


UKTIN

Future Capability Paper

Optical Communications & Photonics




EXECUTIVE SUMMARY

This future capabilities paper has been prepared by the Optical Communications and Photonics Expert Working Group (EWG) for the UK Telecom Innovation Network (UKTIN) as part of the Future Telecoms strategy. This EWG's focus is expressly on optics and photonics for telecoms, with reference to the wider use of technologies in adjacent applications.

Optical communication systems encircle the Earth and form the backbone of the internet. It is estimated that more than 6 billion kilometres of optical fibre have been installed around the world, connecting data centres globally with wireless end-users and delivering broadband services into people's homes. Network bandwidth continues to grow at over 30% annually[1] and we need to innovate at both system and device level, not only to keep pace with accelerating demand but also to establish the most cost-effective and energy-efficient methods of doing so.

The UK Optical Communications and Photonics sector has a long and distinguished history of innovation and technological advancements, stretching back to the invention of optical fibre in the 1960s and the erbium-doped fibre amplifier in the 1980s, which laid the foundations for development of today's telecommunications networks. The value to the UK economy in terms of output is estimated to be circa £2bn, with £1bn gross value added (GVA) and employs c10K people[2]. However, it is worth noting that, with the demise of major UK-based telecom systems vendors after 2002 a significant trade imbalance has been created in the communications equipment sector, where the ratio of imports to exports has grown from being roughly in balance in the early 2000s to an adverse factor of 3:1 today.

Optical communications and photonics technology is a very broad and active research field. This paper considers selected emerging areas that could make a difference to our competitiveness, with focus on discussing the following study topics:

- Transmission Networks Evolution
- RAN and Access Transport
- Data Centre Networks
- Optical Wireless
- Quantum Communications
- Integrated Photonics
- Skills and Training

Each study topic is discussed in the main body of this paper with the key findings for each topic summarised in this section. A Summary of Recommendations, as well as discussion on Supply Chain and a SWOT Analysis are also part of this paper.

[1] Lord, A., et al., 2021. Future optical networks in a 10 year time frame. In: 2021 Optical Fiber Communications Conference and Exhibition (OFC). pp. 1–3.
[2] https://photonicsuk.org/

Transmission Network Evolution

Since 2015, there is evidence that per-fibre capacity is approaching the fundamental limits, leaving little room for further capacity improvements. Current fibre systems now run at maximum spectral efficiency and use the entire optical bandwidth available from erbium-doped fibre based amplifiers.

As part of this challenge, this paper is identifying methods beyond the current usage of single mode fibre. These may include multi-core fibre (MCF), adding more spectral bands and hollow core fibre (HCF).

Opportunities for the UK within the transmission network evolution include the UK's strength in digital signal processing (DSP), optical switches, optical amplifiers for new bands and MCF that could be exploited. Furthermore, the UK has a leading position in disruptive technology such as HCF.

RAN and Access Transport

Fibre remains an ever-growing trend in the UK fixed access market, with a plethora of service providers offering both consumer (fibre to the premises – FTTP) and business services (point-to-point fibre and wavelength services). By 2026, it is expected that 80% of premises will have access to FTTP, with the remaining 20% expected using government funded programmes. Service providers may benefit from the participation in standards bodies, which is currently dominated by Asian companies due to the size of their market driving demands; hence driving in part the standards process with bias towards the Asian market.

Due to low margins in residential fixed access, very few vendors are sufficiently competitive to supply access equipment. In addition, a lack of investment in system inter-operability often leads to vendor lock in.

On the mobile side, different Radio Access Network (RAN) architectures present both opportunities and challenges for optical transport, depending on the geographic location of the split functionality. Future opportunities are presented through introduction of Open-RAN (O-RAN) opening up the vendor ecosystem, enabling the UK to exploit this opportunity based on its technological strength. Neutral host and private mobile networks using O-RAN are applications that could further bolster the productivity across ecosystem beyond communication services. Challenges remain for cost effective transport for increasing mobile cell densities, transport capacities and ultra-low latency on the control flows for certain RAN architectures (especially for Front-Haul).

There is an opportunity for a UK system inter-operability lab to be created for the co-development and integration of FTTP and O-RAN technologies for Fixed and Radio Access Networks to address the complex system-level interactions which now arise with densification of masts and the disaggregated RAN architecture. The lab would complement work with the existing SmartRAN Open Network Interoperability Centre (SONIC) Labs[3] and UK Telecoms Lab (UKTL)[4].

[3] Sonic Labs
[4] UKTL

Data Centre Networks

Accelerating demand for data centre (DC) services is generating new bandwidth requirements for optical interconnections both within and between datacentres. Meeting the needs of hyperscale service providers is now a major driver for the optoelectronics industry, doubling transceiver bandwidths every 3-4 years while striving to achieve lower cost and energy per bit. A recent IEA forecast[5] suggests that DC energy consumption could double in the next 3 years to ~1000TWh pa or ~5% of global demand, fuelled in part by the rapid rise of artificial intelligence (AI) applications. There is a clear need for innovation in photonics and DC network architectures to drive down energy consumption and improve utilisation of computing resources. We see research priorities in the following areas:

- Co-packaged optics chips to bring high density optoelectronics interfaces as close as possible to silicon processors and minimise power lost in electrical interconnects;
- Methods for optical disaggregation and composition of compute resources on demand, to improve utilisation and enable routing around hardware faults;
- Fast optical circuit switch technologies with sub-microsecond reconfiguration, high radix and low loss to enable dynamic topology reconfiguration of AI xPU clusters;
- Low latency connectivity using advanced transceivers and novel media such as hollow core fibre, allowing more flexible DC location and improved efficiency of AI compute operations.

Optical Wireless

Optical wireless communications (OWC) are poised to play a significant role in meeting the evolving demands of future wireless networks.

Different OWC solutions are making their way into the wireless communications market to complement RF-based technologies. These include free-space optics (FSO), visible light communications (VLC), light fidelity (LiFi), ultraviolet (UV) communications, and optical camera communications (OCC). This paper has primarily focused on FSO and LiFi, given their growing applications and rapid development as part of the OWC.

Opportunities exist in both manufacturing and research (i.e. FSO and LiFi) for the UK in OWC. Adopting OWC technologies, particularly the ones utilising light-emitting diodes (LED), can enhance the sustainability of the digital infrastructure and help to reduce the carbon footprint of the telecom sector. LED lightbulbs will account for 85% of all bulbs in the UK by 2030. This is a global opportunity for large scale infrastructure for LiFi deployment.

In addition, OWC has an advantage in electromagnetic interference (EMI) sensitive environments such as those in healthcare and industrial applications. OWC could also be exploited in underwater, terrestrial and non-terrestrial networks.

[5] Electricity 2024 - Analysis and forecast to 2026 (iea.blob.core.windows.net)

Quantum Communications

The UK has been at the forefront of R&D in quantum communication over the past two decades, making several of the most significant research breakthroughs and is major focus area for UK government[6]. The EPSRC Quantum Communication Hub, established as part of the UK Quantum Technology programme in 2014, has galvanised activities in academia, while InnovateUK and ISCF have promoted collaboration with industry. In recent years, however, other countries have taken the lead in the industrialisation and deployment of quantum communication. China has built multi-node quantum networks in Beijing, Jinan, Hefei and Singapore, interconnected these with a 2000km quantum backbone link, and launched the first quantum-enabled satellite. Meanwhile the EU have invested in the Euro Quantum Communication Infrastructure (Euro-QCI), a pan-European network for government comms covering the EU27, providing a considerable advantage for EU27-based industry in the process. Other large-scale quantum networks are under construction in South Korea, Japan, Singapore and Canada.

We see numerous opportunities in the UK to enhance its global leadership in quantum technologies. A key challenge is to provide security at a reasonable cost, thereby making QKD systems sustainable and suitable for widespread deployment beyond niche applications. Addressing this challenge presents a significant opportunity for the UK to capture a substantial share of the global quantum communication market. We recommend several actions to maintain the competitiveness of the UK in quantum communications.

Integrated Photonics

The UK, as a proven knowledge economy[7], has the potential to become a leader in expert integration of photonic and electronic technologies, differentiated Photonic Integrated Circuit (PIC) design and packaging capabilities, and use of emerging materials for improved novel use cases.

In this technology, the UK has a proven world leading research capability, with significant research prototyping infrastructure including a flexible multi-project wafer offering at Southampton University. The UK has good start-up support, though this is dispersed. Consequently, the UK has a growing number of small silicon photonics companies, as well as world-class manufacturers of integrated photonics based on compound semiconductors. The largest of these are however vertically integrated players, and there is a lack of open-access capabilities in this space.

Opportunities for the UK in integrated photonics include applications in terrestrial telecoms and satellite comms, optical interconnects for datacentres and quantum technologies, as well as wider fields beyond communications such as medical devices and automotive sensing for autonomous vehicles.

For the UK to be effective within the Integrated Photonics market, we must consider fabrication and scale-up to commercial volumes. It is unlikely that the UK will invest in a production-scale facility for Integrated Photonics, and therefore we recommend that the UK considers a prototyping to pilot-scale capability[8] that will allow for low

[6] Department for Science, Innovation & Technology (DSIT), National Quantum Strategy
[7] UK Government, UK Science and Technology Framework
[8] Further details of this proposed capability will be elaborated in the UKTIN Future Capabilities Phase 2 paper

to medium commercial volume production across multiple integrated photonic platforms, prioritised by market opportunity (value, differentiation, and sovereign capability) and compatible with large-scale international foundries. This UK-based capability needs naturally to be open-access such that it is accessible to companies across the spectrum of size and maturity. Such a national facility could also service other applications beyond telecoms to leverage any investment to the maximum. The UK has great strengths in compound semiconductor photonics, which represents an important part of the overall integrated photonics picture, both in R&D and in production. Developments in these areas should be coordinated as part of an integrated strategy.

Skills and Training

There is strong investment by the Engineering and Physical Sciences Research Council (EPSRC) in optical communications and photonics research and direct training of post-doctoral researchers and associated PhD students, with ongoing projects in the specific topic areas of “Optical Communications”, “Optical Devices & Subsystems” and “Optoelectronic Devices and Circuits” to the value of £63M, £121M, and £163M, respectively as of March 2024.

Industrial partners for the largest grants in these topic areas (such as so-called programme grants) include ADTRAN (formerly ADVA), AMD, Airbus, BAE systems, BT, Ciena, Cisco, Corning, DTag, Ericsson, Furukawa, Huawei, HUBER+SUHNER, KDDI, Lumentum, MERL, Microsoft, Nokia, OFS, OpTek, Orange, QinetiQ, Rockley, Rolls-Royce, Siemens, Sumitomo, Thales, Toshiba, TRUMPF, Verizon, Xtera.

While there is some industrial activity arising from university R&D, notably from Southampton University, more generally, there is no major optical equipment manufacturers or sub-system suppliers with headquarters in the UK, and as a result there is limited training in universities and colleges guided by the industry. There remains only one UK Network Operator, i.e. BT Labs, with R&D activity in Optical Communications that significantly guides and contributes to external skills and training needs. This leads to limited employment opportunities for R&D roles. There is no dedicated Catapult Centre, though this could be addressed with an increase in telecommunications capabilities via the Compound Semiconductor Applications Catapult, particularly skills and training (or high value manufacturing).

SUMMARY OF RECOMMENDATIONS

1/ Develop a long-term Grand Challenge technology programme similar to Japan's IOWN[9] to foster collaboration and drive direction within the optics/photonics ecosystem, enabling development and demonstration of key innovations at both device and systems level for high-capacity end-to-end all-optical networks.

2/ Build on existing facilities, e.g. the National Dark Fibre Facility (NDFF), to create a field-deployed fibre-rich network connecting major photonics institutions and including novel transmission media, e.g. hollow core fibre (HCF), multi-core fibre (MCF), and few-mode fibre (FMF), etc., to accelerate Research and Development (R&D) in optical and quantum communications systems.

3/ Define initiatives that will attract investment from global optical network equipment vendors to establish systems R&D facilities in UK to drive vision and cohesion within the photonics ecosystem and to generate market pull for new technology innovations.

4/ Create pilot capabilities for integrated silicon photonics and compound semiconductor chips including open access to advanced fab, assembly and packaging facilities, in coordination with national and international semiconductor initiatives.

5/ Increase take-up of undergraduate and doctoral training in photonics, communications and systems engineering particularly for UK candidates by a) increasing profile of hot topics in AI/6G infrastructure, free-space optics and quantum networks and b) addressing apparently uncompetitive remuneration issues. Reinforce efforts to stimulate interest and engagement of young people in photonics and technology generally, from school age onwards.

6/ Reduce barriers to entry for SMEs in fixed wireless and broadband access networks by a) facilitating UK voice on standardisation activities, both formal and informal; b) promoting adoption of open initiatives, e.g. O-RAN, Open ROADM, Open Line Systems that disaggregate the physical layer and avoid vendor lock-in. Develop programmes to facilitate access for SMEs to leading edge technologies including integrated photonics.

7/ Establish programme addressing energy consumption in communications networks and data centres, emphasizing architectural developments and technology improvements through photonics and photonic-electronic codesign that can offer radical improvements in power efficiency and allow sustained traffic growth with minimal environmental impact.

8/ The UK should establish recognised security certification processes for quantum communication technologies to lower the barriers to widespread adoption by Government and industry, building as appropriate on initiatives underway in the UK and other nations to establish third-party verification standards.

[9] Innovative Optical and Wireless Network

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1/ INTRODUCTION & BACKGROUND

This paper reviews Optical Communication and Photonics and its role in telecommunications, through the understanding of a group of volunteer experts from academia and industry in the UK, on how the emerging trends and techniques will lead to new ways of building and operating the network and delivering new services in telecommunications. This group has considered the evolution of optical technologies in the network beyond the use of single mode fibre. Future directions for research, development and innovation are also highlighted.

This Expert Working Group (EWG) with their Terms of Reference from UKTIN has been driven by three primary external motivations which align with the overall objectives of UKTIN. These are to:

- Support and grow strategic capability in telecoms within the UK;
- Foster the growth of SMEs in the telecoms sector;
- Facilitate the move towards 'net zero' for the telecoms industry in the UK.

The following subsections in this introduction give the background on optical communications and photonics in relation to the UK's position in the global market.

1.1/ Strategic capability within the UK

The telecoms industry is part of the UK's critical national infrastructure, a drive behind UKTIN is the desire to increase the level of self-sufficiency in the full supply chain for telecoms service from device manufacturers, through major component system suppliers, systems integrators, to network operators. Each of these includes different stages from research and innovation, through product development, possible standardisation, to production/operation. The importance of research and development is not restricted to optical device technologies, but also topics such as optical network architectures, prototype system performance, the optimal combination of optical and electronic components, and the use of AI/ML in monitoring and configuring optical networks are also areas requiring further study.

1.2/ Fostering growth of SMEs in the UK

A major objective of UKTIN is to support both existing and new SMEs in the telecoms sector by providing information, resources, contacts, expert advice, and other facilities to build a strong foundation for the industry in the UK. Many SMEs have close ties with UK academia, which results in a strong position for the UK in this globally-active field. This also aligns well with UKTIN objectives.

The UK telecoms network is a significant consumer of energy (BT/EE alone consume just under 1% of the UK electricity supply) and when the networking within data centres is added, this becomes even more significant. The objective of net zero is a particularly relevant drive for optical networking as very broadly, for the same bandwidth, optical devices consume much less power than electronic devices. However, while optical devices very successfully transmit information over long distances and have replaced electronics for this function for many decades, it is also very unlikely the logic processing that semiconductor chips do especially well will be displaced by an optical technology any time soon. In addition, there are still specific areas where electrical transmission is still economic and dominant, for example very short-range equipment interconnection, and there are specific forms of elementary optical logic, for example for optical switching, which are emerging. This means that the optimal mix of optics and electronics balancing functionality and power consumption is a complex and continuously evolving area of research and development and is a potential area for UK leadership.

1.3/ Role of optical networking within end-to-end telecoms networks

Figure 1 shows the top level architecture of most state of the art end to end telecoms networks today.

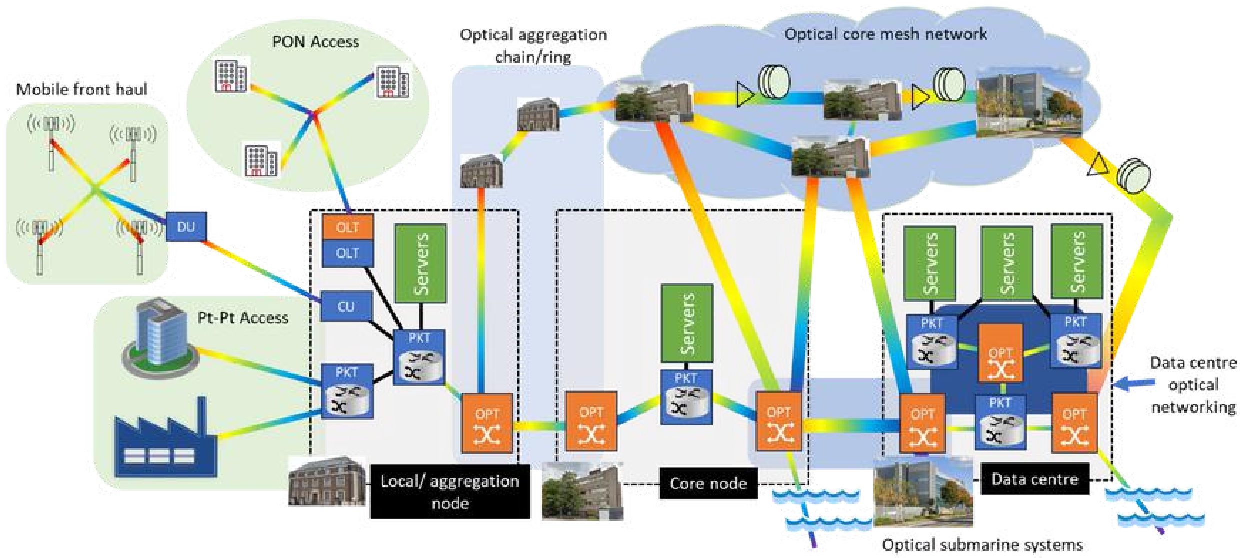


Figure 1 Top level end-to-end telecoms networks.

From such architecture two points are evident about the use of optics in today's networks:

- Optical networking interconnects layers of electronic switching;
- Optical networking as connection between two or many end points of communication sub-systems falls currently into six main parts of the network each with its own specific requirements and optimisations of optical technology, namely:
  a. Consumer access – e.g. using passive optical network (PON) systems,
  b. Business access and mobile x-haul – e.g. using point to point (PtP) access systems,
  c. Fixed network backhaul – e.g. chain/ring systems using rearrangeable optical add/drop multiplexers (ROADMs),
  d. Core network – e.g. using a wavelength division multiplex (WDM) mesh technology,
  e. Intra data centre – e.g. using optical switching to manage interconnection between electronic packet switches,
  f. Submarine systems – supporting the global internet and increasingly for direct interconnection of data centres.

In each case the optical network does considerably more than simply transmit bits between the electronic switches. Optical communication systems are organised as remotely-managed transport networks which can flexibly allocate, monitor, and protect capacity. The architectures meet a number of essential operational requirements of both conventional telecoms networks and also networking within data centres, including the following:

- The independent transport network allows more than one electronic service level network to be supported on the same physical infrastructure;
- It is possible to simultaneously support two generations of electronic service level network on the same physical infrastructure greatly simplifying evolution between generations;
- The independent transport network can offer fully transparent bulk capacity as a service to 3rd party networks without interacting with or compromising any service level protocols;
- Planning and installation of bulk transmission capacity can be implemented on different time horizons (normally longer) than that of electronic service networks;
- The independent transport network can use simple and ultra-reliable protection/restoration schemes without the complexity and risk of interacting with service level routing and control protocols.

The broad characteristics of the optical transport networks in each of these six areas are set out in Table 1.

Table 1 Optical transport network characteristics.

	System Capacity (relative)	Current Topology (UK)	Maximum optical span (UK)	Global variation
Consumer Access	Low	Hub and Spoke	Now: <10km Aim: <100km	Similar across the world
Business Access and mobile x-haul	Low	Point to Point Hub and Spoke	Now: <30km Aim: <100km	Similar across the world
Fixed Backhaul	Medium	Ring/Chain	Now: <100km Aim: <100km	Some variations depending on geography
Core Network	High	Mesh	Now: <1000km Aim: <1000km	Big variations depending on geographic size of country
Intra-Data Centre	High	Mesh	Now: <1km Aim: <1km	Similar across the world
Submarine	High	Point to Point Chain	Now: <10000km Aim: <10000km	Same across the world

From Table 1 the following two points emerge for the use of optical technology in the UK telecommunications networks:

- As the flexibility of optical technology is currently limited, different optical solutions emerge for the different parts of the network;
- As the requirements for access, data centres, and submarine are reasonably uniform around the world, a global market for equipment is readily sustainable, however, because the geographic distances involved with a specific country's core network can vary considerably, the optical technology of core networks is more likely to be tailored to an individual country's needs.

In this paper, we have identified 7 key topics where the most impact can be delivered. These key topics are as follows:

- Transmission Network Evolution
- RAN and Access Transport
- Data Centre Networks
- Optical Wireless
- Quantum Communications
- Integrated Photonics
- Skills and Training

Additional topics, including space photonics and analogue radio-over fibre for 6G networks, are also of relevance and will be covered in a future capability paper. Optical Communications and Photonics technology has strong synergies with the Semiconductor and Wireless EWGs, as well as with future Non-Terrestrial Networks, as presented in Table 2.

Table 2 UKTIN Expert working group synergies with the Optical Communications and Photonics group.

Expert Working Group	Synergies with Optical Communications and Photonics
Artificial Intelligence (AI)	Device/link optimization, RWA, telemetry, HPC infrastructure
Core	Physical layer interfaces, control, routing awareness
Semiconductors	Silicon photonics, III-V integration, packaging
Network Management	Dynamic routing, slicing, open networks, interfaces
Non-Terrestrial Networks	Intersatellite links, LEO-ground comms, space photonics, SWaP
Security	QKD coexistence, trusted nodes, control plane, authentication
Standards	Quantum communications, telemetry, interfaces
Wireless	6G fixed network, analogue/THz radio-over-fibre, WiFi/LiFi UI

2/ Study Topics

The following sections present an analysis of each of the topics selected by this EWG.

2.1/ Transmission Networks Evolution

Optical fibre underpins the global communication infrastructure, carrying over 99% of global internet traffic data, connecting cities, countries, and continents. It is estimated that there are more than 6 billion kilometres of fibre installed globally. In today's information-driven society and economy, internet traffic data has been growing at an unabated annual growth rate of 30% year-over-year[10]. Up to 2015, significant progress has been made in finding innovative ways to increase the amount of data carried in a single optical fibre; however, since 2015, there is clear evidence that per-fibre capacity is approaching the fundamental limits, leaving little room for further capacity improvements. Current fibre systems now run at maximum spectral efficiency (SE) and use the entire (10 THz) optical bandwidth available from erbium-doped fibre based amplifiers (C-band and L-band 1530nm-1620nm) and carry up to 128 channels at up to 400 Gb/s on a 75-GHz grid, supporting an aggregate long-haul capacity of around 50 Tb/s at a SE of 5 b/s/Hz, and for short-reach applications up to 600 Gb/s at 8 b/s/Hz, for a total capacity of around 75 Tb/s (see Figure 2) updated after [11].

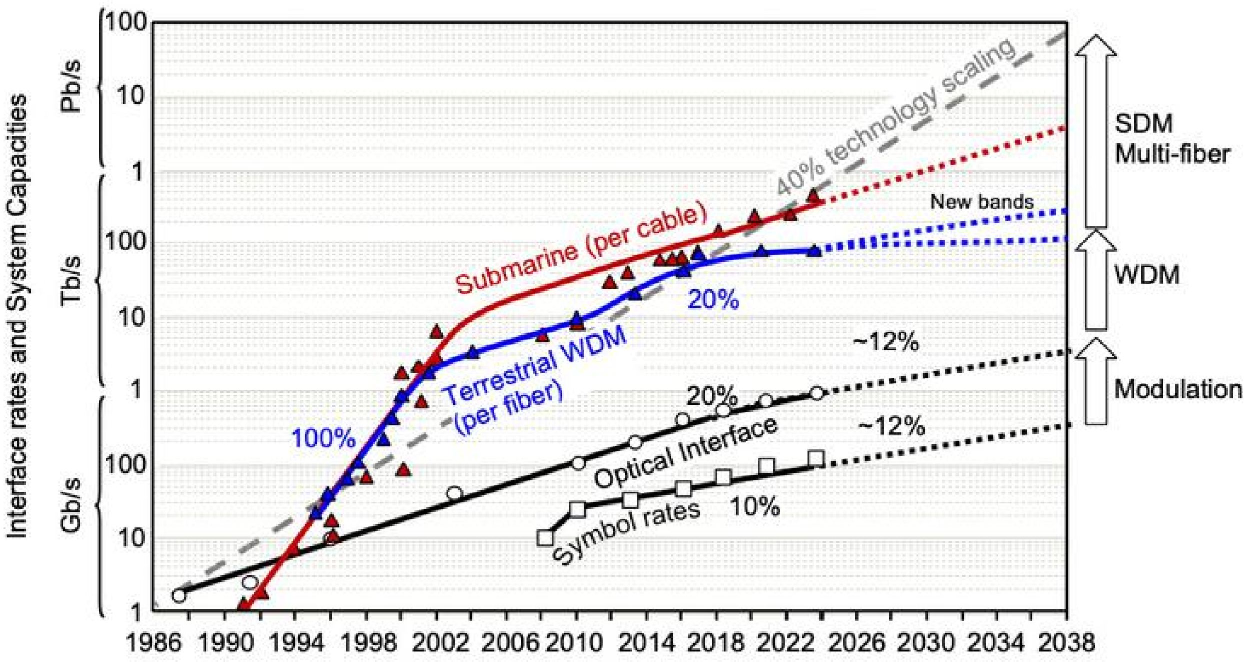


Figure 2 Evolution of commercial optical transmission systems and extrapolations (updated after [5]).

[10] Lord, A., et al., 2021. Future optical networks in a 10 year time frame. In: 2021 Optical Fiber Communications Conference and Exhibition (OFC). pp. 1–3.
[11] P. J. Winzer, D.T. Neilson, and A. R. Chraplyvy, "Fiber-optic transmission and networking: the previous 20 and the next 20 years [Invited]," Opt. Express 26, 24190-24239 (2018)

Spectral efficiency has been achieved via the use of flexible optical multiplexing and advanced coherent transceivers that are approaching their fundamental limits[12]. For spectral efficiency and only small improvements of a few percent remain possible.

In the rest of this section, we describe the technology enablers along with key research and development (R&D) areas that will enable the next generation of high-capacity transmission networks.

2.1.1/ Optical transceivers

Long-haul and, increasingly, metro and data centre interconnect (DCI) networks utilize digital coherent technology where the analogue optical signal is converted to and from a digital representation using a combination of coherent optical mixing and complementary metal-oxide semiconductor (CMOS) digital signal processing (DSP). Many of the optical techniques used are borrowed from those established for RF transmission, albeit at frequencies and data rates that are orders of magnitude greater. While spectral efficiency is unlikely to increase significantly, the capacity per optical transceiver continues to scale with the use of more advanced silicon CMOS DSP. Access to latest silicon CMOS nodes[13] (currently at a few nm and ultimately sub nm) and the design skills for these is critical to future lower cost and lower power systems. Additionally optical transceivers utilize photonic integration approaches including silicon photonics, and are becoming tightly integrated systems between the CMOS electronics and the optical systems.

2.1.2/ New optical spectrum bands

Current C-band (1530-1565nm) and L-band (1565-1625nm) optical transmission systems represent 10THz of spectrum and around 50Tb/s of capacity today, limited by the available bandwidth of established EDFAs, as shown in Figure 3 (from [14]). Adding new spectrum bands beyond these could open up another 50THz of capacity (300Tb/s potential total throughput) though at higher fibre losses. Recent advances in optical fibre amplifiers, exploiting new dopants such as bismuth and thulium, offer opportunities to open up these bands.

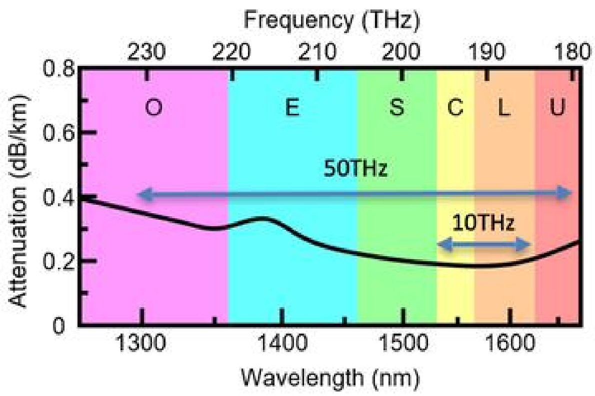


Figure 3 Low-loss window of the transmission fibre specified in ITU-T G.652, spanning over 50 THz from 180 THz to 230 THz. Currently deployed metro and long-haul systems utilize the C and L bands (10 THz). The horizontal axis is linearly scaled in frequency. Letters indicate bands [14].

[12] The fundamental limit on fiber capacity is set by its Shannon capacity outlined in his seminal 1948 paper on information theory, “A Mathematical Theory of Communication” and limits on the maximum optical power that can be launched in a fiber because of optical nonlinearity in the glass.
[13] Node refers to manufacturing process and its design rules.
[14] T. Hoshida et al., "Ultrawideband Systems and Networks: Beyond C + L-Band," in Proceedings of the IEEE, vol. 110, no. 11, pp. 1725-1741, Nov. 2022

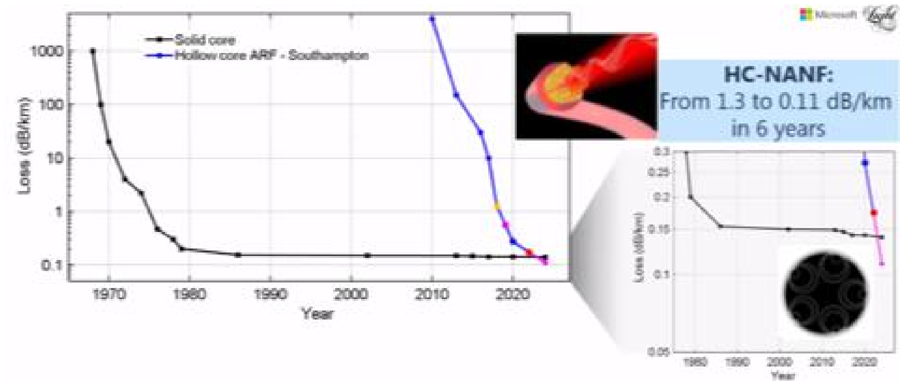
2.1.3/ Space Division Multiplexing (SDM)

Scaling of future network capacity by adding bandwidth either by increasing the number of spatial channels or parallel paths often called space division multiplexing (SDM) to overcome the capacity limitations of single-core fibre with massive parallel data transmission is proposed as a solution to scale internet traffic data. Space division multiplexing can be achieved by deploying cables with many fibres or by using multi-core fibre (MCF), where silica fibre is fabricated with multiple guiding cores, enables a linear scaling of transmission with the number of cores. For over a decade, the global research community has made significant progress on MCF design, and in 2023, MCF was announced as a commercial product [15], with a 2-core MCF being planned for deployment in a submarine cable branch [16]. Exploitation of MCF beyond the particular constraints of subsea cable networks will require a substantial shift in fibre ecosystem costs to compete with standard SMF. SDM approaches that use the deployment of cables with large numbers of parallel single mode fibres (cables today are available with approaching 7000 fibres) allows capacity for terrestrial systems but will create the need for integrated optical amplifier solutions and new approaches for switching and managing the additional capacity.

2.1.4/ Hollow core fibre (HCF)

This represents a more innovative and potentially disruptive solution. Unlike MCF, which is still a silica fibre with light traveling through the solid glass core, HCF allows light to travel through an air-filled core (Figure 4). This design enables better optical properties, including a wider bandwidth, alternate operation bands, lower attenuation, lower dispersion and reduced nonlinear effects, allowing higher launch powers and lower impairments. These advantages can translate into a higher data rate compared to silica fibre. Another crucial benefit of HCF is its lower latency, which is becoming critical and fundamentally important in enabling latency-sensitive applications, such as the next generation of AI data centres. Further unique HCF properties have potential applications in other fields such as sensing, and high-power laser delivery. Southampton University and Microsoft have recently presented [17] a landmark HCF attenuation result of <0.11dB/km, lower than any other transmission medium.

Figure 4 Record progress in Hollow Core Fibre attenuation [17].



[15] Sumitomo Electric Launches World's First Mass-produced Ultra-low Loss, Multi-core Fiber Sept 2023
[16] Boosting Subsea Cables with Multi-Core Fiber Technology, Google Blog, September 12, 2023
[17] Y. Chen, et al., "Hollow Core DNANF Optical Fiber with <0.11 dB/km Loss," in Optical Fiber Communication Conference (OFC) 2024, Technical Digest Series (Optica Publishing Group, 2024), paper Th4A.8.

2.1.5/ All-optical switching

An important aspect of today's optical transmission systems is harnessing the available transmission capacity through optical networking and bandwidth management. Management of the bandwidth directly in the optical layer eliminates unnecessary optical to electrical conversions and high-speed electronic switching in the path of an optical signal, leading to reduced complexity, power consumption and costs. Currently, reconfigurable optical add-drop multiplexers (ROADMs) are positioned at network nodes (where two or more fibres intersect) and use wavelength-selective switch (WSS) technology to groom up to 96 wavelength channels per band with a variable width which is now adapted to match the baud rate of the transmitter. ROADMs enable wavelengths to be dropped or added locally or equalised and routed on express fibre paths towards a remote destination, all under control of the network management software layer. Low-noise optical amplifier technologies enable all-optical transmission and routing through thousands of fibre-km and many such ROADM nodes before requiring data regeneration.

As capacity demand continues to grow, technologies to exploit new wavebands and parallel spatial channels are being developed, which will require addition of optical spatial switching to ROADM nodes alongside wavelength- and possibly waveband-switching. With developments in transceiver data rates anticipated to approach 10Tb/s or more on a single channel, spatial multiplexed solutions and a shift from wavelength to fibre switching are becoming attractive approaches as capacity scales. There will likely be a migration towards optical fibre switching technologies, as has already happened in data centre networks.

2.1.6/ Subsea fibre optic cables

Subsea cables are a critical component of the global telecommunications infrastructure. They provide interconnection between the continents and islands of the world and provide access to the cloud in otherwise underserved countries. They are some of the most complex and challenging high-performance communication links ever developed. The lack of electrical power supplies in the ocean drives a need for maximum energy efficiency. Besides transoceanic links, there are undersea cables connecting oil rigs, remote islands and strait crossings, each with their own set of particular design requirements and challenges. These challenges include increasing power efficiency and reducing size of optical amplifiers, while maintaining reliability and lifetime; increasing the density of fibre cores by reducing fibre diameter or using multicore fibres. This wide range of applications adds further dimensions to the problem while the goals for all undersea fibre systems are always the same: more capacity, lower cost, longer lifetime.

2.1.7/ Research Priority

- Building an ecosystem to leverage hollow core fibres.
- Continued support for work on fundamentals of hollow core fibre design and fabrication. Also, in related areas of cabling, splicing, test and measurement.
- Work to create new system opportunities including on high power and alternative band amplifiers.
- Transceivers for other wavelength bands.
- DSP's that take advantage of lower dispersion.

2.2/ RAN and Access Transport

In the UK as with most of the rest of the world, optical fibre systems are used for both fixed access to homes and businesses as well as connecting mobile masts to the rest of the mobile network.

In fixed access, homes and the smallest businesses are increasing being connected directly with optical fibre, known as (residential) fibre to the premises (FTTP). This is replacing earlier technologies where optical fibre reached either only as far as the local telephone exchange building or the 'green cabinet' in the street, known as fibre to the cabinet (FTTC). After this point copper cables make the final connection to the premises. This upgrade to FTTP is a major national initiative operating under regulation by Ofcom. The technology used for FTTP does not dedicate a single optical fibre all the way between the premises and the 'head end' electronics (normally in a large network node), but uses a one to many passive optical splitter/combiner located a few tens of metres from the premises, so that one fibre at the head end typically can serve 32 to 64 customer premises. For signals going from the head end to the customer premises, the splitter simply broadcasts the signal to all premises. However, for the signal from the customer premises to the head end, a transmission protocol is used so that each customer node transmits signals in precise allocated time slots which then interleave with each other at the optical combiner so that the head end sees a sequence of transmissions coming from different customers in consecutive time slots. This is known as a passive optical network (PON) system.

Businesses whose requirements are larger than what can be met by PON systems are provided with dedicated fibre between their premises and the network node building, often called point to point (PtP) fibre. Currently mobile cells are also served with dedicated PtP fibre.

The standards for PON systems are defined in the ITU-T, specifically in ITU-T Study Group 15. As technology has developed, the capacity of PON systems has also increased and will continue to do so into the future. This means the PON fibre is a long-term investment which can be reused by these successive generation of PON system electronics by changing out the electronic boxes on the ends.

The current installed generation is called GPON and has 2.5Gbit/s downstream capacity with a new generation called XGS-PON with 10Gbit/s downstream capacity emerging for the latest deployments[18]. ITU-T standards include PON technologies with 50Gbit/s capacity and are working towards the definition of Very High Speed PON technologies, expected to have a capacity of 200Gbit/s. All these systems use a time slot interleaving protocol in the upstream direction, known as time division multiple access (TDMA), as noted above. There are other variants of PON systems which exploit wavelengths channels (WDM) which ITU-T SG15 address currently including TWDM-PON (Time & Wavelength Division Multiplex PON) at 4 x 10Gbit/s and WDM-PON (Wavelength Division Multiplex PON) with 20 x 10Gbit/s.

[18] A national roll-out of a fixed access technology takes many years and this means that more than one generation of PON system is likely to be co-exist in the overall network.

The standards for the PtP systems deployed for the large business and mobile markets are currently developed by both IEEE802 (who define the standards for Ethernet) and ITU-T SG15. They are based on IEEE802 optical interfaces (1GbE and 10GbE) standards but there can be important optical aspects not covered in these standards which means that these PtP systems are effectively proprietary and require compatible optical plugins from the same vendor on each end of the fibre. In some cases, PtP WDM systems at 10Gbit/s per wavelength are also being used for PtP access. ITU-T SG15 have standards published at 1, 10 and 50 Gbit/s and currently working with a 100Gbit/s version, although again they are being largely as a guide by vendors and it is still necessary to have optical plugins from the same vendor at each end of the fibre.

In a mobile network, a radio access network (RAN) connects a user equipment (UE) with its core network. In 5G, the architecture allows for a disaggregated RAN where the functionality of the base station is split between the radio unit (RU), distributed unit (DU) and central unit (CU) which do not need to be co-located. While the RU must be at the mast, the DU and CU can be in more centralised locations. The interconnection between these functional blocks and further to the mobile core network is now a growing focus for optical access technology innovation, particularly between the DU and the RU (Front-Haul) which has especially exacting requirements.

5G allowed its RAN elements, 5G new radio (5G-NR), to be deployed in advance of any upgrade to the mobile core and is rapidly being deployed in the UK, working mainly in the 700MHz and 3.5GHz spectrum bands. Such bands are well suited to macro cell sites (typically mounted on masts), because of the radio frequency (RF) transmission reach in the order of a few kilometres. However, even with the new spectrum and 700MHz and 3.5GHz, the bandwidth is still limited and increasing the mobile cells capacity requires an increase in the density of cells which requires more mobile backhaul optical fibre infrastructure and the number of active masts in the UK is rapidly increasing.

There is also much discussion on deploying mobile in the spectrum region known as the millimetre wave (mmWave) region, e.g. around 26GHz and beyond, where the available RF channel widths are roughly 10 time greater, however, at these RF frequencies effective coverage of a cells is limited to a few hundreds of metres which would further increase the need for optical fibre x-haul. Other service applications of small mobile cells are for indoor venues, for example manufacturing plants.

Small cell infrastructure, therefore, will require a large amount of fibre infrastructure and optical transport interfaces to interconnect the different RAN functionality, and the cost of such infrastructure will be an important factor in determining the extent of small cell deployments[19]. In effect, 5G and future 6G mobile radio access technologies bring together mobile network technology and fibre transport technologies.

[19] Albert Rafel and Jochen Maes, "Comparing optical transport technologies for x-hauling 5G small cells in the sub-6 GHz," J. Opt. Commun. Netw. 14, 204-210 (2022)

2.3/ Data Centre Networks

Demand for optical interconnects within and between datacentres is growing at unprecedented rates. The primary driver of innovation in optical interconnect technologies is no longer the requirements of telecom network operators, but comes from the needs of hyperscale service providers who continually strive for greater transceiver bandwidth, reliability and energy efficiency at ever lower cost per bit. Further, the exponential growth in compute requirements for AI/ML workloads (Figure 5) is accelerating these trends, with the market for Ethernet optical transceivers alone forecast[20] to rise with double-digit CAGR to over $10bn in the next 5 years, nearly 50% of which being destined for AI compute clusters.

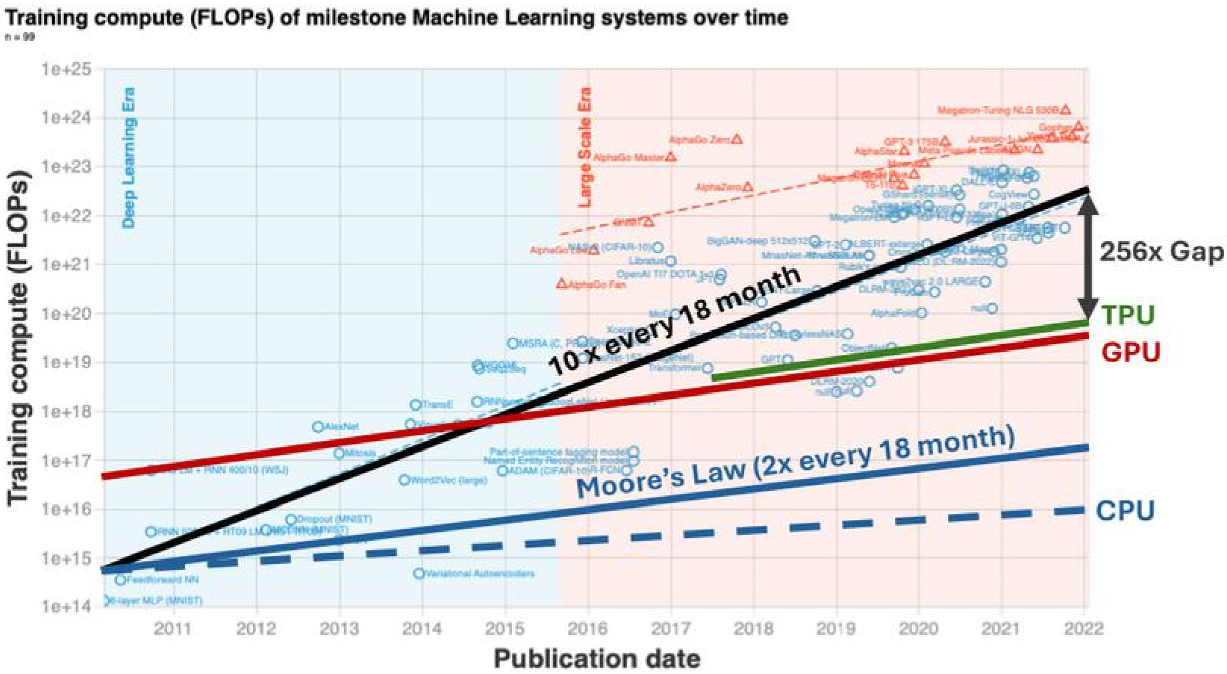


Figure 5 Exponential rise in compute requirements for AI/ML workloads, CPU (central processing unit), GPU (graphics processing unit), TPU (tensor processing unit)[21].

Most of the processing power behind the internet is hosted in warehouse-scale datacentres, each containing tens of thousands of servers interconnected by a fibre-rich, fault-tolerant network with a spine-leaf architecture, as illustrated in Figure 6. Fibre runs can span up to 2km between server end points. Each link in the network is typically running at 100-400Gb/s, with line rates expected to double several times over the next few years as transceivers become available. 800Gb/s links are already beginning to be deployed, with 1.6Tb/s and 3.2Tb/s in development.

[20] www.lightcounting.com
[21] Parameter, Compute and Data Trends in Machine Learning by Jaime Sevilla, Pablo Villalobos, Juan Felipe Cerón, Matthew Burtell, Lennart Heim, Amogh B. Nanjajjar, Anson Ho, Tamay Besiroglu and Marius Hobbhahn; 2021.

The limitation in transfer rates is seen increasingly at the electrical interfaces to the silicon processors. Co-packaged optics (CPO) devices implemented as integrated photonics chiplets enables the optoelectronic interface to move from front-panel pluggable transceivers to the boundaries of the silicon chip itself, resulting in higher data rates and lower energy consumption. Challenges remain in achieving sufficient reliability and link margin to enable widespread deployment, together with developing compact and efficient modulators that allow direct drive off-chip with maximum shoreline density at the chip boundary.

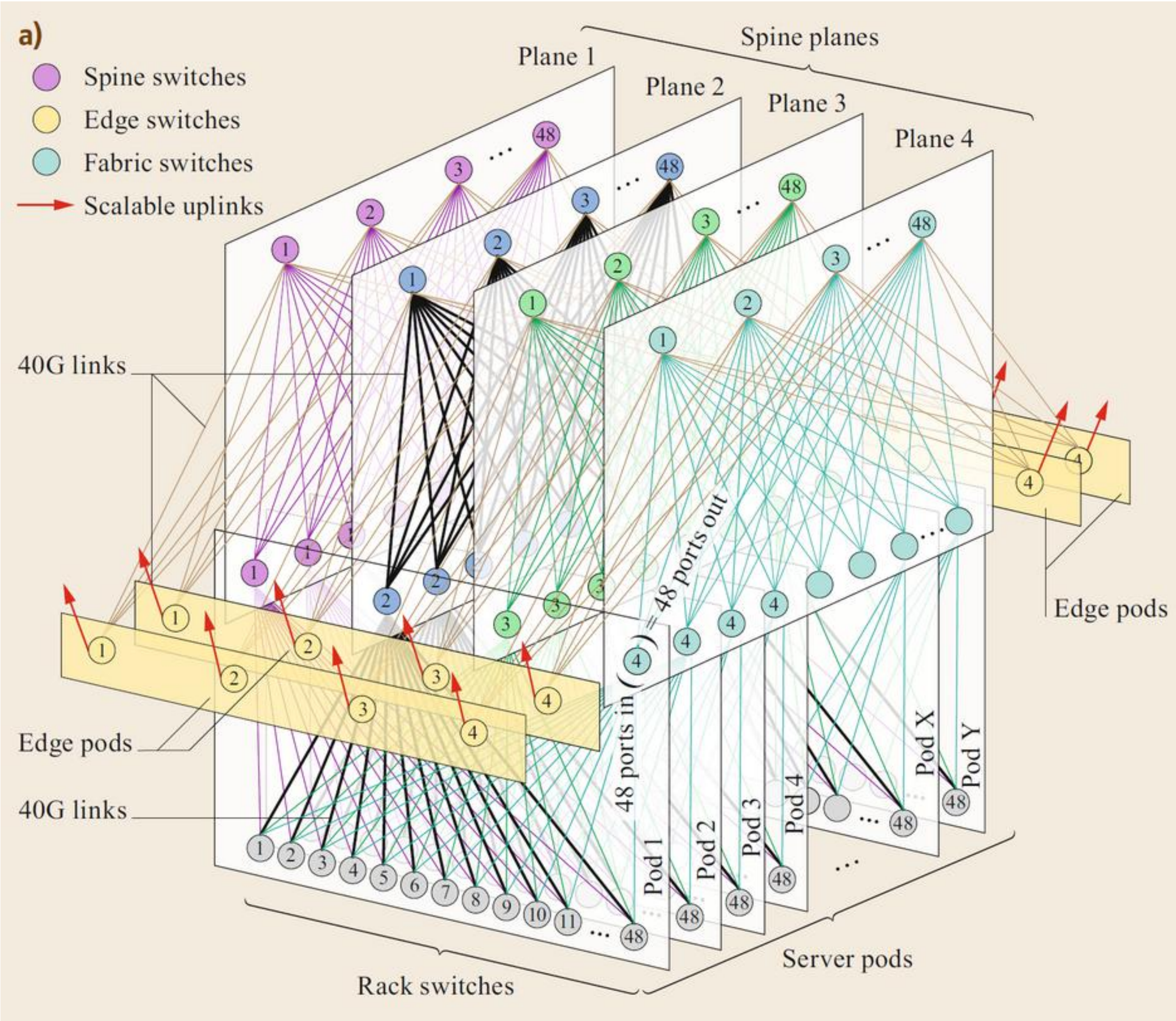


Figure 6 Typical spine-leaf hyperscale datacentre network architecture [22].

[22] A. Andreyev: Facebook's data center fabric, Networking @scale (Feb 2015)

At each node in the spine-leaf network, electronic packet switches are conventionally used to route traffic, requiring multiple optical-electrical-optical (OEO) conversions between source and destination. The time taken for packets to traverse these networks is dominated by the delay (latency) caused by buffering, routing and arbitration inside the OEO switches. But not all dataflows are short-lived; and not all aggregated packets need their headers inspected. Moreover, implementing faster data rates as transmission technologies evolve requires a forklift upgrade of all transceiver and switch hardware across the network.

Recently, Google[23] disclosed that by deploying all-optical circuit switches (OCSs) to replace OEO spine switches in the DC fabric, savings of over 30% in network capex and 40% in energy consumption have been achieved, together with a remarkable 50x improvement in network uptime. Additionally, the data-rate transparency of OCS devices enables progressive upgrade of network bandwidth across the DC fabric. Over 95% of east-west (intra-DC) traffic now flows through this OCS layer, enabled by OCS-aware traffic engineering functions at the management plane. The same OCS technology has also been used to realise reliability, availability and throughput benefits in AI supercomputer clusters[24].

2.3.1/ Research priorities

We see research priorities in the following areas:

- Co-packaged optics chips to bring high density optoelectronics interfaces as close as possible to silicon processors and minimise power lost in electrical interconnects;
- Methods for optical disaggregation and composition of compute resources on demand, to improve utilisation and enable routing around hardware faults;
- Fast optical circuit switch technologies with sub-microsecond reconfiguration, high radix and low loss to enable dynamic topology reconfiguration of AI xPU clusters;
- Low latency connectivity using advanced transceivers and novel media such as hollow core fibre, allowing more flexible DC location and improved efficiency of AI compute operations.

[23] Jupiter evolving: transforming google's datacenter network via optical circuit switches and software-defined networking L Poutievski, et al., Proceedings of the ACM SIGCOMM 2022 Conference, 2022
[24] TPU v4: An Optically Reconfigurable Supercomputer for Machine Learning with Hardware Support for Embeddings, Jouppi et al., 50th Annual International Symposium on Computer Architecture (ISCA '23), June 17–21, 2023, Orlando, FL, USA.

2.4/ Optical Wireless

Over the recent years, there has been a clear indication that optical wireless communications (OWC) are poised to play a crucial role in meeting the evolving demands of future wireless networks. This trend is underscored by the substantial body of research, numerous case studies, and practical implementations originating from both academic and industrial sectors. OWC provide a two-fold advantage to the wireless networks landscape, offering both a broader spectrum and an increased cell density. While utilising the entirety of this spectrum is currently not feasible due to constraints in transceiver technology, ongoing enhancements in front-end devices are progressively enabling higher data rates and increased capabilities. Different OWC solutions are making their way into the wireless communications market to complement radio frequency (RF)-based technologies, these include free space optics (FSO) communications, visible light communications (VLC), light fidelity (LiFi), ultraviolet (UV) communications, and optical camera communications (OCC). This discussion will primarily focus on FSO and LiFi, given their widespread applications and rapid development.

FSO is designed to establish outdoor point-to-point optical wireless links, primarily using Infra-red (IR) as a transmission medium. Its main application is enabling cost-effective wireless backhaul systems, achieving long transmission distances in the range of a few kilometres and high data rates in the range of several hundred gigabits per second for line-of-sight (LoS). Due to the use of coherent laser sources, up to tens of gigahertz of modulation bandwidth is available for wireless data transmission in FSO. Installing FSO systems is more convenient and cost-effective compared to laying optical fibre. However, due to the large divergence of laser beams relative to the size of the optical detector, FSO links pose significant power loss compared to optical fibre links. Moreover, the FSO channel is susceptible to atmospheric effects and weather conditions, which results in link reliability issues. FSO is efficient when either very rapid deployment is needed and/or when an optical fibre cable doesn't exist and would be expensive to provide. For example, even when measured purely in terms of energy efficiency, the higher energy consumption of the FSO optics can be more than compensated for by the saving in the embedded energy required to lay a new optical fibre cable. An application area for which FSO is ideally suited is inter-satellite communications.

LiFi constitutes a comprehensive network solution for indoor coverage. It employs optical links, predominantly VLC for the downlink and IR for the uplink, to realise bidirectional connectivity with mobility support and seamless coverage. LiFi is considered a promising solution to offer extremely high data rates within a small coverage range of a few meters, known as LiFi attocells. Each lightbulb in a room or a corridor could act as a LiFi access point (AP) causing very little to no interference to neighbouring LiFi attocells and zero interference to the Wi-Fi network. As a result, LiFi can add a new dimension to the spectrum heterogeneity and allow extra cell densifications for future internet of things (IoT) and Industry 4.0 applications.

2.4.1/ Research Priorities

Chipset and optical components: OWC systems commonly employ unipolar and real-valued intensity modulation/ direct detection (IM/DD) signals. This requires specific modules for encoding, modulation, and signal pulse-shaping/amplification that are distinct from those used for conventional RF communications. The lack of purposely designed chipsets and optical components means that product manufacturers must design and prototype their own chipsets and optical components. This is one of the main barriers facing a wider commercialisation of LiFi.

Transceiver capabilities: The speed of the current OWC systems is strongly limited by the bandwidth and nonlinearity of transceivers, particularly for systems employing LEDs at the transmitter side. New materials and devices are needed to solve the transceiver bandwidth limitation and nonlinearity issues. In recent years, research groups utilised novel light sources such as micro-LEDs and organic LEDs (OLEDs), that can mitigate the bandwidth limitation but come at the expense of low transmission power and high cost.

LiFi operational limitations: LiFi equipment currently existing in the market is still limited to line of sight (LoS) implementations due to the highly directional and narrow beamwidth of light sources. The link quality is severely affected by blockages in the light propagation between the transmitter and the receiver, which limits the applicability in practical setups that involve user mobility and random channel impairments. Novel technologies such as intelligent reflecting surfaces (IRS) are currently being investigated to add new degrees of freedom, support mobility, and enhance the system performance. The integration of machine learning (ML) present exciting potential to support the service provisioning in such systems.

Optical wireless integrated communications & sensing: precise indoor positioning is essential for many applications including factory automation, assisted living, indoor navigation, and IoT. Integrated communications and sensing have been identified as a key component for future 6G networks. OWC has been proven to offer sub-cm accuracy indoor positioning, but realising the same accuracy outside lab settings is hindered by many factors such as installation inaccuracies, environmental influences, and the adoption of generic Lambertian channel models. There is a need to develop robust and resilient indoor positioning by combining time-based approaches with signal strength approaches, and by adopting more realistic channel modelling that considers multi-path propagation and the effect of reflections caused by different surfaces and materials.

Mitigating FSO path loss: the main challenge that faces FSO is related to signal attenuation due to free space loss, absorption, and scattering by atmospheric elements. Environmental factors like fog and clouds further compound the issue, potentially obstructing the signal. Atmospheric turbulence interferes with the signal, causing beam wander and signal degradation, where the point-ahead angle must be carefully considered in scenarios like inter-satellite links. There is a need to develop advanced mitigating techniques that can lessen the effect of FSO losses. Examples include aperture averaging, where larger apertures are deployed to reduce the impact of atmospheric turbulence, and diversity techniques, which improve system performance by transmitting uncorrelated signals in the time, frequency, or space domains. Also, adaptive optics can be used to correct both amplitude and phase fluctuations.

2.5/ Quantum Communications

The advancement of quantum technologies offers both opportunities and threats. Quantum computing, in particular, holds promise for executing calculations of certain tasks beyond the reach of any classical supercomputers. However, an unintended consequence of quantum computing is its potential to compromise existing encryption mechanisms, rooted in intractable mathematical problems that would require classical computers thousands of years to solve.

In contrast, quantum communication, specifically quantum key distribution (QKD), promises unparalleled security exploring the fundamental principles of quantum mechanics: superposition and the no-cloning theorem. Superposition empowers matter at the quantum level with an inherently unpredictable nature, yielding pure random measurement outcomes without any mathematical pattern. Meanwhile, the no-cloning theorem prohibits the replication of unknown-state particles. QKD harnesses these properties to establish non-cloneable yet identical pure randomness between two parties over long distance. This identical randomness, dictated by physical laws, serves as a symmetrical secret key for encrypting and decrypting messages, ensuring the security of classical communications such as WiFi, 5G, and optical communications via fibre or free space.

Typically, QKD technologies utilize photons or light for several reasons: firstly, their low-loss propagation characteristics in optical fibre or free space; secondly, their long decoherence times and resilience to environmental noise. This discussion primarily focuses on quantum communication, particularly QKD, exploring its enabling technologies and diverse applications. Broadly, QKD protocols and implementations fall into two main categories: continuous-variable (CV) QKD and discrete-variable (DV) QKD. Here we provide a short introduction to these two solutions used in QKD.

Discrete-Variable Quantum Key Distribution (DV-QKD)

DV-QKD uses finite Hilbert space, typically leveraging time, phase, spatial mode, or polarization of photons for information encoding. The photon source can employ various methods, including single photon sources such as quantum dots, spontaneous parametric down-conversion (SPDC)-based photon sources, or four-wave-mixing-based photon sources. Alternatively, attenuated lasers modulated by intensity and phase modulators can be used to achieve an average of N photons (where N<<1) per pulse. In contrast to single-photon-based QKD systems, employing highly attenuated modulated light can yield significantly higher secret key rates, typically exceeding 1 Mb/s for 10 dB channel loss and can tolerate higher channel losses, typically > 30dB.

Among DV-QKD protocols, decoy-state BB84 QKD stands out as one of the most successful, addressing the photon-number splitting (PNS) attack, offering a relatively high secret key rate with relatively low-cost. Conversely, protocols like Coherent One-Way QKD and Differential Phase Shift QKD provide lower security levels compared to decoy-state-based approaches. The Measurement Device Independent (MDI) QKD protocol mitigates the detection side-channel attack loophole, bolstering security with an additional layer of protection. Twin-field QKD, a specialised MDI-QKD protocol, has recently attracted attention for its demonstrated capability to achieve quantum communication distances exceeding 1000 km in laboratory settings and over 500 km in field-deployed fibre networks.

Continuous-Variable Quantum Key Distribution CV-QKD

CV-QKD can be described by its utilization of infinite-dimensional Hilbert space, typically encompasses encoding in amplitude and phase or position and momentum of weak electromagnetic field. Similar to the prepare-and-measured DV-QKD approach, CV-QKD employs telecom modulators to prepare states, often in a Gaussian distribution fashion via probabilistic constellation shaping. Alongside coherent states, squeezed states find its application within the CV-QKD framework. Diverging from DV-QKD's reliance on single photon detection, CV-QKD is able to utilise telecom-based homodyne detection. This involves the interference of the incoming CV-QKD signal with a laser beam generated by a local oscillator. Such a setup mandates a phase stabilization process employing digital signal processing techniques akin to those used in classical coherent transmission systems. In comparison to DV-QKD, CV-QKD offers similar key rates, but with a reduced loss budget (typically <10 dB) and reach distance and a compromised security level.

2.5.1/ R&D Priorities

Improving Performance

The main performance metrics of QKD are the secure key rate and the maximum channel loss (or equivalently maximum propagation range). Currently typical secure key rates are of the order of 1 Mb/s for a 10dB channel loss, corresponding to ~4,000 AES-256 encryption keys per second. Higher key rates are important to facilitate quantum networks that can serve many users and processes in parallel.
It is arguably even more important to increase the maximum channel loss that can be tolerated. As quantum signals cannot be amplified without the use of a quantum repeater, which remains an elusive goal (see “Entanglement-based Quantum Communication” below), the maximum loss defines the maximum separation of nodes in a quantum network. Typical maximum losses today are ~35dB (corresponding to ~175km of fibre with a standard loss of 0.2dB/km at 1550nm) using practical semiconductor detectors and ~55dB using cryogenic superconducting detectors. Further improvements in photon detection technology, as well as new protocols, can be expected to further extend the range. Recently QKD links exceeding 1000km of fibre have been demonstrated in the lab using a recently discovered protocol, Twin-Field QKD.

Satellite and Free-space Quantum Communications

The range of QKD, and quantum communications more generally, can be extended using ground-to-satellite quantum links. In particular, a low earth orbit satellite can be used to form secure keys between the satellite and ground stations in different locations around the world, allowing national/continental fibre optic quantum networks to be extended to global scale. Satellite QKD could also enable secure quantum links to remote locations, which are difficult to connect securely using fibre communications.

To date the only demonstration of space-to-ground quantum communications has been made by the Chinese Micius mission. However, several launches of quantum satellites are expected in the coming years involving teams from the UK, EU, Japan, Singapore, Canada and other countries. Many technical challenges remain for Satellite QKD, such as reducing the sensitivity to atmospheric turbulence, background light and high channel losses. There is also a strong motivation to increase satellite key rates, as they are often much lower than fibre-based systems and thus present a bottleneck in an integrated fibre-space network. The UK Quantum Communications Hub at York University is planning to use satellites as trusted nodes for QKD and is working towards an in-orbit demonstration of QKD from a CubeSat to an optical ground station, expected to launch in 2025. This also linked to the National Dark Fibre Facility (NDFF) for terrestrial interconnection.

Beyond space-to-ground communication, free-space QKD also explores the use of high altitude platforms, drones, and point-to-point fixed optical-wireless environments. These research efforts have recently gained significant attention, offering quantum-secure services across various environments.

Integrated Quantum Photonics

Today's commercially available systems are based on discrete fibre optic devices and are relatively expensive. Although price points are expected to reduce as volumes increase, a step change can be expected through the introduction of integrated photonics. Integrating the optical circuit of a quantum transmitter/receiver onto a semiconductor chip, which can be mass manufactured using standard processing techniques, will enable much larger production volumes at lower cost. Other advantages which could result from the use of photonic integrated circuits include improved repeatability and reliability, as well as smaller form factors, thereby enabling new applications.

Prototype QKD systems based on photonic integrated circuits have already been demonstrated. The most promising approach to date has been the use of high performance InGaAsP/InP photonic integrated circuits for the quantum transmitter and low loss SiON/Si circuits for the quantum receiver. Quantum transmitters based on Si photonics are also of interest for photonic/electronic integration and to further reduce the cost.

Quantum and Classical Network Integration

The main application for quantum communication today is to distribute the cryptographic keys required to secure a conventional telecommunications network. A quantum-secured network can be considered to consist of a QKD network, which distributes keys between two or more locations connected to the network and a conventional telecom network, which transports the payload encrypted with the quantum keys. The QKD network requires not only point-to-point QKD hardware, but also key management software that can deliver quantum keys through the network and control the QKD equipment.

Cost effective deployment of a quantum-secured network requires QKD systems to be developed that integrate into conventional architectures used in the backbone, metro and access segments. In particular, the access segment requires solutions that are much cheaper than those available today, for example deploying integrated photonics and passive optical networks.

Another important aspect of network integration focuses on the co-existence of quantum and classical communication channels within the same optical fibres using wavelength-division multiplexing (WDM). Using data carrying fibres for the quantum signals would substantially reduce deployment costs by eliminating the requirement for dedicated, dark fibre. However, nonlinear impairments from classical channels, such as Raman scattering and four-wave-mixing, can increase the quantum bit error rate and reduce the fidelity and visibility of quantum channels. Significant progress has been made on combining quantum and classical channels using a variety of WDM schemes.

Cryptographic Integration

Efficient attacks using a quantum computer have been developed for the asymmetric (i.e. public key) cryptographic algorithms in use today. Developing new asymmetric algorithms, for which no quantum attack is known, provides a solution which is complementary to QKD. Post-quantum cryptography, as it is known, provides a solution closer to today's maths-based techniques, although their bandwidth and computational requirements can be considerably more demanding. However, it is unknown if a quantum (or classical) attack on these new algorithms will be found in the future, as they have not been subjected to the same scrutiny as today's algorithms. Indeed, several of the most promising post-quantum candidates have already been broken. Given the potential devastating impact of a quantum attack, many advocate a hybrid approach that combines quantum, post-quantum and conventional approaches. Compromising the security of hybrid keys formed by combining the three approaches, requires an adversary to break each of them, mitigating the risk of a new attack in the future.

Entanglement-based Quantum Communication

Today's quantum networks are based on communication of single photonic qubits between adjacent nodes. In the longer term, quantum networks will build on this capability to exploit the entanglement of qubits located in different nodes. Entanglement distribution over single fibre links of ~100km has already been demonstrated. With further improvements in entanglement generation, distribution and storage technology, this could allow the development of a "quantum repeater", a device which can extend the range of a single quantum link, in an analogous way that the optical repeater extends conventional fibre optic communication links.

Entanglement-based networks may eventually enable applications beyond secure communications, allowing quantum computers to be accessed remotely and securely "in the (quantum) cloud", or allow two or more quantum processors to be connected. Given that each additional qubit added to a quantum processor doubles its computational strength, distributed quantum computing has the potential to realise extremely powerful computing infrastructures. Other applications include accurate time distribution by entangling remote atomic clocks, or distributed quantum sensing.

2.5.2/ Opportunities for the UK

The UK has been at the forefront of R&D in quantum communication over the past two decades, making several of the most significant research breakthroughs. The EPSRC Quantum Communication Hub, established as part of the UK Quantum Technology programme in 2014, has galvanised activities in academia, while InnovateUK and ISCF have promoted collaboration with industry. In recent years, however, other countries have taken the lead in the industrialisation and deployment of quantum communication. China has built multi-node quantum networks in Beijing, Jinan, Hefei and Singapore, interconnected these with a 2000km quantum backbone link, and launched the first quantum-enabled satellite. Meanwhile the EU have invested in the Euro Quantum Communication Infrastructure (Euro-QCI), a pan-European network for government comms covering the EU27, providing a considerable advantage for EU27-based industry in the process. Other large-scale quantum networks are under construction in South Korea, Japan, Singapore and Canada.

We recommend several actions to maintain the competitiveness of the UK in quantum communications:

The UK should invest in a national quantum-secured network, which can serve as a model for the integration and operation of quantum communications in the telecom network, a testbed for the deployment of new quantum technologies and applications and enable trial use by early adopters, industry and academia across the UK.

The UK should establish a security certification process for quantum technology, or support initiatives which are underway in other parts of the world. Although there has been good progress to create standards for testing quantum systems, the lack of third-party verification is a significant barrier to widespread adoption by Government and industry[25].

Integrated photonics will have a transformational impact on quantum communications in the coming years. To remain competitive, it is essential that the UK invests in semiconductor foundries for fabrication of essential quantum components, quantum photonic integrated circuits and their packaging. Most importantly these facilities should offer open access to industry and be supported by a commercial model, rather than academic research grants.

Continue to invest in R&D of next generation quantum communications in both academia and industry to enable entanglement-based networking, and to train the workforce needed for expanding the quantum industry.

[25] BT Group LinkedIN post

2.6/ Integrated Photonics

Integrated photonics is a technology that combines many optical and photonic functions on a single chip, known as a photonic integrated circuit (PIC). Optical signals can be generated, manipulated, modulated and detected within a single photonic circuit, which may be fabricated on silicon, compound semiconductors (e.g. indium phosphide (InP)) or dielectric materials. Each material technology offers a specific range of functions. Silicon photonics (SiPh) is an important category of integrated photonics, in which the required functions are realised on a silicon wafer, taking advantage of fabrication on large wafers using silicon IC industry tools. InP PICs are widely used in the communications industry, since this material provides the widest range of functions, including efficient on-chip light generation. Multiple technologies can be combined in heterogeneous and hybrid integration schemes, which often use silicon as the platform on which everything else is built.

Interfaces are required for such electronics in converting electronic signals into optical signals, which are then processed and transmitted; and then at the receive end, to detect the resultant optical signal and transform it back into an electrical signal. Conversion from electrical to optical signals is achieved using a compound semiconductor laser or laser array. This can be integrated monolithically on InP, or in a heterogeneous or hybrid scheme in silicon photonics. Detection can readily be integrated in compound semiconductors or in silicon photonics using silicon germanium technology.

Silicon photonics chips are most commonly fabricated in silicon-on insulator (SOI) wafers, in which the buried insulator is silicon dioxide. A surface layer of silicon dioxide on top of the silicon is also typically added. Light is guided in waveguides, essentially optical wires, formed in the silicon layer, with the silicon dioxide layers above and below forming waveguide cladding layers. Multiple metal layers are typically available for interconnection of electronic devices. The most common SOI structure utilises a 220nm guiding layer thickness, but other variants also exist.

One of the key advantages of using silicon for integrated photonics is that the fabrication processes are similar to those utilised in complementary metal-oxide semiconductor (CMOS) electronics, albeit with photonics devices (chip-level components) being much larger than electronic devices, because of the relative difference in wavelength. Consequently, SiPh circuits and devices can be fabricated in CMOS-compatible manufacturing foundries, making them reproducible and at low cost in volume production.

In contrast, the challenge with silicon as a material for integrated photonics is that it has several material properties that make it inefficient vs other materials. In particular, the indirect bandgap of silicon makes it unsuitable for lasers, and modulation mechanisms are relatively inefficient.

Compound semiconductor technologies, especially InP, are accordingly used very widely in communications transceivers. Ultimately, however, there will be great advantages in combining the required technologies in an efficient, heterogeneous integration scheme.

In one commercial foundry (Global Foundries, New York, US), monolithic integration (integration on a single piece of silicon in the same chip) of electronics and photonics is available, although the speed of such circuits is limited by the speed of the electronics in such cases. Most foundries do not offer monolithic integration, and therefore heterogeneous integration (combining multiple separate chips) of electronics and/or lasers, with PICs is common.

Although silicon is becoming the most prevalent material used for photonic devices and circuits, and benefits from CMOS-compatibility, other materials can also be used to achieve different, or more efficient manipulation of the signal light. Examples of this include silicon nitride (potentially lower insertion loss but no modulation mechanism), indium phosphide (laser generation, modulation and detection, together with passive waveguide functions), and lithium niobate (high-speed modulation and nonlinear effects). For the purpose of this paper, the term SiPh is considered to encapsulate all materials that confine, manipulate and process optical signals at the chip-level that are based around silicon or silicon compounds as the waveguiding platform.

The key challenges, common to all optical telecommunications solutions, of improved power consumption and density, represent a major opportunity for integrated photonics. For example, the current focus for data centre applications is on co- and near-packaged optics, i.e. bringing the optics closer to the electronics to reduce latency and power consumption. To do this, manufacturing challenges exist, for example, increasing the number of channels (lines of data) that can be integrated with a PIC, otherwise known as the shoreline density, i.e. the measure of bandwidth on/off a PIC per millimetre of PIC edge. Packaging PICs alongside electronics is a nontrivial and rapidly growing field of expertise that offers huge opportunity. However, SiPh is recognised as a key technology for addressing such challenges, particularly because the fabrication processes are essentially the same as for CMOS electronics, and hence are among the most well controlled and well understood semiconductor processes in use today.

It is also worth noting that all SiPh chips require the use of a light source, typically a laser, and thus applications are therefore intrinsically linked to compound semiconductor technology which provides the best semiconductor laser sources, and where the UK also has significant strength. In fact, many of the SiPh and integrated photonics applications, including telecoms, represent a significant market for compound semiconductors. The use of heterogeneous silicon-based platforms can provide highly effective solutions in this space.

2.6.1/ Opportunities for the UK

There are opportunities for the UK in multiple aspects of telecommunications, that is: 1) in various parts of the terrestrial network, 2) in space (or mobile platform) communications, as well as wider integrated photonics applications. Although these wider applications are not the focus of this paper, it is important to consider, as it may be impacted by the wider UK semiconductor strategy, and we recommend that these two as part of the terrestrial network and that of space communication should not be considered separately.

For the UK to be effective, fabrication and scale-up to commercial volumes must also be considered. Whilst the UK may not be able to invest in a large-scale production facility for silicon photonics, we recommend that the UK needs a prototyping capability that will feed into international foundries for scale-up. That prototyping capability needs to be open source so as not to compromise intellectual property (IP) ownership prior to scale up.

Regarding compound semiconductor PIC technologies, the most advanced InP technologies are presently in production with vertically integrated companies, e.g. Lumentum, through its wafer fabrication facility in Northamptonshire. First steps towards a prototyping capability that could support the wider photonics community are however already underway, notably in South Wales, and it is important that these developments are integrated into a wider photonic integration strategy in the UK. There are opportunities to scale these technologies to production using facilities within the UK, and companies providing semiconductor laser and other related device technologies operate successfully in the UK.

A national silicon fabrication facility, besides providing prototyping for silicon photonics devices, could potentially also incorporate back-end processing for packaging and heterogeneous integration. Such a national facility could also service other applications beyond telecoms leverage any investment to the maximum. i.e. it would make sense for the prototyping facility to serve all of the UK silicon photonics needs because emerging applications such as lidar, imaging, AI, and healthcare are potentially true mass markets where the UK also have significant opportunities and is directly relevant to the UK semiconductor strategy[26]. We should look at how silicon and other technologies can be brought together in a unified prototyping and pilot production programme, with links to full scale manufacturing both in the UK and internationally.

[26] National semiconductor strategy

2.6.2/ Research Priorities

The term "silicon photonics" originally meant that the material within a silicon photonics chip was just crystalline silicon, plus the silicon dioxide claddings. Today however, the term is used to incorporate a whole range of materials that are integrated with silicon to enhance performance of the PIC. The earliest material to be integrated was Germanium for the detector, but today a plethora of materials are utilised, particularly in the research environment. Furthermore, even entirely different guiding platforms are now regarded as falling under the silicon photonics umbrella definition, such as silicon nitride (SiN), which provides very broad transparency and low insertion loss, silicon germanium (SiGe), or germanium on silicon, which extend transparency into the mid-infrared wavelengths, indium phosphide (InP), which is able to lase – i.e. create light – and perform many passive functions (waveguides etc.), and lithium niobate (LiNbO3), which can be used for high-speed modulation and nonlinear operations on account of its electro-optical properties and high second-order nonlinear coefficient.

Within the telecoms space, there are a range of trends and priorities, which are most easily discussed in terms of device performance, but overarching targets are smaller size, higher speed, lower power:

Light Sources

Reliable integration of lasers on-chip is required, which could be monolithic or heterogeneous integration. Fully monolithic solutions are available in InP but silicon photonics demands a heterogeneous approach. The UK has pioneered quantum dot lasers on silicon, and this this technology is presently being developed into a high functionality, monolithic PIC platform (www.qudos.ac.uk). Hybrid solutions such as automated pick and place, or laser bar integration are also being developed.

Waveguides

Waveguide loss is clearly a key parameter, and particularly important in some applications such as quantum photonics. Losses of a few dB/cm are typical today for circuits processed on 200mm wafers, whereas sub 1dB/cm losses are typical for 300mm wafer processes. This is predominantly due to the higher resolution lithography utilised for 300mm wafers, resulting in smoother sidewalls. Power handling capability of waveguides is also important and is limited by two-photon absorption in silicon, which is in turn related to power density within the waveguide. The need for greater power density is one reason that other materials are interesting which can comfortably transfer higher powers, and has led for example, to combinations of silicon and silicon nitride waveguides within the same PIC. There is also a desire for better dimensional uniformity of waveguides across a fabricated wafer, to avoid phase errors in propagating signals, or wavelength errors in resonant devices. The thermal drift of silicon in such structures is another reason why Silicon Nitride is interesting for critical designs.

Detectors

The performance of integrated germanium photodetectors is among the most mature within silicon photonics, and remains impressive, with pin devices operating beyond 65GHz, and avalanche photodiodes (APDs) up to 300GHz. However, the selective area epitaxy required for growing germanium detectors is complex and expensive, leading researchers to investigate alternative forms of integration such as heterogeneous integration, or alternative device structures such as defect-based detectors, or resonant detectors.

Modulators

The modulator is arguably the most difficult device to design in any silicon photonics circuit, requiring high speed performance, low power, low insertion loss, low RF loss, small footprint, and high efficiency. Consequently, a variety of research approaches have been adopted to improve one or more of these parameters.

Silicon does not exhibit a Pockels effect as used in traditional photonics modulators, and so the modulation mechanism most commonly used is the plasma dispersion effect, in which variations in carrier density are used to vary refractive index. The most widely utilised modulator, both in industry and research, is the Mach Zehnder Interferometer (MZI) modulator. Because the plasma dispersion effect is relatively weak, modulators are typically several millimetres long. This necessitates travelling wave electrodes that can be lossy. In order to reduce power consumption, much smaller resonant structures are popular, such as ring resonator modulators, which are switched between on and off resonance to facilitate modulation. This is much more efficient from a power perspective, but makes the devices vulnerable to thermal drift, and consequently stabilisation is required, which diminishes the power saving. Silicon-Germanium modulators utilising the Franz-Keldysh effect, or the quantum confined stark effect (QCSE) can be efficient and compact but are typically more complex in terms of fabrication. Heterogeneous integration with compound semiconductors, e.g. InP or quantum dots based on gallium arsenide (GaAs), provide another attractive solution.

Due to the perceived “topping out” of the speed of all-silicon modulators, heterogeneous integration of other materials on silicon such as thin film lithium niobate, graphene, barium titanate and III-V semiconductors have all been considered, with some excellent results reported. In parallel, the performance of all-silicon modulators has also progressed more than expected, with data rates exceeding 150GBd per wavelength. Research reporting transmitters with energy efficiency of less than 1pJ/bit for MZI-based silicon devices and a few fJ/bit for resonant devices have been reported. Trends are now to combine performance metrics into single devices that can deliver aggregate data rates beyond 800GBd, with energy efficiencies ultimately targeting below 1fJ/bit.

Optical I/O

The number of inputs/outputs required for systems makes optical solutions attractive, and integrated photonics particularly attractive. There is a significant trend towards maximising I/O, or shoreline density on chip, and maximising GB/s/mm2.

2.6.3/ Roadmap of Photonic Integrated Circuits

The Integrated Photonic Systems Roadmap-International (IPSR-I)[27] is an international collaborative program organized by the Massachusetts Institute of Technology Microphotonics Center (MIT-MphC) and represents the merger of two previously independent road-mapping activities. Their aim is to "work together to define and create future Photonic Integrated Circuit (PIC) technology and systems requirements" and incorporates silicon photonics, compound semiconductors and associated PICs. The roadmap has recently been updated (March 2024) and is available online. The roadmap identifies key technological performance for the next decade and beyond, as well as other critical issues such as infrastructure, workforce, and potential show-stoppers. The UK has a number of representatives contributing to the development of the roadmap and playing an active role in guiding the direction of the roadmap.

Other relevant roadmaps include the following:

- Photonics21 [29]
- Photonics UK [30]
- AIM Photonics [31]
- Optica Integrated Photonics [32]

[27] About IPSR-I
[28] Integrated Photonics Systems Roadmap – International 2024
[29] "New Horizons: Securing Europe's Strategic Autonomy through Photonics", Multi-Annual Strategic Research and Innovation Agenda, 2023, especially see chapters 3.1, "Digital Infrastructure" and 3.7, "Core Photonics"
[30] Photonicsuk.org
[31] AIM Photonics Technology Roadmap
[32] Madeleine Glick, Lionel C. Kimmerling, and Robert C. Pfahl, "A Roadmap for Integrated Photonics," Optics & Photonics News 29(3), 36-41 (2018)

2.7/ Skills and Training

The UK has a well-educated workforce and a strong tradition of research and innovation in optical communications and photonics, with pioneering historical achievements such as the development of optical fibre, and it is host to several world-leading universities and research institutions, such as the Optoelectronics Research Centre (ORC), Southampton, which contribute to advancements in technology, development of people, skills and training, providing a strong foundation for the potential development and re-growth of the UK telecommunications sector. Collaboration between academia and industry is strong, with long-standing partnerships encouraged by government via multiple UKRI (EPSRC) research projects, including longer-term "programme grants" and "prosperity partnerships", and via Innovate UK through a range of schemes which support the transfer of research findings into industrial applications, including "collaborative R&D projects" and "knowledge transfer partnerships".

There is strong investment in optical communications and photonics research and direct training of post-doctoral researchers and associated PhD students, with ongoing projects in the specific topic areas of "Optical Communications", "Optical Devices & Subsystems" and "Optoelectronic Devices and Circuits" to the value of £85M, £120M, and £174M, respectively as of April 2024. World-leading universities active in optical communications and photonics research, simultaneously providing PhD-level and post-doctoral training include Aston, Bangor, Bristol, Cambridge, Cardiff, Glasgow, Heriot-Watt, Imperial, KCL, Leeds, Oxford, QUB, Southampton, St Andrews, Strathclyde, Surrey, and UCL.

A snapshot of the research industrial partners names on EPSRCs website for some of the largest grants presently held include ADTRAN (formerly ADVA), AMD, Airbus, BAE systems, BT, Ciena, Cisco, Corning, DTag, Ericsson, Furukawa, Huawei, Huber+Subner, KDDI, Lumentum, MERL, Microsoft, Nokia, OFS, OpTek, Orange, QinetiQ, Rockley, Rolls-Royce, Siemens, Sumitomo, Thales, Toshiba, TRUMPF, Verizon, Xtera.

There are also relevant Centres for Doctoral Training (CDTs)[33] providing skill centres and cohort-based training in: "Connected Electronic and Photonic Systems" hosted by UCL and Cambridge University, "Applied Photonics" at St Andrews, Strathclyde and Heriot-Watt Universities, "Photonic Integration and Advanced Data Storage" at Glasgow University and Queen's University, Belfast, "Industry-inspired photonic imaging, sensing and analysis" at Heriot-Watt University and "Compound Semiconductor Manufacturing" at Cardiff, UCL, Sheffield, and Manchester. In March 2024, ongoing support for existing and new CDTs were announced in "Photonic and electronic systems" (UCL), "Future Open Secure Networks" (Surrey), "Compound Semiconductor Manufacturing (Cardiff), and "Quantum Computation and Quantum Communications (Imperial).

[33] List of current CDT Awards

Study Topics

Masters programmes (MRes/MSc) enabling specialisation in optical communications and photonics include:

UCL	**Cambridge Connected Electronic and Photonic Systems**
UCL	**Wireless and Optical Communications**
Bangor	**Broadband and Optical Communications**
Bristol	**Optical Communications and Signal Processing**
Cardiff	**Condensed Matter and Photonics**
Glasgow	**Electronics and Photonics Manufacturing**
Imperial	**Optics and Photonics**
Sheffield	**Semiconductor Photonics and Electronics**
Strathclyde	**Optical Technologies**
Southampton	**Optical Engineering**
Sussex	**Quantum Technology**

2.8/ Supply Chain

The UK optical communications and photonics sector has a long and distinguished history of innovation and technological advancements, stretching back to the invention of optical fibre[34] in the 1960s. The value to the UK economy in terms of output is estimated to be circa £2bn, with £1bn gross value added (GVA) and employs c10K people[35]. However, it is worth noting that, with the demise of major UK-based telecom systems vendors after 2002 a significant trade imbalance has been created in the communications equipment sector, where the ratio of imports to exports has grown adversely from being roughly in balance in the early 2000s to an adverse factor of 3:1 today.

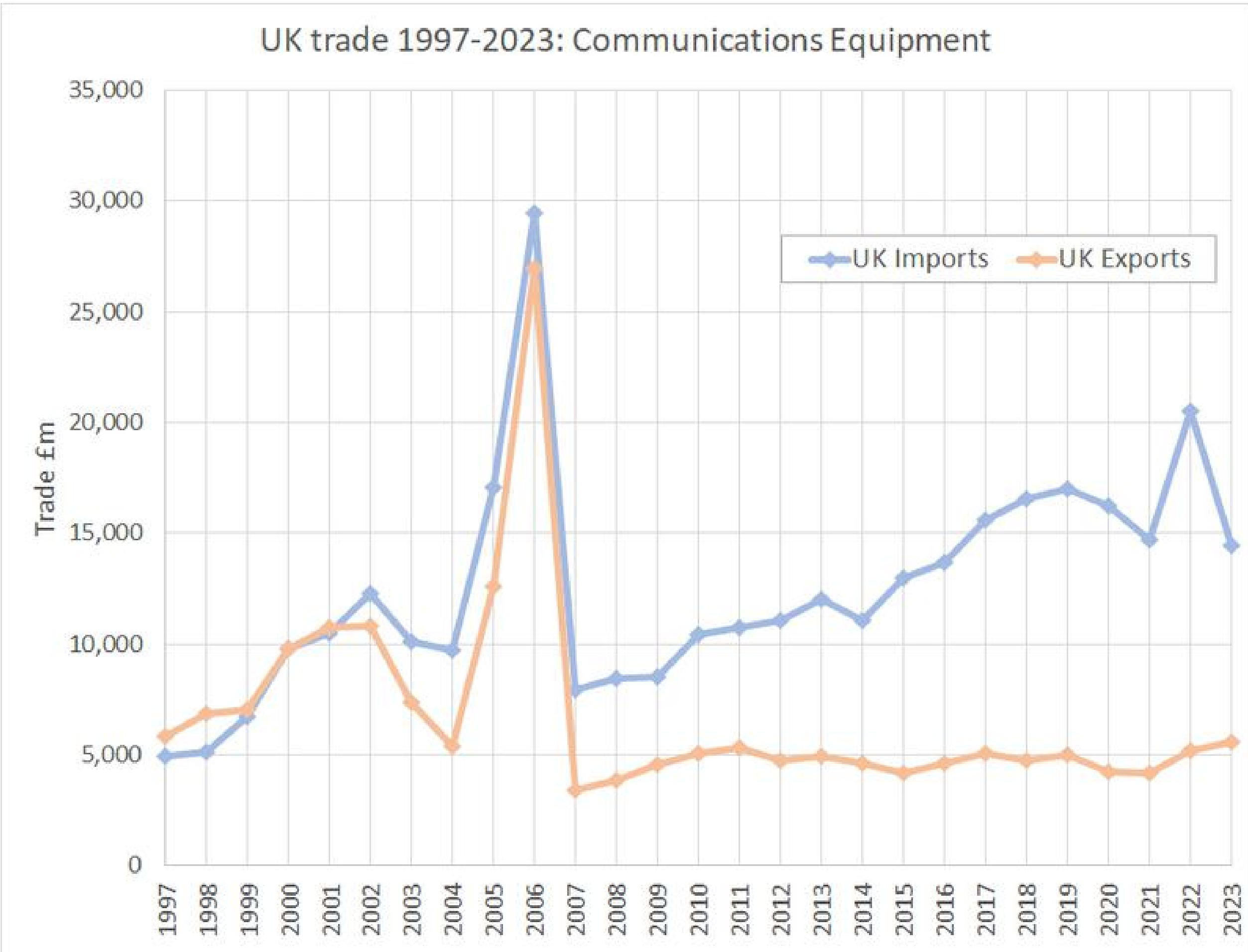


Figure 7 UK trade 1997-2023 Communications Equipment. The peak in both imports and exports for this time series in Q1/Q2 2006 is due to trade fraud [36].

[34] Charles K. Kao Wikipedia profile
[35] Photonics.Org
[36] Overseas trade in goods statistics methodology and quality report

2.8.1/ Background

The UK has around 200 businesses in Photonic communications. This is shown as a heatmap in (Figure 6) Photonics UK breaks these down as follows:

- 31 system suppliers,
- 75 subsystem suppliers,
- 55 photonics supply chain,
- Output estimated at c£2bn; £1bn GVA; c10k employees.

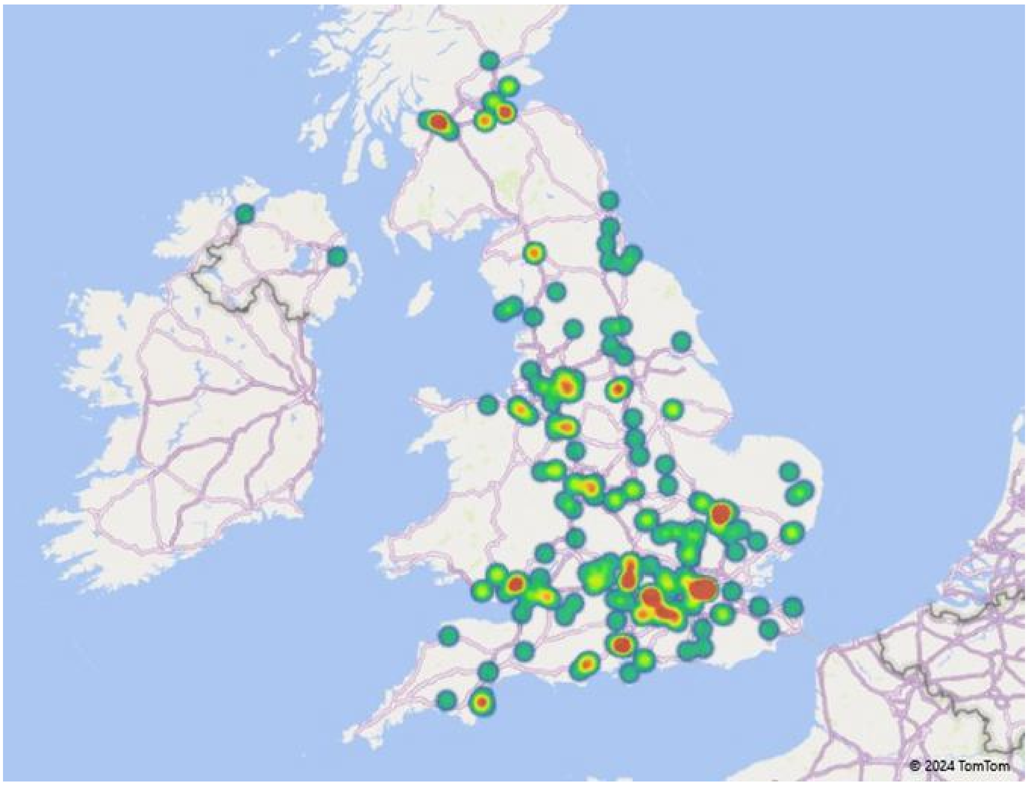


Figure 8 Heatmap of UK organisations in optical communications and photonics (courtesy John Lincoln, Photonics UK).

The UK also has a leading research base in optical comms:

- Long history of innovation in optical communications.
- EPSRC funding of >£150m in optical communications & optoelectronics.
- Quantum communications hub +£50m.
- Strong international collaborations.

However, there is a challenge to turn research into industry exploitation:

- Lack of cohesion in the ecosystem.
- Early- and growth-stage investment is difficult to obtain.
- No major UK based communication system integrators to drive vision and pursue novel applications.

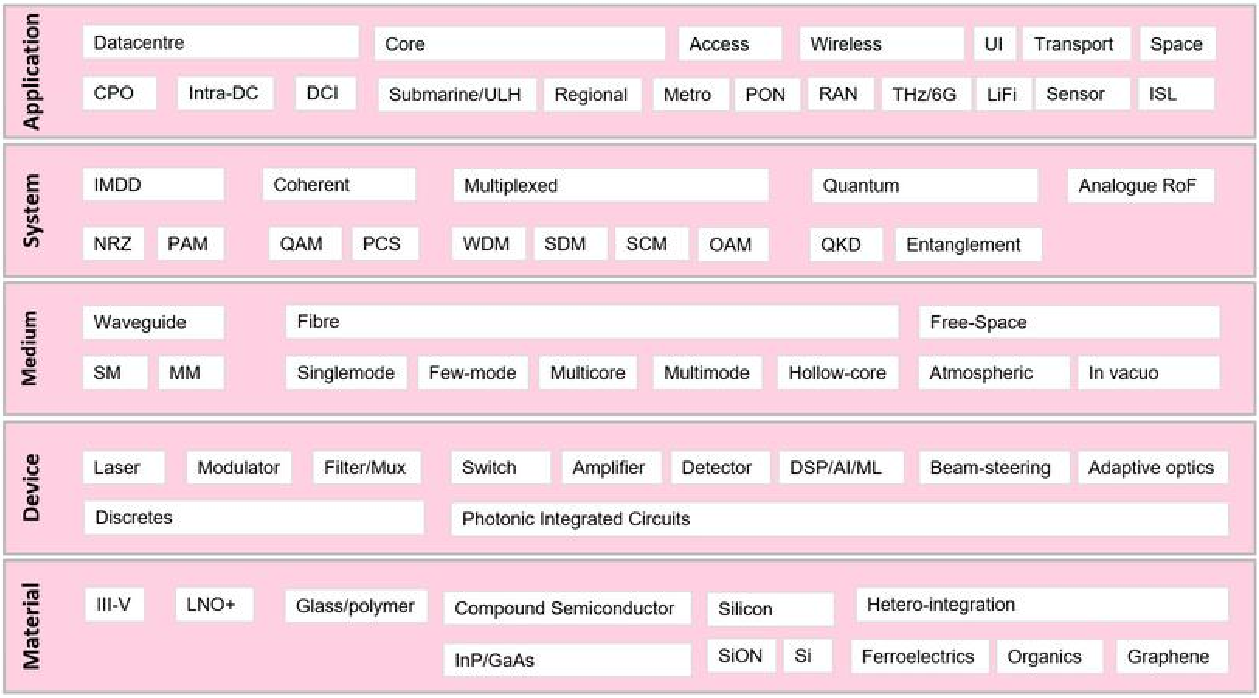


Figure 9 High Level Taxonomy for Optical Communications and Photonics technologies – Courtesy Nick Parsons

A rough illustration of the breadth of applications and technologies covered by the field of optical communications and photonics is shown in Figure 7. Value is added at each layer of the supply chain and, while the greatest value creation and revenue opportunities clearly exist at the system and application layer, such opportunities could not exist without the critical supporting materials and device technologies. Consequently, to accelerate growth in this sector it is vital that we stimulate cohesion and innovation across this ecosystem, from photonics chips through to advanced communication systems.

A brief description of each element is summarised in Table 3 below.

Table 3 Summary of Ecosystem tier.

Ecosystem tier	Element	Description	Section ref
Application	Datacentre	Hyperscale datacentres use high-speed optical interconnects both internally (intra-DC) and between DC locations. Optics is steadily moving closer to the electronics; co-packaged optics (CPO) brings interfaces as close as possible to the silicon processor chips	2.3
	Core	Core optical communications spans trans-oceanic (submarine) and trans-continental ultra-long haul (ULH) distances, through regional and metro networks	2.1
	Access	Distribution of broadband data towards end-users employs tree-structured passive optical networks (PONs) to achieve minimum cost per user	2.2
	Wireless	Radio access networks (RANs) connect wireless antennas to the core. Future 6G wireless will require (sub)-THz carrier frequencies to achieve the desired data rates.	2.4
	UI	The user interface (UI) is typically a smartphone connected wirelessly by 5G, WiFi or future Light Fidelity (LiFi) media	2.4
	Transport	Increasing need for high bandwidth optical connectivity within moving platforms (automotive, rail, air, sea) both for users and for sensor fusion in autonomous systems	
	Space	Non-terrestrial networks are starting to deploy optical communications for high bandwidth inter-satellite links and also space-ground comms where atmospherics permit.	
System	IM/DD	Intensity modulation/direct detection systems are the cheapest to deploy at any data rate and use various modulation formats, including non-return-to-zero (NRZ) and pulse amplitude modulation (PAM), especially for short-reach (e.g. DC) applications	2.4
	Coherent	Borrowing from modern radios, coherent systems use lasers at both transmitter and receiver. Exploiting the phase information in an optical carrier, quadrature amplitude modulation (QAM) and probabilistic constellation shaping (PCS) can be used to extract maximum capacity within a transmission band.	
	Multiplexed	Techniques used to combine multiple data streams onto a single transmission medium include wavelength-division multiplexing (WDM), space-division multiplexing (SDM) and sub-carrier modulation (SCM), the later exploiting coherent DSP schemes such as Open-XR. A specialised form of multiplexing can use orbital angular momentum (OAM) modes to transmit data streams in some media, typically on free-space links	2.2
	Quantum	Quantum communications is a growing and well-funded research topic of particular importance to security of future networks and applications, with two main classes. Quantum key distribution (QKD) is a relatively mature physical encryption method that exploits the quantum nature of light (photons) to exchange secret keys between users without risk of eavesdropping. Future quantum entanglement networks are envisaged to enable coherence between distributed clusters of quantum computing elements.	2.5
	Analogue	Optical networks can be used to transmit analogue radio frequency signals over fibre (A-RoF) to allow separation between base station and antennas. Of increasing relevance to 6G mm-wave and sub-THz systems where excessive bandwidths are required by conventional digital fronthaul techniques and where optics can also be used to directly convert modulation waveforms to the desired carrier frequencies.	

Study Topics

Ecosystem tier	Element	Description	Section ref
	Waveguide	Dielectric optical waveguides can take many forms and support both single-mode (SM) and multimode (MM) propagation. The basic interconnecting element of planar optical circuits, wave guides can also form passive functions such as splitting, filtering and delay lines.	
Medium	Fibre	The backbone of the internet is interconnected by single mode (silica) glass optical fibre, where information-carrying capacities are approaching fundamental limits. New fibres are emerging to enable SDM transmission including few-mode fibre, multicore fibre and variants of multimode fibre, the latter also being used for low-cost short reach applications in both glass and polymer media. Hollow-core fibre is a novel microstructured glass waveguide where light is confined to an air-filled core and so not only travels at 50% faster speeds than in glass fibre but also removes most of the scattering and nonlinear limitations of glass to enable higher capacity transmission over longer distances.	2.1
	Free-Space	Free-space optical communications can re-use many of the components used in conventional telecom networks to establish point-to-point links between satellites (in vacuo), aerial platforms and certain terrestrial locations (assuming atmospheric conditions allow) where fibre deployment is either expensive or impractical.	
	Discrete	Many photonic device functions are required to realise optical communications networks, including lasers, modulators, filters, multiplexers, switches, amplifiers and detectors. Initial systems integrated discrete devices, each of which was optimised for a particular function.	
Device	Photonic Integrated Circuits	Increasingly device functions are being combined together on an integrated photonic platform to benefit from improvements in reliability, economies of scale and device stability. Closer integration with interface electronics also improves performance and reduced power consumption. The challenge is always to find a materials platform where the benefits of integration are not outweighed by reduction in subsystem performance.	2.6
	DSP/AI/ML	Digital signal processing (DSP) techniques borrow extensively from radio systems and are often combined with optimisations using artificial intelligence (AI) or machine learning (ML) algorithms. DSPs allow systems to overcome common channel impairments such as dispersion and nonlinearity and are now an integral part of many transceivers.	
	Beam-steering	For free-space communications, beam-steering methods are needed for pointing, alignment and tracking of target beams. Adaptive optics are particularly used in terrestrial applications to overcome wavefront distortion caused by atmospheric turbulence.	
	Discrete	Discrete photonics functions use a variety of materials systems, notably compound semiconductor (III-V) materials for lasers and detectors, lithium niobate and other ferroelectrics for modulation and glass/polymer waveguides for passive functions.	
Material	Integrated	PICs can be made in a number of materials systems where association of device functions makes sense. Compound Semiconductor platforms have been used to make integrated laser-modulator devices for some time. Silicon is emerging as the favoured integration platform for complex photonics functions because of the scale and maturity of the semiconductor electronics industry. However, it does not possess the best properties for all device functions, so there is much research into hetero-integration techniques where other materials can be selectively integrated as required on a silicon platform to benefit from both the performance of heterogeneous devices and the integration economics of silicon. Examples of materials integrated into or on top of silicon include ferroelectrics (lithium niobate, barium titanate) electro-active organics and graphene layers.	

The UK has strengths in many of the above areas, but will need to be strengthened to support the larger industrial developments that we envisage in the communications and semiconductor sectors.

2.9/ SWOT Analysis

The table below sets a summary of the current strengths and weakness and the key future opportunities and threats for the UK in the field of optical communications and photonics. Each of the primary points is the considered in more detail below together with further points under each of the strengths, weaknesses, opportunities, and threats (SWOT) sections.

Strengths • Long UK track record of innovation in photonics • World leading research capability & PhD training • Industry competitive in specialised technologies • Significant research prototyping infrastructure	**Weaknesses** • Lack of major UK telecom system integrators • Low margins in access networks inhibit UK vendors • Little cohesion within the UK photonics ecosystem • Poor awareness of photonics at school/UG level
Opportunities • AI/ML & quantum need advanced optical infrastructure • Open initiatives may enable entry of smaller players • UK testbeds, interoperability labs to accelerate adoption • Grand systems challenges to stimulate collaboration • Re-engagement in international R&D partnerships	**Threats** • Increasing commoditization, dependence on Asian manufacturers • Inward investment captures advanced technology • No direct route to mass photonics manufacturing for SMEs and non-vertically integrated companies • Cost of R&D a barrier to market entry for SMEs • UKRI PhD training becoming globally uncompetitive

2.9.1/ Strengths

The following are seen at the current strengths the UK has in optical communications and photonics.

Long UK track record of innovation in photonics

- Photonics clusters in Southampton / Cambridge / Scotland (optical communications and photonics research excellence of golden triangle).
- Substantial UK quantum technology research programme.
- Hollow core fibre: The UK has a leading position in research and development of this disruptive technology. The first low loss hollow core fibre (HCF) technologies was develop by Lumenisity, a spinout company of Southampton University. Lumenisity was recently acquired by Microsoft. The UK continues to lead HCF research across several universities, including Southampton, Bath and Heriot-Watt.
- Space division multiplexing and new spectrum bands: The UK has pioneered optical amplifiers and has continued to conduct world leading research into new bands and multicore amplifiers.

World leading research capability & PhD training

- Multiple world-leading university research groups.
- Strong UK and worldwide academic-industry collaborations in optical communications.
- World leading training at PhD level through funded Centres for Doctoral Training.
- Digital signal processing (DSP): world leading research in leading UK universities include Bangor University (DSP Centre of Excellence), University College London, University of Cambridge and Aston University.
- Optical wireless communications (OWC) research clusters in leading UK universities and research centres including Universities of Cambridge, Edinburgh, and Northumbria; as well as LiFi R&D Centre and Fraunhofer UK.
- Recently funded TITAN hub with 17 universities supported by 4 industrial partners working on the interfaces of wireless communication technologies.

Industrial competitiveness in specialised technologies

- Soft power associated with UK history in this field, ranging from BT Labs, STC, Plessey, Marconi, Bookham etc; academic strengths, origins of ECOC, PLG, OFC, etc.
- First commercial deployments of quantum key distribution (QKD) for securing financial data.
- Expert R&D for integration of photonic and electronic technologies, differentiated photonic integrated circuit (PIC) design and packaging capabilities, and emerging materials for improved performance.
- Compound semiconductor growth and fabrication expertise[37], both captive to photonic component suppliers and foundry services.
- Optical switch: while there are few all-optical switching companies globally, the UK has a leading optical circuit switch (OCS) manufacturer[38],
- Leading LiFi start-up (pureLiFi, Edinburgh).
- Healthy if disjointed ecosystem of SMEs/start-ups on enabling optical technologies.
- Several privately funded UK start-ups aiming to exploit photonics for distributed quantum computing (QC) and AI datacentres.

Significant research prototyping infrastructure

- Flexible multi-project wafer offering for chip prototyping in the UK.
- Member of EU Chips-JU, to facilitate partnerships with EU.
- Government support through UKRI funding, including EPSRC Programme Grants.
- Mature government funded (Innovate UK) programmes facilitating technology translation.
- Growing number of silicon photonics SMEs.

Strongly developed access infrastructure

- Plethora of service providers deploying fibre to the premises (FTTP) across the country.
- Over 50% of premises have access to FTTP and 80% expected by end of 2026.
- Remaining 20% expected using government funded programmes.

Standards involvement in emerging technologies

- standardisation of OWC technologies through the Light Communications 802.11bb Task Group chaired by pureLiFi.

[37] Lumentum fabrication at Caswell as an example of captive and IQE as foundry service.
[38] www.polatis.com

2.9.2/ Weaknesses

The following are seen at the current weaknesses the UK has in optical communications and photonics.

Lack of major UK telecom system integrators

- There are no UK-based telecom equipment vendors or systems integrators
- Lack of focus on low-power, high-density, low-cost at network & system level

Low margins in access networks inhibit UK vendors

- Due to the narrow margins in access networks, there are very few vendors worldwide that are able to supply access equipment
- Solutions to increase mobile cell capacity beyond existing 5G/3.5GHz deployments will be difficult as technologies for small cells (antennas using 26GHz region and RAN transport) remain expensive

Little cohesion within the UK photonics ecosystem

- Integrated photonics ecosystem is not established; requires collaboration between R&D, start-ups, service providers, and system integrators
- Industry involvement, adoption, and support for optical wireless comms (OWC) research is limited
- No major UK-based silicon photonics company or high-volume foundry

Poor awareness of photonics at school/undergraduate level

- In contrast to some other industry sectors such as space and sub-atomic physics, the syllabus of physics for A level and for both physics and electronic engineering degrees at undergraduate level give little or no visibility to optical communications or photonics so there is little awareness of the career opportunities at this early stage.

Training

- Insufficient training at graduate / technician level.
- Only one active network operator (BT) with an R&D activity, guiding training & skills needs.
- Limited R&I/D employment opportunities in industry.
- No major network equipment manufacturers or sub-system suppliers headquartered in the UK to strongly guide skills and training agenda.
- Local investment decisions in skills and training made abroad, often with limited awareness of UK
- Dependency on importing people due to limited interest of UK nationals in PG courses.
- No dedicated Catapult Centre, though stronger linkage possible via Compound Semiconductor Applications Catapult (or High Value Manufacturing Catapult).

Gaps for Data Centre network evolution
- Co-design of resilient, modular, scalable AI compute network solutions.
- Faster high-radix optical circuit switching.
- Fast & intelligent network control, monitoring, management.
- Limited public investment to capture AI infrastructure market opportunity.

Technology availability
- Quantum key distribution (QKD) key rates are still relatively slow and range-limited.
- Distributed QC clusters will need advanced optical interconnects for a future quantum internet.
- Limited availability of photonics design software and optical wafer scale test provision.
- UK funding to participate in EU Chips-JU at £5M to get 'foot in the door'.

Competitiveness in international market
- Slow translation from IP to high-volume products for LiFi and free space optics (FSO) technologies.

2.9.3/ Opportunities

The following are seen at the future opportunities for the UK in optical communications and photonics.

AI/ML & quantum need advanced optical infrastructure

Open initiatives may enable entry of smaller players
- O-RAN may open the vendor supply chain to smaller players.
- Large number of service providers deploying FTTP might benefit of participation in standards, giving UK a more influencing role.

UK testbeds, interop labs to accelerate adoption
- Transmission Networks Evolution: Network Platform Testbeds.
- Transmission Networks Evolution: Optical networks for future radio networks, x-haul micro cells.
- Utilize UK interoperability testing, e.g. JOINER[39] for UK inter-operability testing for the FTTP & O-RAN technologies.
- Expansion of SONIC labs to include OWC for interoperability testing.

Grand systems challenges to stimulate collaboration
- Form an integrated ecosystem

[39] University of Bristol, Smart Projects, JOINER

2.9.4/ Threats

The following are seen at the future threats to the UK in optical communications and photonics.

Increasing commoditization, dependence on Asian manufacture

- Standards dominated by Chinese companies drives volumes and hence influence standardisation. This constrains the UK service providers strategies, being forced to follow Chinese service providers strategies. (Note that American and Japanese companies have a higher influence than European companies, including UK).
- The UK RAN market is dominated by 2 mobile equipment vendors, none of them British, that can be used by MNOs. There are other (non-Chinese) smaller equipment manufacturers based in Asia like Samsung, Rakuten, and NEC among others.

Inward investment captures advanced technology

- While the UK creates many leading ideas and does create many good start-up companies, these companies normally aim to be purchased by a larger player which is almost always owned and controlled from outside the UK.

No direct route to mass photonics manufacturing

- RF solutions still dominate the market which may delay advancing and adopting OWC systems.
- No defined standards for FSO equipment Interoperability which makes joint missions/collaborations difficult.

Cost of R&D a barrier to market entry for SMEs

- Lack of investment in system inter-operability potentially leads to vendor lock-in.
- High development cost of Integrated photonics devices required to bring technology from lab to commercially viable exploitation is a barrier for start-ups/small companies.

UKRI PhD training becoming globally uncompetitive

- International competition in R&D that can translate into IP generation.
- Stand-alone UKRI PhD level training is increasingly globally uncompetitive.
- UK technical expertise could wane due to lack of industry drive and good opportunities.
- Strong international competition for talent at all levels.
- Geopolitical factors impacting on international R&I collaborations and attractiveness of UK-based student training at MSc/PhD-level.

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Competitiveness

- Introduction of low latency services forces service providers to deploy more (small) datacentres like resources, which are high in power consumption.
- Lack of interoperability may make it difficult to sell “glass-only” services or change service provider in the FTTP space.

Funding

- Without UK government funded programmes, many rural areas may be left without access to FTTP.
- Without the right radio and transport technologies, deployment of small cells may be very limited.

Abbreviations

5G-NR	5G new radio
AP	Access point
APDs	Avalanche photodiodes
AI	Artificial intelligence
CAGR	Compound annual growth rate
CMOS	Complementary metal-oxide semiconductor
CPO	Co-packaged optics
CPU	Central processing unit
CU	Central unit
DCI	Data centre interconnect
DSP	Digital signal processing
DU	Distributed unit
Euro-QCI	Euro Quantum Communication Infrastructure
EMI	Electro magnetic interference
EPSRC	Engineering and Physical Sciences Research Council
EWG	Expert Working Group
FSO	Free space optics
FTTC	Fibre to the cabinet
FTTP	Fibre to the premises
GaAs	Gallium arsenide
GPU	Graphics processing unit
GVA	Gross value added
HCF	Hollow core fibre
IM/DD	Intensity modulation/ direct detection
InP	Indium phosphide
IoT	Internet of things
IP	Intellectual property
IPSR-I	Integrated Photonic Systems Roadmap-International
IRS	Intelligent reflecting surfaces
LED	Light-emitting diodes

LiFi	Light fidelity
LoS	Line-of-sight
M	Spatial channels
MCF	Multi-core fibre
ML	Machine learning
MZI	Mach Zehnder Interferometer
mmWave	Millimetre wave
O-RAN	Open radio access network
OCC	Optical camera communications
OCS	Optical circuit switch
OEO	Optical-electrical-optical
OLEDs	organic LEDs
ORC	Optoelectronics Research Centre
OWC	Optical wireless communications
PICs	Photonic integrated Ccircuits
PON	Passive optical network
PtP	Point-to-Point
QC	Quantum computing
QCSE	Quantum confined stark effect
QKD	Quantum key distribution
R&D	Research and development
RAN	Radio access network
RF	Radio frequency
ROADMs	Reconfigurable optical add drop multiplexers
RU	Radio unit
SDM	Space division multiplexing
SE	Spectral efficiency
SiGe	Silicon germanium
SiN	Silicon nitride
SiPh	Silicon photonics
SMEs	Small and medium-sized enterprises

Abbreviations

SOI	In silicon on insulator
SONIC	Labs SmartRAN Open Network Interoperability Centre
SWOT	Strengths, weaknesses, opportunities, and threats
TDMA	Time division multiple access
TPU	Tensor processing unit
TWDM-PON	Time & wavelength division multiplex passive optical network
UE	User equipment
UI	User interface
UKTIN	UK Telecom Innovation Network
UKTL	UK Telecoms Lab
UV	Ultraviolet
VLC	Visible light communications
WDM	Wavelength division multiplex
WDM-PON	Wavelength division multiplex passive optical network
WSS	Wavelength-selective switch

Contributors

Members of the Expert Working Group are listed below. Members are voluntary, selected via an open selection process, and participate in an independent capacity, not on behalf of their organisations. Organisation of the contributors are at the time of drafting this report.

Chair: Nick Parsons, nick.parsons@hubersuhner.com
Secretariat: Ulrike Obst, ulrike.obst@bristol.ac.uk

Contributors	Organisation
Nick Parsons	CTO Communications, HUBER+SUHNER
Andy Reid	Sector Specialist, University of Bristol
Justin Boon	Telecom-Systems Engineering Specialist, University of Bristol
Ulrike Obst	Senior Research Project Manager, University of Bristol
Lidia Galdino	System Engineering & Innovation Manager, Corning
Graham Reed	Deputy Director & Professor of Optoelectronics Research Centre, University of Southampton
Albert Rafel	Optical Networks Consultant, BT
Wladek Forysiak	Professor in Applied Physics, Aston University
Mark Rushworth	Founder and CEO, Finchetto
David Neilson	Leader of the Optical Transmission Group, Nokia Bell Labs
Hanaa Abumarshoud	Lecturer (Assistant Professor), James Watt School of Engineering
Michael Wale	Professor of Integrated Photonics, University College London
Rui Wang	Lecturer, University of Bristol
Andrew Shields	Head of Quantum Technology Division, Toshiba Europe