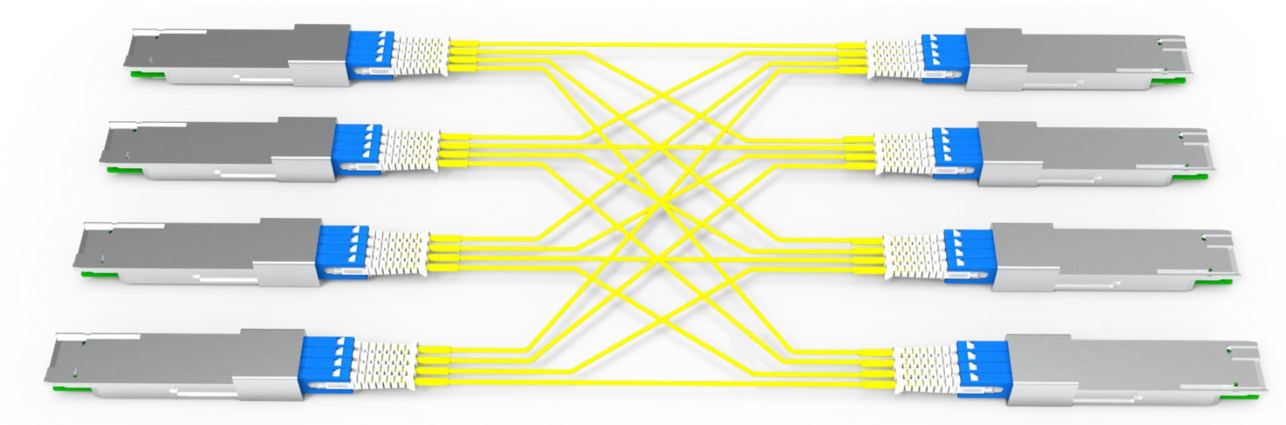


Figure 6: Leaf and Spine Interconnection directly from the transceiver module

This in turn has encouraged the industry to make the innovative leap. In the same way that the CS® doubled the density of the LC, the SN® has doubled the density of the CS®. The SN® connector is a new duplex optical fiber connector designed for Data Center 400G optimization and was designed as a more efficient, reliable and lower cost alternative to the MPO connector providing individual and independent duplex fiber breakout in quad style transceivers (QSFP, QSFP-DD, OSFP). SN® holds two (2) LC style 1.25 mm outer diameter zirconia ferrules in a single housing, with a centre-to-centre pitch of 3.1 mm, half that of a duplex LC connector, which has centre-to-centre pitch of 6.25 mm.

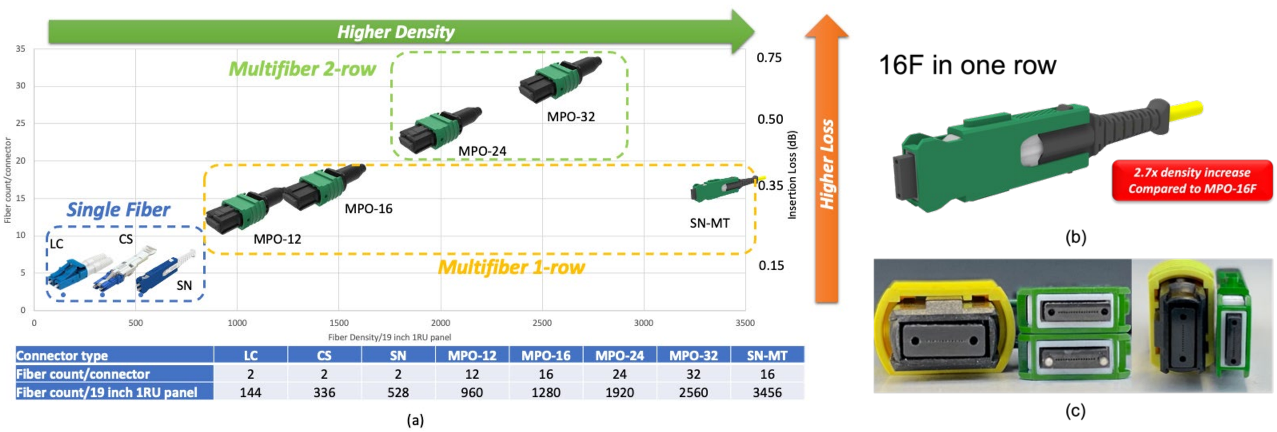
2.1.3 Path towards Co-packaged Photonic Integration

At OFC 2018 in San Diego, market analysts and technologists discussed the need for moving optical interconnect closer to the ASIC. In fact in 2017, the Consortium for On-Board Optics (COBO) published the first industry wide specifications for on-board optics. The key driver for this has been the inherent limitations of copper interconnect at high data rates. As data rates go up, the attenuation in copper traces increases significantly and the absolute transmission limitation of copper has been set at 100Gbp/s/m [6]. For data rates above this threshold, it will become increasingly more practical to use optical channels. These limitations are driving the need for not optics not only in midboard modules, but actually inside the packages of the high speed signal source chips (such as switch ASICs or GPUs) themselves. The latter is referred to as co-packaged optical (CPO) modules. The optical interconnect eco-system has to evolve to not only cater to front panel or face-place optical connectors, but now also optical backplane connectors, connectors for midboard optical transceiver modules and CPO modules. Many standards organizations, industrial consortia and government research projects have started activities to identify specifications that could ease the adoption of the new technology.

Co-Packaged Optics (CPO) is being considered to address the burgeoning bandwidth demands of hyperscale data centers, in particular data center switches, which are projected to require bandwidths of 51.2 Tbps by 2023-2024 and 102.4 Tbps by around 2026. At these bandwidths front pluggable modules alone will not be able to cope, however the integration of the corresponding optical engines (OEs) into a common ASIC package will present considerable challenges on many fronts including OE design, thermal management, and test and qualification to meet the extremely critical failure criteria. One key challenge will be managing the dense, high-fiber-count chip, board and system level optical connections within the CPO package and the host-board.

Currently a 12.8 Tbps switch can be accommodated by 32 400G face-plate pluggable (FPP) transceivers, which fills the face-plate area of a standard 1 RU high enclosure. In order to accommodate a 51.2 Tbps switch with four times the I/O bandwidth of a 12.8 Tbps switch, it is envisaged that sixteen 3.2 Tbps CPO engines [2] will be required with potentially four times the number of fibers at the front face plate. In addition, most CPO solutions will use an external light source (ELS) to provide the source of continuous wave light to the modulators in the OE, and this ELS module will preferably also be a pluggable module on the face plate, which will further reduce the available space on the faceplate.

The densest optical connector used in datacom applications is the multi-fiber ferrule based MPO. Commercially, MPO type connectors are available in 12F, 16F and 24F counts for singlemode, however increasingly end-users in the data center industry prefer smaller, lower port count connectors, which provide greater routing flexibility without the need to resort to fiber-breakout cassettes between enclosures. The LC connector is a popular dual fiber connector first standardized in 2002 (IEC 61754-20), but it is too large to convey the numbers of fibers through the faceplate. Recently smaller stackable versions of dual-fiber connector have been introduced such as CS® and SN® connectors. They are “uniboot” style duplex connectors allowing 2-3 times the density of LC duplex connectors.



Connector type	LC	CS	SN	MPO-12	MPO-16	MPO-24	MPO-32	SN-MT
Fiber count/connector	2	2	2	12	16	24	32	16
Fiber count/19 inch 1RU panel	144	336	528	960	1280	1920	2560	3456

Figure 7: VSFF Connectors with MT Ferrules enabling unprecedented fiber density a) graph of showing different fiber counts on a 1 RU panel for different optical connector types on that panel, b) SN-MT connector with 16F per row, c) photos of MPO compared to SN-MT connectors

The SN®-MT connector is the new connector being developed to carry 8F~16F per connector. This connector uses a smaller MT ferrule to be housed in the SN connector sized housing. With the size being smaller than MPO, SN-MT would provide 2.7 times density improvement at the faceplate compared to MPO-16.

In systems with high bandwidth CPO modules (see Figure 7), on-board efficient fiber routing and management between the optical engines (OEs) in the CPO assembly and the front face-plate will be a critical requirement. The arrangement of the OEs in the CPO modules plays an important role. If the OEs are arranged around the periphery of the switch as shown in Fig. 3, then this can lead to pigtail length variations and other risks of damage to the fiber during installation, which in turn impacts yield.

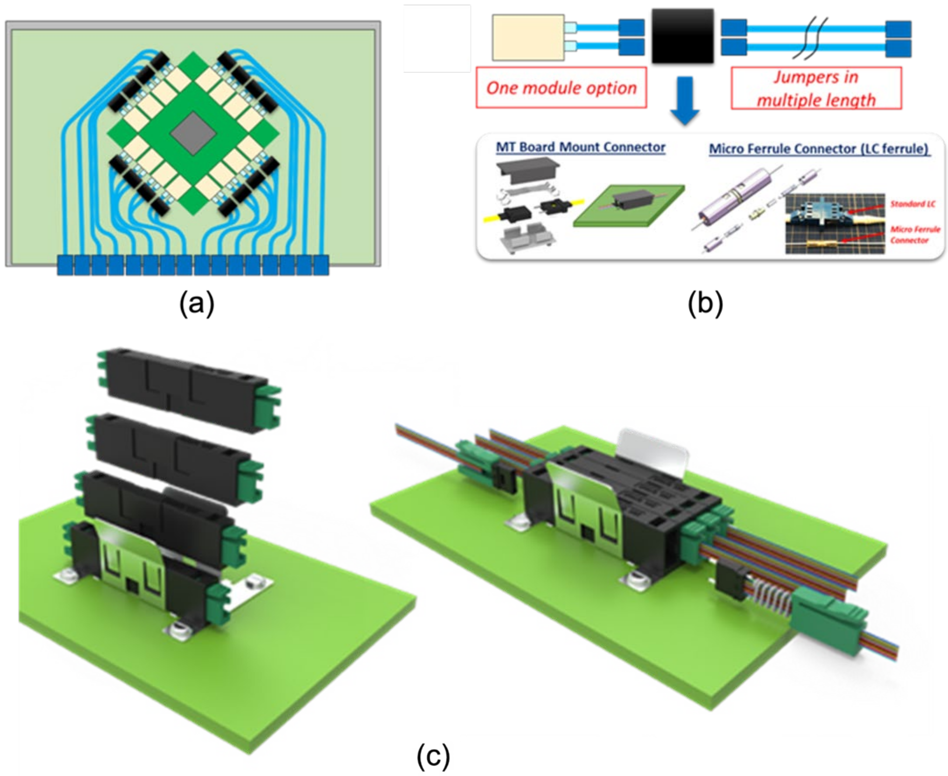


Figure 8: a) Schematic view of mid-board connectors on CPO module, b) Example of CPO and midboard connector eco-system, c) CAD models for Micro Board Mount Connector (MBMC) midboard fiber management and connector systems

The use of mid-board/on-board optical interconnect solutions would provide local mechanical detachment points enabling controlled strain relief. However, this approach would add additional connector losses. The system designers would need to consider the appropriate trade-off depending on the targeted end-to-end interconnect length and number of connection points. They would also need to keep connector loss as low as possible, such as using IEC 61753-1 Grade B rated connectors. As space is at a premium within the enclosure, the mid-board interconnect solution must be compact. The Micro Board Mount Connector (MBMC) series shown in Figure 8 is an example of a size-reduced on-board connector system with usability features such as a pluggable latching design and stacking options.

Advanced mid-board optical connectors such as the MBMC will become more common place as on-board fiber counts increase to hundreds, possibly thousands of fibers within a limited area already densely populated with electronic components. The stackable design of the MBMC series allows large numbers of multi-fiber ferrules to be densely plugged in the middle of the board in a very space efficient configuration.

For CPO engines, Silicon Photonics (SiP) technology is often considered for the cost and operational efficiency benefits. There have been substantial advances over the past decade in coupling of fibers to SiP chiplets with vertical and horizontal coupling methods emerging as the two most viable approaches. The horizontal coupling approach, whereby fibers are passively assembled into V-grooves within the silicon PIC itself, would take up too much space in front of each PIC and would not be suitable for the very space constrained environment within the CPO package, therefore vertical coupling solutions are preferred.

Figure 9: a) CAD model of MT ferrule to 90 degree bending Fiber Array Coupler, b) cross-section of 90 degree bending Fiber Array Coupler connection to the vertical grating coupler interface of a silicon PIC

One solution to reduce the profile height of vertical coupling arrays is to use a special fiber array that will tolerate tighter bending without compromising reliability or service lifetime. Special fibers with smaller cladding sizes such as 80 µm reduce failure probability compared to standard cladding sizes of 125 µm (See Figure 9) [3]. The height for such vertical coupling elements can be as low as 3.5 mm - 4.0 mm for an 8-fiber coupler. However, this is still prohibitively high as it would interfere with the heatsink.

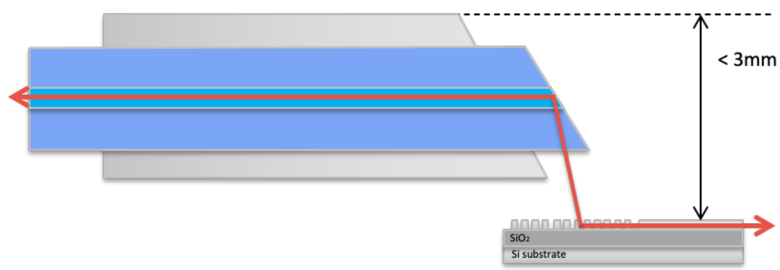


Figure 10: Cross-section of 45 degree cleaved Fiber Array Coupler coupling light into the vertical grating coupler interface of a silicon PIC

In order to further reduce the connector height, another approach is to use a fiber array, the ends of which have been cleaved at 45 degrees to reflect the signals directly into and out of the PIC. This approach shown in Figure 10 enables a much lower coupling height compared to the conventional fiber bending technique shown in Figure 9 . However, one drawback of the technique is the 45 degree polishing itself. Conventional 45 degree cleaved fiber ends will have a flat polish. This will inevitably cause divergence of the reflected light (Figure 11a). An additional lens may be added to collimate or focus the light (Figure 11b), which will increase the cost and the complexity of manufacturing the component.

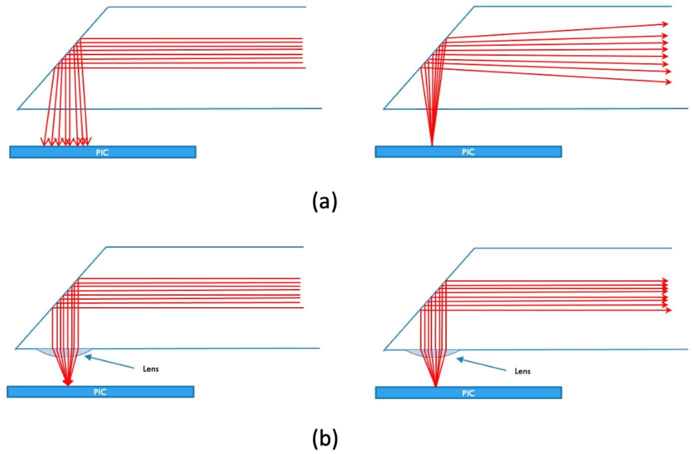


Figure 11: Ray diagrams in low profile flat 45 degree cleaved Fiber Array Couplers with (a) direct reflection to PIC (b) lens focussing element between reflecting facet and PIC

A modified low-profile vertical fiber-to-PIC solution is proposed that will incorporate a curved rather than flat 45 degree facet enabling both perpendicular deflection and optima focusing depending on the element to which the fiber is coupled (See Figure 12).

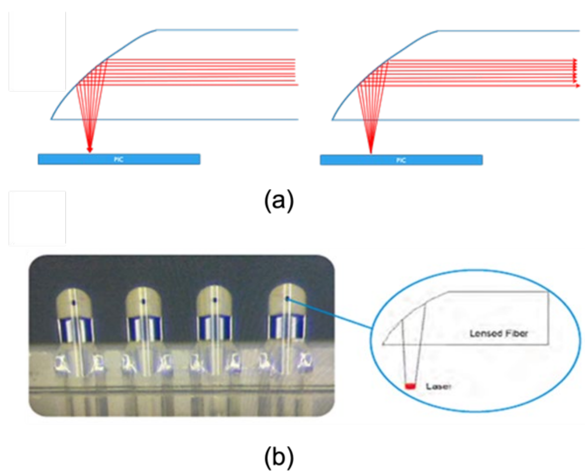


Figure 12: a) Ray diagram in cross-section of 45 degree cleaved fiber coupler with curved polished end facet, b) photo of fiber array with curved polished end facet

3. OPTICAL INTERCONNECT FOR QUANTUM NETWORKS

3.1.1 Quantum Networks

As described in our previous papers [4-6] quantum communication and quantum computing applications are expected to gain traction over the coming decade. Quantum communication methods such as Quantum Key Distribution (QKD) offer a means of enabling secure encryption and authentication in the presence of the unbounded computational power to be introduced by quantum information technologies.

Quantum Key Distribution (QKD) provides procedures for generating and distributing symmetrical cryptographic keys with information security based on the quantum behaviour of photons. QKD is not a standalone security feature, but a complementary technology and service for communication networks. Keys generated by QKD modules that implement the QKD protocol can be used by any cryptographic applications that use symmetric keys such as One Time Pad (OTP), Hash Based Message Authentication Mode (HMAC), and Advanced Encryption Standard (AES). QKD can exploit either the measurement of single photons (BB84 protocol) or the measurement of entangled photon pairs (E91 protocol) to derive a random string of numbers used to form a secure quantum key. The statistical results of the measured photons indicate whether the photon has been intercepted or not [7].

The main challenge of introducing QKD into existing communication networks is the requisite change to the network infrastructure and cryptographic protocols. QKD technologies have unique features and restrictions, such as the requirement for point-to-point links and ultra-low loss, “quantum” channels. The basic elements of a QKD communication system are the transmitter and receiver (QKD modules), and a QKD link between them comprising a Classical Channel and a Quantum Channel. The Classical Channel is used for data exchange between the QKD modules, while the Quantum Channel transmits quantum signals such as single or entangled photons, from which the cryptographic keys are derived [8].

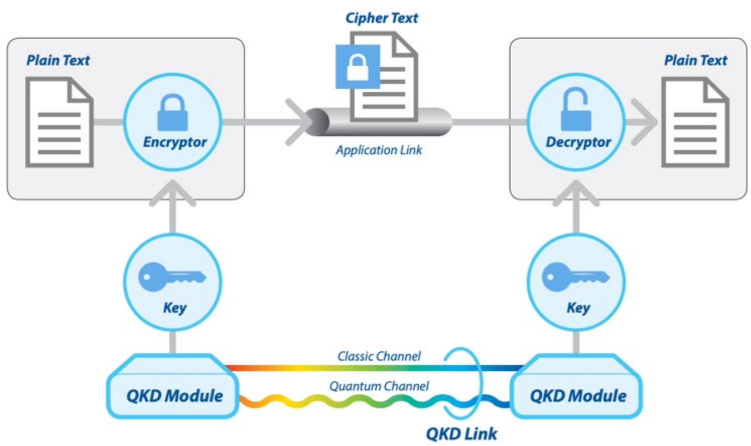


Figure 13: Application of QKD for secure communication link

3.1.2 Ultra-high Performance Grade Optical Connectors for QKD Networks

Higher densities of communications networks are leading to the miniaturization of cables, connectors, passive components and network accessories and infrastructures. This in turn leads to newer classes of performance requirements and test methods to ensure the requirements of the optical transport system. This has given rise to new optical fibre designs, including alternatives to all glass silica-based fibres such as plastic or plastic clad silica, and new designs of optical fibres optimized for ultra-tight bends that will have a positive impact on installation practices and on the size of network elements.

3.1.3 Quantum Physical Layer Requirements

QKD protocols try and account for decoherence due to environmental factors, such as poor quality of the optical fibre and imperfections in the optical connector, however if these are too great, QKD becomes less useful. The chances of transmitting a photon from transmitter to receiver without disruption, absorption or decoherence through other means, go down as the length of the Quantum Channel increases and the quality of the Quantum Channel (i.e., optical fibre and connectors) decreases. Given that the power of a single photon can be of the order of -100 dBm, transmission over longer Quantum Channel distances represents a considerable challenge and thus the optical losses in the Quantum Channel must be minimized. To address this, Senko developed a family of physical contact optical connectors called QuPC® (Quantum Physical Contact), which exhibit insertion losses and return losses similar to those of a fusion splice, thus exceeding the most stringent current optical connector performance standards. The two main areas of improvement required to increase connector performance are the material quality and manufacturing process.

3.1.4 Material Quality

The coherent single or entangled photon string is transmitted through an optical fibre network. This makes the optical fibre itself an important factor in improving the connector quality. Light does not propagate through the whole optical fibre, but only through the core, therefore the relative dimensions of the core and cladding of the optical fibre will have a big impact on the connector quality. There are three main parameters that must be tightly controlled: 1) the core-cladding concentricity, 2) core ovality, and 3) cladding ovality. The core-cladding concentricity is the measure of how symmetrically central the position of the core is with respect to the cladding. The deviation of fibre core from the centre of the cladding is known as the core-cladding concentricity error, which all fibres exhibit, to some degree. To produce a QuPC® Connector, this error must be minimized.

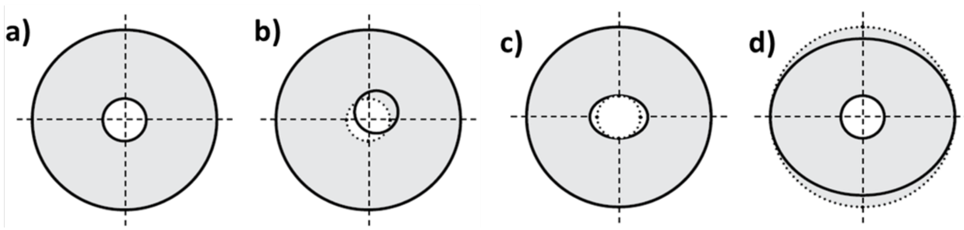


Figure 14: Examples of Core and Cladding Concentricity and Ovality a) Ideal fibre with perfectly circular core and cladding and the centres of core and cladding aligned, b) fibre with perfectly circular core and cladding, but where the geometric centre of the core is offset to the centre of the cladding, c) fibre where cladding is circular, but fibre exhibits slight ovality, d) fibre where core is circular, but cladding exhibits slight ovality

Core ovality and cladding ovality is the degree of deviation of the core and cladding from being a perfect circle. An oval core will cause imperfect core connections, which will increase insertion loss and back reflection, while an oval cladding will cause high ferrule concentricity error. The ferrule is the part of an optical connector, which holds the optical fibre in place and is physically mated to another ferrule to make a continuous pathway for light to pass from the core of one fibre to the core of another.

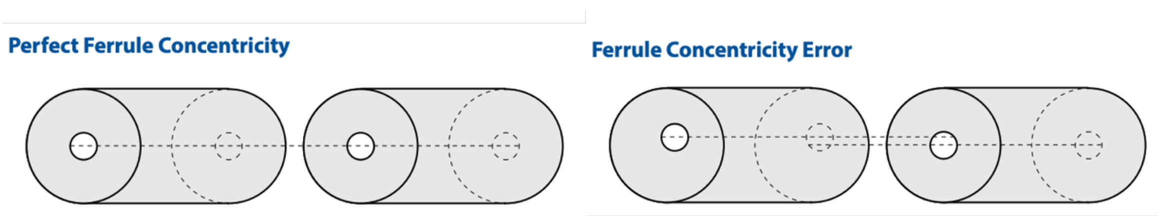


Figure 15: Ferrule Concentricity

The concentricity of a ferrule is the measure of how symmetrically central the position of the ferrule hole (or bore) centre is relative to its circumference. It is also crucial to minimize the size of the ferrule hole diameter. A larger hole will cause higher variability in the position of the optical fibre, which will then lead to increased fibre core misalignment. The diameter of a Single Mode optical fibre is 125µm, thus the ferrule hole must be reduced to a diameter that is as close to the fibre diameter as possible accounting for tolerances and additional space for epoxy adhesive to secure the optical fibre.

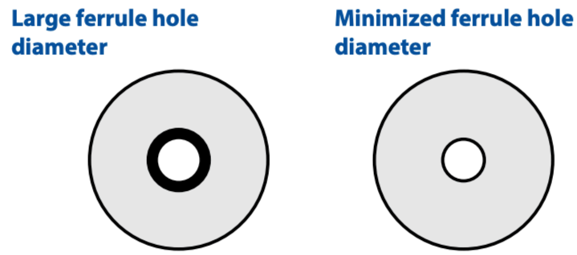


Figure 16: Ferrule fiber hole diameter error

3.1.5 Manufacturing Process

Even with high quality optical fibre and ferrule components with tight tolerances, the connector manufacturing processes must also be tightly controlled to produce high quality connectors. One of the connector manufacturing processes is the mixing of epoxy and curing process. There are multiple controlled steps to ensure proper management, application, and curing.

- Storage - Epoxy has a shelf life and must be stored in a specific temperature range depending on the type of epoxy used.
- Mixing - Most epoxy used is a two-part mixture where the correct ratio must be used. The mixing process must be controlled to eliminate any air bubbles because they will expand during the curing process, which cause imperfect fibre to ferrule adhesion..
- Application - Once the epoxy is mixed, it has a short pot life where it must be used as it will start to crystalize. Using epoxy that has started to crystalize can cause fibre microbends inside the ferrule. The right amount of epoxy must be inserted into the ferrule hole. Too little will cause imperfect fibre to ferrule adhesion, while too much will cause an overspill onto the connector ferrule.
- Curing - The temperature range and duration of the curing process must be suitable for the type of epoxy used. A curing temperature that is too low will result in incomplete curing while a temperature that is too high can cause air bubbles to form, both of which will lead to imperfect fibre to ferrule adhesion.

Improvements to the ferrule polishing process are determined by the careful adjustment of the polishing pad, level of applied pressure, the type of polishing film, accuracy of the polishing angle and the polishing apex of curvature. These factors control the granularity and smoothness of the connector end-face, reduce the apex offset, and centralize the apex of curvature, all of which serves to reduce the air gap between the optical fibre cores being connected.

As it is impossible to perfectly centre the fibre core in the ferrule due to manufacturing tolerances, a connector tuning process is used to correct concentricity errors caused from using ferrules with larger hole diameters. Although the quality control measures to improve the optical performance of Senko's QuPC® Connector include reduction of the ferrule hole diameter, tuning can still further improve the connector's performance. IEC 61755-1 [9] is the seminal optical interface standard defining location of the fibre core in relation to the datum target and key parameters including lateral offset, end face separation, end face angle, end face high index layer condition.

The tuning process involves assembling the optical fibre connector while measuring the signal characteristics through the connector and examining its physical properties to determine the optimal position of the fibre and ferrule in the connector. The objective of the tuning process is to ensure that the center of the is fibre core within the connector ferrule falls within predetermined region on the connector endface. This will ensure the misalignment between any two mated QuPC® Connector will be minimal hence reducing the insertion loss caused by the fibre core misalignment.

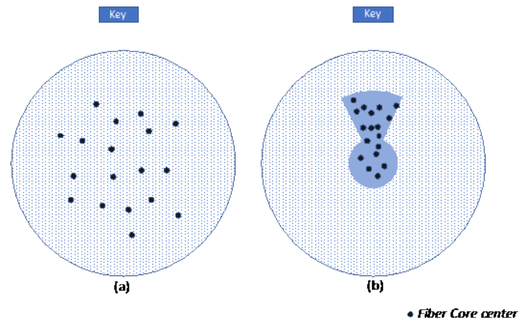


Figure 17: Fibre Core center location in (a) Untuned Connector and (b) Tuned Connector

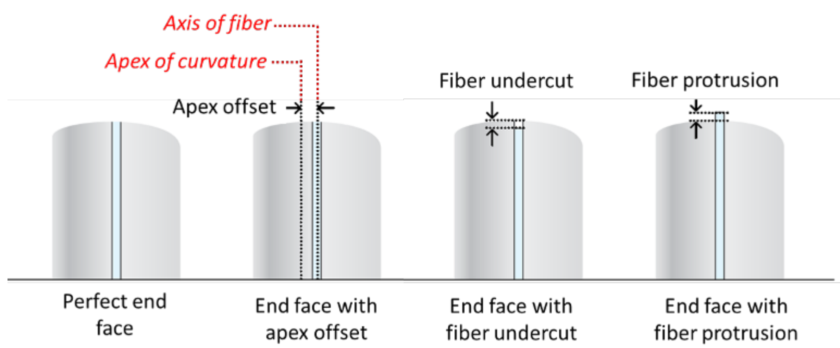


Figure 18: Connector End-face parameters

4. CONCLUSION AND FUTURE WORK

In this paper we have reported on the development of a new class of ultra-low loss, "quantum grade" optical interconnect technologies to address the emerging requirements of the quantum networks.

The next phase of research and development into quantum grade connectivity will focus on novel, ultra-low loss coupling solutions between fibre and quantum integrated circuits (QPICs).

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