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Unlocking the Future with Photonic Integrated Circuits: A Strategic Technology and Market Outlook

Catapult Compound Semiconductor Applications

UKRI Innovate UK

Executive summary

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Photonic integrated circuits (PICs) are emerging as a transformative technology, enabling faster, more efficient and scalable systems across various applications, including communications, computing, sensing and quantum technologies. Unlike traditional electronic integrated circuits that rely on electrons, PICs use photons to process and transmit information, offering superior bandwidth, lower latency, reduced power consumption, and resilience to electromagnetic interference.

This report provides a comprehensive market and technology outlook for PICs, examining material platforms, applications across multiple sectors, technical challenges, and opportunities for the UK to lead.

The global PIC market is projected to expand from $3.9 billion in 2024 to $54.5 billion by 2035, with a compound annual growth rate (CAGR) of 24%. Growth is driven by established sectors such as data centres and telecoms, alongside high-growth emerging applications in quantum technologies (56.1% CAGR) and sensing (47.5% CAGR).

Several material platforms underpin PIC development, each with distinct advantages: silicon-on-insulator and silicon photonics dominate due to CMOS compatibility and scalability; silicon nitride provides ultra-low loss and visible-spectrum operation; indium phosphide is critical for efficient light generation; and thin-film lithium niobate is advancing high-speed modulation and quantum-ready systems.

PICs are already reshaping 5G/6G networks, data centres and LiDAR systems, while also enabling breakthroughs in biosensing, healthcare diagnostics, environmental monitoring, AI acceleration and quantum computing. These advances are complemented by co-packaged optics, which bring photonic and electronic components together to improve performance and energy efficiency.

However, challenges remain. High initial prototyping costs, packaging complexity, immature design ecosystems and thermal management issues continue to slow adoption. Overcoming these barriers requires investment in design automation, scalable packaging solutions and cross-sector collaboration.

The UK is well-positioned to lead in PIC innovation. The photonics sector contributes £18.5 billion annually to the economy and supports over 84,000 jobs, making it one of the most productive UK manufacturing industries. With its expertise in compound semiconductors, strong academic base, and innovation-led companies, the UK can expand its leadership by embedding PICs into national AI and quantum strategies, scaling up manufacturing, and developing specialist skills.

Executive summary

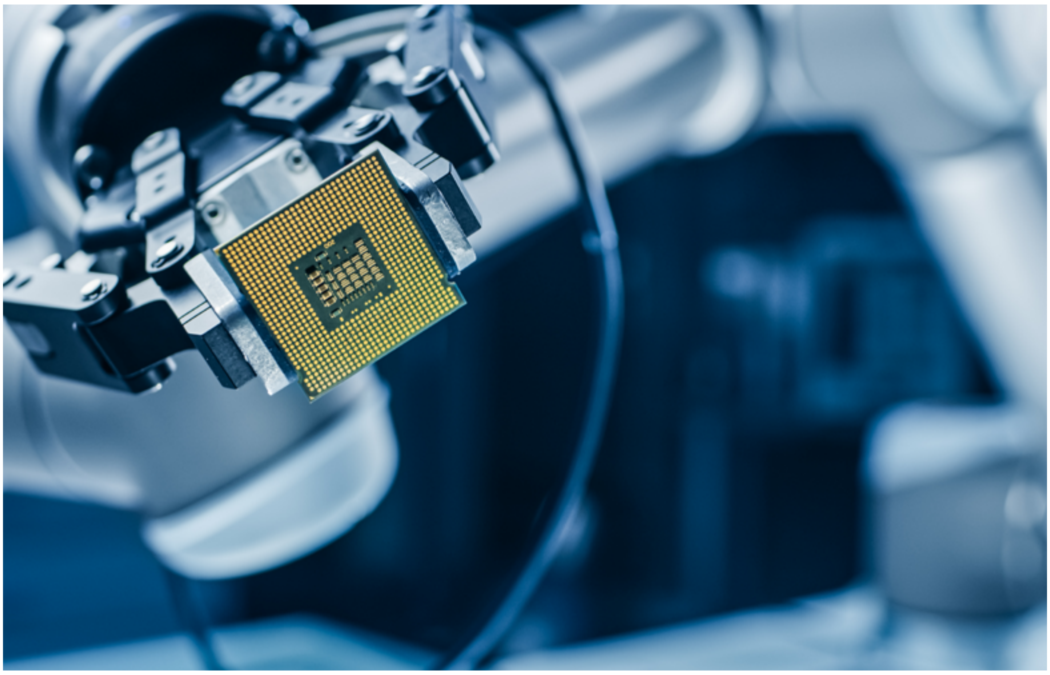
To secure long-term leadership in PICs, the UK should:

1. **Invest in scale-up, manufacturing and supply chain capacity** – establish pilot and production facilities and strengthen domestic supply chains to bridge the gap between research and industrial deployment, enhancing the UK's technological sovereignty.
2. **Embed PICs within national AI and quantum strategies** – position PICs as a core enabler of the UK's 10-year compute roadmap and national quantum programmes.
3. **Strengthen integration and prototyping capabilities** – expand co-design, packaging and validation services to reduce adoption risk and accelerate innovation.
4. **Develop specialist talent pipelines** – expand training, apprenticeships and fellowships to address skills gaps in photonic design, packaging and testing.
5. **Promote cross-sector adoption and international collaboration** – showcase PIC applications across telecoms, data centres, healthcare and quantum, while fostering global partnerships to secure market competitiveness.

CSA Catapult is central to delivering these outcomes, providing co-design and co-packaging platforms, reusable IP and scalable prototyping services. By acting as a national integration hub and skills enabler, the Catapult is working to accelerate industrial adoption of PICs, strengthen the domestic supply chain, and secure the UK's position as a global leader in photonics.

Introduction

Introduction



Integrated circuits (ICs) are compact electronic assemblies that integrate transistors, resistors, capacitors and diodes onto a single semiconductor chip. Their miniaturisation revolutionised electronics by replacing bulky, complex setups with smaller, more reliable and energy-efficient designs.

ICs form the foundation of modern technology, enabling everything from smartphones and consumer electronics to industrial automation and scientific instruments. Their benefits include improved functionality, faster processing, cost-effective manufacturing, and broad application versatility, which have allowed them to evolve alongside increasingly sophisticated technological demands.

However, as chip sizes continue to shrink, the semiconductor industry is approaching the limits of Moore's Law. By around 2036, adding more components to a single wafer will become increasingly impractical.[1] At the same time, data-driven technologies such as big data, IoT and AI are creating unprecedented strain on digital infrastructure.

Global data creation is expanding rapidly, projected to rise from 149 zettabytes[i] in 2024 to more than 394 zettabytes by 2028. This surge began in 2020, when remote working, online education and home entertainment during the COVID-19 pandemic drove record levels of data creation and replication. Storage capacity is rising in parallel, with the installed base expected to grow at a 19.2% CAGR between 2020 and 2025, after reaching 6.7 zettabytes in 2020.[2]

[i] Zettabyte is approximately equal to a thousand Exabytes, a billion Terabytes or a trillion Gigabytes.

Introduction

Volume of data/information created, captured, copied and consumed worldwide from 2010 to 2023 with forecasts from 2024 to 2028 (in zettabytes)

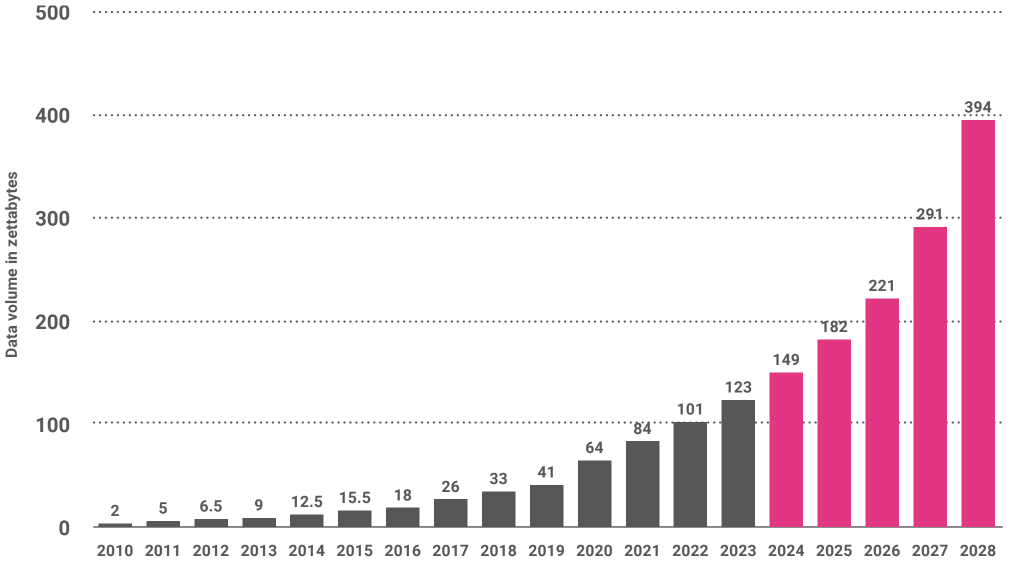


Figure 1: Volume of data/information created, captured, copied, and consumed worldwide. (source: Statista)

The growing volume of data is directly affecting energy consumption. In 2022, data centres consumed around 333 TWh of electricity, accounting for roughly 1.3% of global demand. By 2030, this figure is projected to exceed 1,000 TWh, nearly tripling to around 3.7% of worldwide use.[3]

Electricity consumption of data centres worldwide in 2022 with forecasts until 2030 (in terawatt-hours and as a percentage)

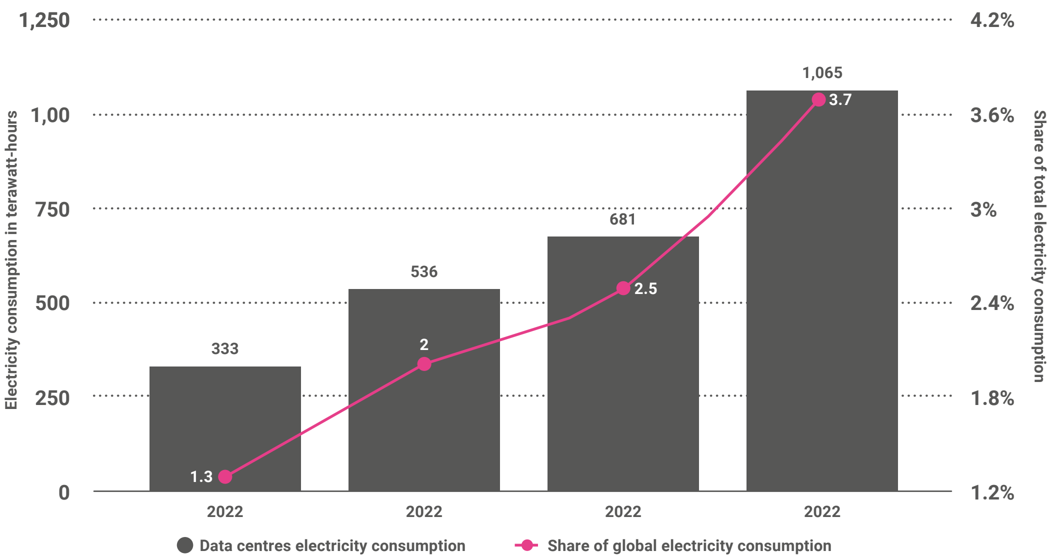


Figure 2: Global data centre electricity consumption. (source: Statista)

To address these bottlenecks, photonic integrated circuits offer a promising alternative. By transmitting data using light instead of electrical signals, they have the potential to reduce energy consumption and enable the scalability required for future digital infrastructure.

Introduction

What is a photonic integrated circuit?

A photonic integrated circuit (PIC), also known as a planar light wave circuit or an integrated optical circuit, integrates multiple photonic components onto a single microchip. These circuits generate, guide, manipulate and detect light, handling information as optical signals.[4]

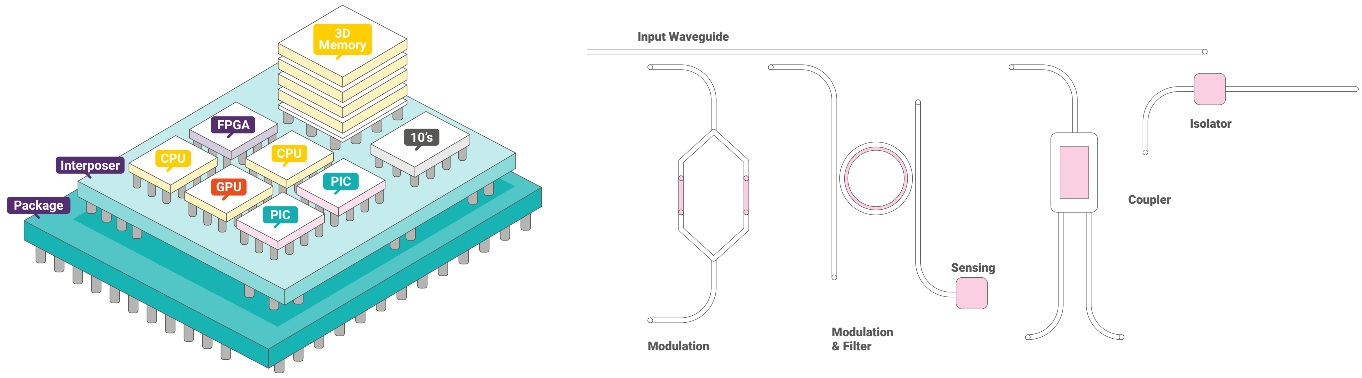


Figure 3: Illustration of heterogeneous integration (left), where CPUs, GPUs, Field-Programmable Gate Array (FPGAs), PICs and 3D memory are combined on a common interposer within a single package. The right-hand schematic shows typical PIC building blocks.

PICs incorporate a variety of optical elements, including waveguides, lasers, modulators, amplifiers and photodetectors. By integrating these on a single chip, they achieve compactness and high reliability while offering significant advantages over electronic circuits, such as higher bandwidth, lower power consumption, faster data transmission, and reduced sensitivity to electromagnetic interference.

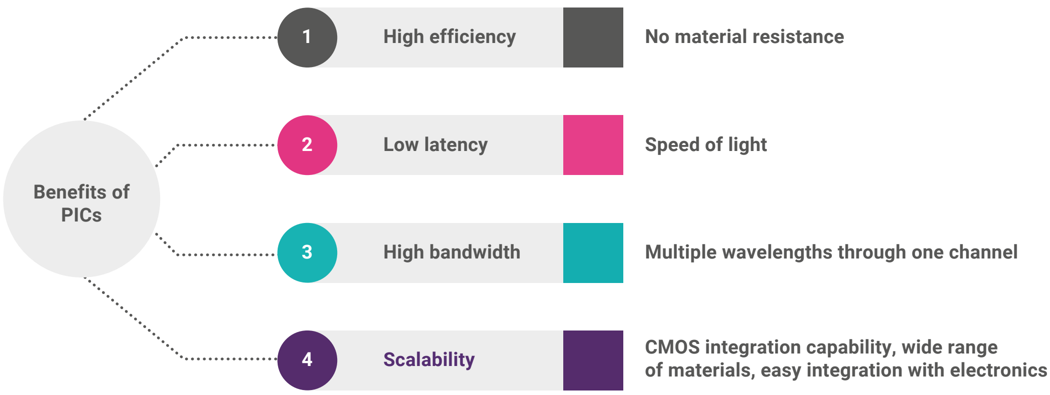


Figure 4: Key benefits of PICs. Their high efficiency arises from the absence of electrical resistance; low latency is enabled by transmission at the speed of light; high bandwidth is achieved by multiplexing multiple wavelengths through a single channel; and CMOS compatibility, diverse material platforms, and straightforward integration with electronics support scalability.

Industry and academia are actively developing PICs for applications in telecommunications, computing, sensing and quantum technologies, where these benefits are critical.

Introduction

PICs vs. electronic ICs

PICs and electronic ICs share a similar foundational concept, integrating multiple components onto a single microchip to process information. However, they differ fundamentally in the nature of the signals they handle and the components they employ.

Signal type and transmission

Electronic ICs process electrical signals through the movement of electrons in conductive materials such as silicon. In contrast, PICs use photons (particles of light) to carry information, typically operating within the visible and near-infrared range.[4] This enables data transmission at the speed of light, offering higher bandwidth and lower energy loss than their electronic counterparts.

Components and activation

Electronic ICs are composed of transistors, resistors, capacitors and diodes, which require electrical power to operate. These elements control the flow of electrons to perform logic and memory functions. PICs, as noted earlier, employ optical components that are driven by light sources, typically lasers, rather than electrical switches.

Efficiency and performance

Electrons, due to their interaction with other particles and resistance in conductive materials, generate heat and experience energy loss. Photons, being virtually frictionless, can travel faster and more efficiently, making PICs ideal for high-speed, low-power applications. This efficiency also reduces thermal management requirements in densely packed systems.

Fabrication and design

In electronic ICs, the transistor is the dominant building block. In contrast, PICs do not rely on a single dominant component; instead, they integrate a variety of optical elements tailored to specific functions.

Applications

Electronic ICs are the backbone of conventional computing and consumer electronics. PICs, while still an emerging technology, are increasingly used in fields such as high-speed optical communications, sensing and quantum computing. Their ability to operate in environments with minimal electromagnetic interference further enhances their appeal in specialised applications.

Introduction

Table 1: Comparative overview of electronic ICs and PICs.

Aspect	Electronic ICs	Photonic ICs (PICs)
Signal type	Electrical signals (electrons)	Optical signals (photons)
Transmission medium	Conductive materials (e.g. silicon)	Optical waveguides (e.g. silicon photonics)
Core components	Transistors, resistors, capacitors, diodes	Waveguides, lasers, modulators, photodetectors, optical power splitters and combiners, grating couplers and edge coupler
Activation	Electrical power	Light sources (typically lasers)
Efficiency	Higher energy loss, heat generation	Lower energy loss, minimal heat, high-speed
Design philosophy	Transistor-centric	Diverse optical elements tailored to function
Applications	Computing, consumer electronics	Optical communications, sensing, quantum computing
Thermal management	Requires significant cooling	Reduced cooling needs due to low heat generation
Electromagnetic interference	Susceptible	Resistant

The table above summarises the fundamental differences between PICs and traditional electronic ICs, as well as the advantages that make them attractive for next-generation systems. With this understanding established, the report now turns to the market landscape to examine where PICs are already making an impact and how their adoption is expected to develop over the coming decade.

Market landscape

Market landscape

Global PIC market forecast

The global PICs market is anticipated to expand significantly over the next decade, driven by the inherent advantages of the technology and continuous innovation. In 2024, the market was valued at $3.9 billion, with forecasts indicating a rise to $24.2 billion by 2030, and further to $54.5 billion by 2035.[5] This represents a compound annual growth rate (CAGR) of 24% between 2025 and 2035, highlighting the increasing adoption of photonic technologies across various sectors, including telecommunications, data centres, high-performance computing, sensing, and emerging fields such as quantum technologies, as discussed in the later sections.

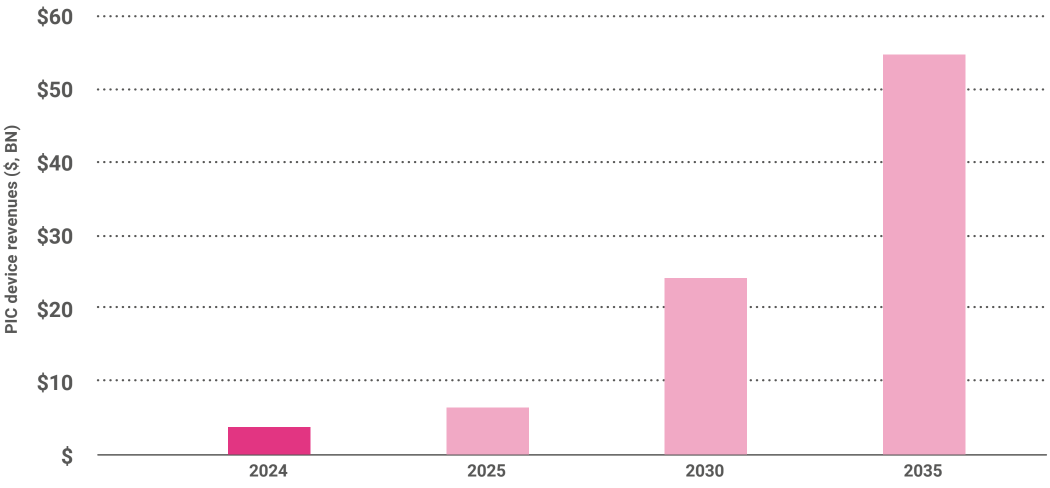


Figure 5: Global PICs market forecast. (source: IDTechEx, 2025)

Forecast by segments

An analysis of sector-specific forecasts and CAGRs reveals clear patterns in the evolving global PIC market. While datacom applications, including data centres and high-performance computing, currently dominate in market share, the fastest growth is expected in emerging sectors, particularly quantum technologies and sensor-based applications.

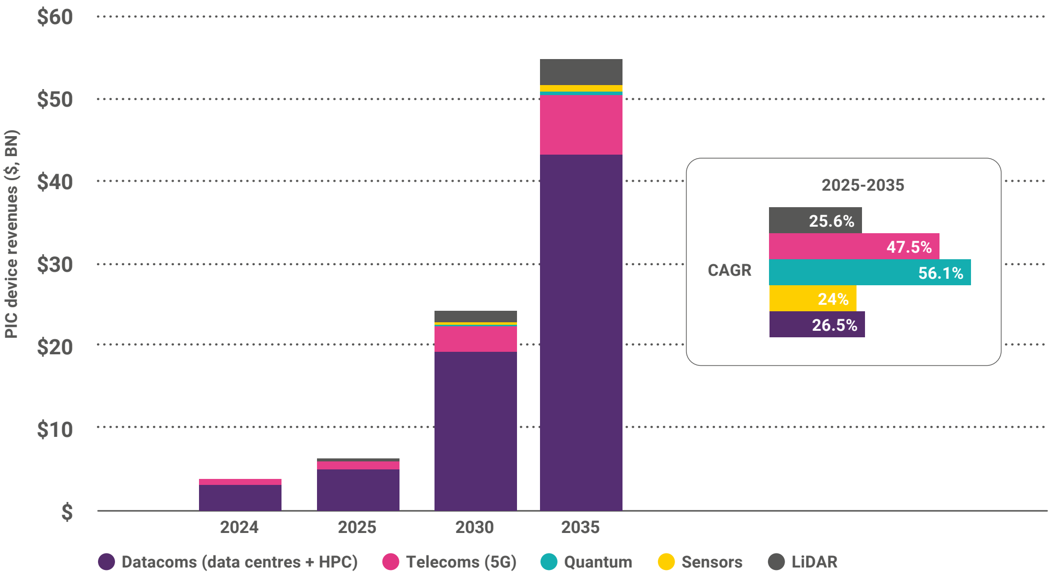


Figure 6: Global PICs market by sectors. (source: IDTechEx, 2025)

Market landscape

Between 2025 and 2035, the quantum segment is projected to grow at an exceptional CAGR of 56.1%, highlighting the central role of integrated photonics in quantum computing and communications, where scalability, low-loss routing and compact integration are essential. The sensors segment follows with a CAGR of 47.5%, reflecting strong uptake in autonomous vehicles, environmental monitoring and biomedical diagnostics — areas that benefit from miniaturisation and optical sensitivity.

By contrast, established sectors such as telecoms (24.0% CAGR) and datacoms (23.6% CAGR) expand more steadily but from a far larger base. Datacoms in particular is forecast to grow from $5.2 billion in 2025 to $43.1 billion by 2035, underscoring its continuing importance for bandwidth scaling in data-intensive systems. LiDAR, with a projected CAGR of 25.6%, shows a more measured trajectory shaped by regulatory hurdles, cost pressures, and its close ties to the pace of investment in autonomous and next-generation vehicles.

Overall, the market outlook shows a balance between steady growth in established areas and rapid expansion in emerging fields. To understand how these opportunities will be realised, it is necessary to examine the technology foundations of PICs, starting with the material platforms and integration approaches that underpin their performance and scalability.

Technology landscape

Technology landscape

The opportunities highlighted in the market outlook are underpinned by advances in the underlying PIC technology. The choice of material platform is especially important, as factors such as optical transparency, refractive index and electro-optic response directly determine device performance, fabrication complexity, and suitability for applications ranging from high-speed communications to sensing and quantum photonics.

In addition to intrinsic properties, practical considerations such as fabrication maturity and compatibility with existing CMOS-based processes strongly influence platform selection, particularly where scalable production is required. Packaging also plays a decisive role and is often overlooked in early design stages; it has a major impact on system reliability, thermal management and integration efficiency, and can introduce mechanical constraints, particularly in hybrid or heterogeneous integration.

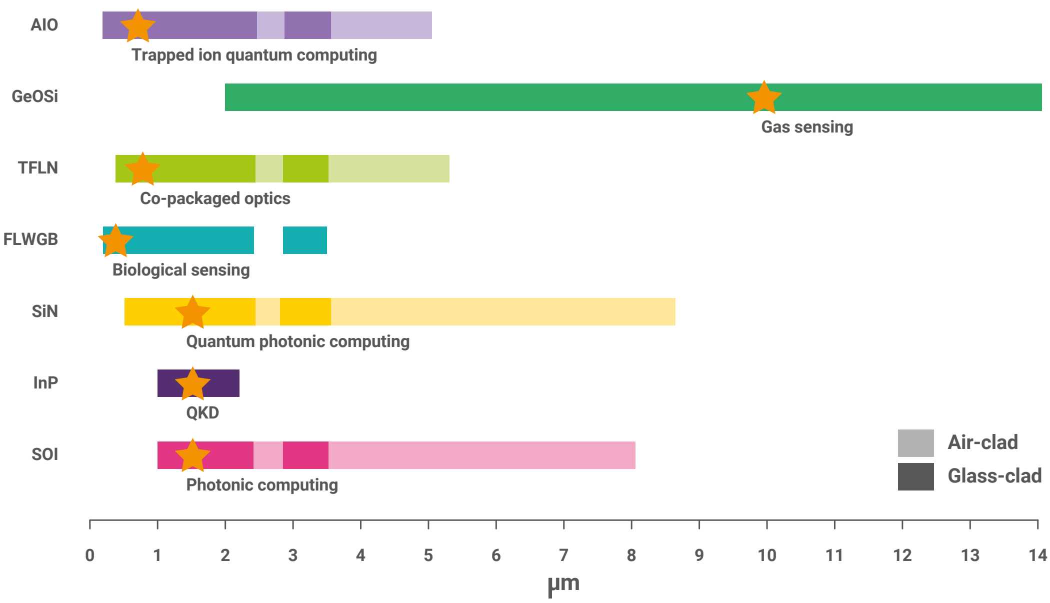


Figure 7: Spectral operating ranges of different PIC material platforms with associated application domains. Shaded regions indicate air-clad and glass-clad configurations.[6] (credit: Light Trace Photonics)

Figure 7 illustrates the operational wavelength ranges and primary application domains of several key photonic material platforms used in PICs. The next sections examine the main material platforms in detail, beginning with silicon-on-insulator and silicon photonics.

Technology landscape

Silicon-on-insulator and silicon photonics

SOI platform

Silicon-on-insulator (SOI) is one of the most widely used material platforms for PICs due to its abundance, low cost, and compatibility with CMOS manufacturing. SOI wafers consist of a thin silicon layer separated from the substrate by a buried silicon dioxide layer, which enables strong optical confinement, low propagation loss and efficient passive components. The buried oxide also reduces parasitic capacitance, supporting closer integration with electronic circuits. These attributes make SOI highly suitable for dense photonic-electronic integration on a single substrate.

Silicon photonics (SiPh)

Silicon photonics refers to the broader technology of implementing photonic functions on silicon, most commonly using SOI. It exploits the high refractive index contrast of SOI waveguides to achieve compact routing and high-speed modulation, while extending functionality through the addition of other materials: germanium for fast photodetectors, silicon nitride for low-loss broadband routing, and III-V semiconductors such as indium phosphide or gallium arsenide for efficient light sources. These are integrated via hybrid or heterogeneous bonding.

Applications

SOI-based silicon photonics underpins a wide range of applications:

- Communications: intensity modulation with direct detection (IMDD) and coherent transceivers for intra- and inter-data centre links, and emerging co-packaged optics for high-performance computing.
- Sensing: frequency-modulated continuous-wave and time-of-flight LiDAR, photonic biosensors, optical coherence tomography and gyroscopes.
- Computing and signal processing: photonic accelerators for AI, quantum key distribution, integrated single-photon detectors, and microwave photonic circuits.

Limitations and challenges

Silicon's indirect bandgap makes it inefficient as a native light emitter, necessitating integration of III-V materials for laser sources. Plasma-dispersion-based modulators, while widely used, have modest efficiency and relatively high insertion loss. Optical power loss can be significant over long waveguide lengths, and packaging remains a complex and costly process. The supporting design ecosystem also lags behind electronics, with less mature process design kits and photonic-electronic co-design workflows.

Nevertheless, SOI remains a cornerstone material for PICs, and silicon photonics is maturing as a leading integration platform. Its scalability, CMOS compatibility, and ability to incorporate multiple material systems on one substrate make it a key enabler of next-generation photonic systems.[5,7,8]

Technology landscape

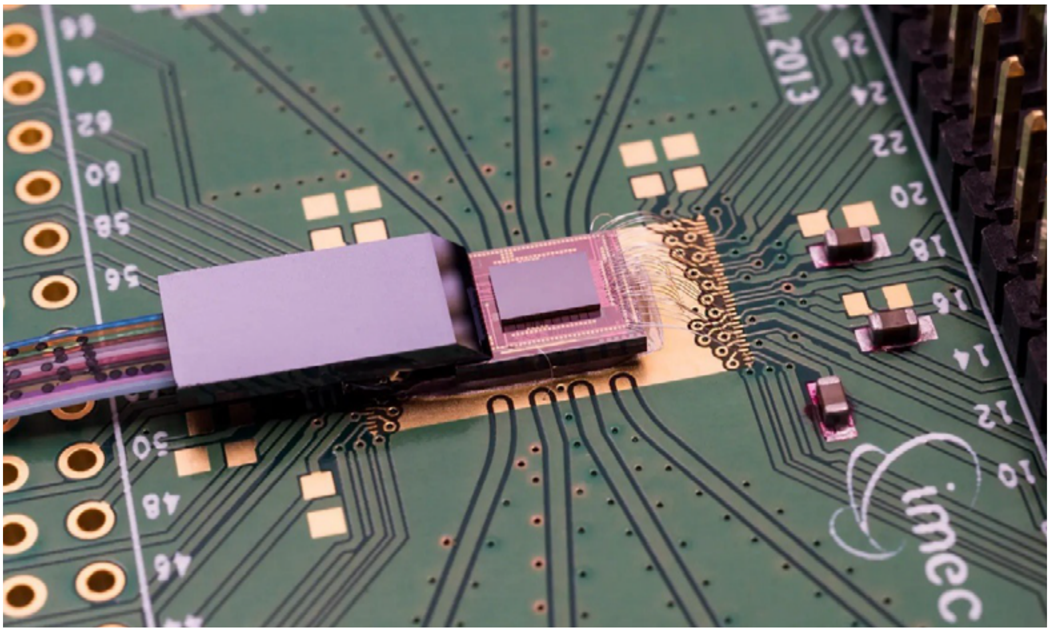


Figure 8: Imec's silicon photonics demonstrator showing 50 Gb/s performance with integrated modulators, detectors and fibre coupling. Fabricated on a CMOS-compatible platform, it also supports additional layers such as low-temperature SiN photonics and fluidics through monolithic post-processing, enabling scalable multifunctional systems.[9] (image credit: Imec)

Technology landscape

Silicon nitride

Advantages

Silicon nitride (SiN) has been part of integrated photonics since the 1970s but has gained renewed attention in recent years. Although it is less widely adopted than SOI, SiN offers several distinctive benefits. Its wide spectral window extends from the near-ultraviolet to the near-infrared, covering not only the standard telecom bands but also the visible and short-wave infrared ranges.

Equally important is its exceptionally low optical loss: SiN waveguides have demonstrated propagation losses as low as ~0.01 dB/cm, compared with ~0.5 dB/cm for silicon photonics and ~1.5 dB/cm for indium phosphide. The platform also benefits from established CMOS processing, which allows fabrication to leverage decades of semiconductor manufacturing experience.[10]

Applications

These properties support a broad set of applications.

- Life sciences: compact sensing and imaging systems, including portable diagnostic devices operating in the visible and near-infrared.
- AR/VR and quantum: integration of laser diodes and optics on millimetre-scale chips for lightweight headsets, and ultra-low-loss waveguides for quantum photonic processors.
- High-power systems: tolerance of higher optical powers than SiPh or InP, making it suitable for projection displays, LiDAR and security scanning.

Limitations

SiN also presents challenges. The material lacks native active functionality, as it cannot generate, modulate or amplify light, so it depends on hybrid integration with other materials, typically InP, for active components. Cost is another limitation: while CMOS-compatible, SiN does not benefit from the same large-scale infrastructure as SOI, making it less cost-effective for very high-volume production.[5,10]

Despite these constraints, SiN remains an essential PIC material in areas where ultra-low loss, visible-spectrum operation and high sensitivity are required.

Technology landscape

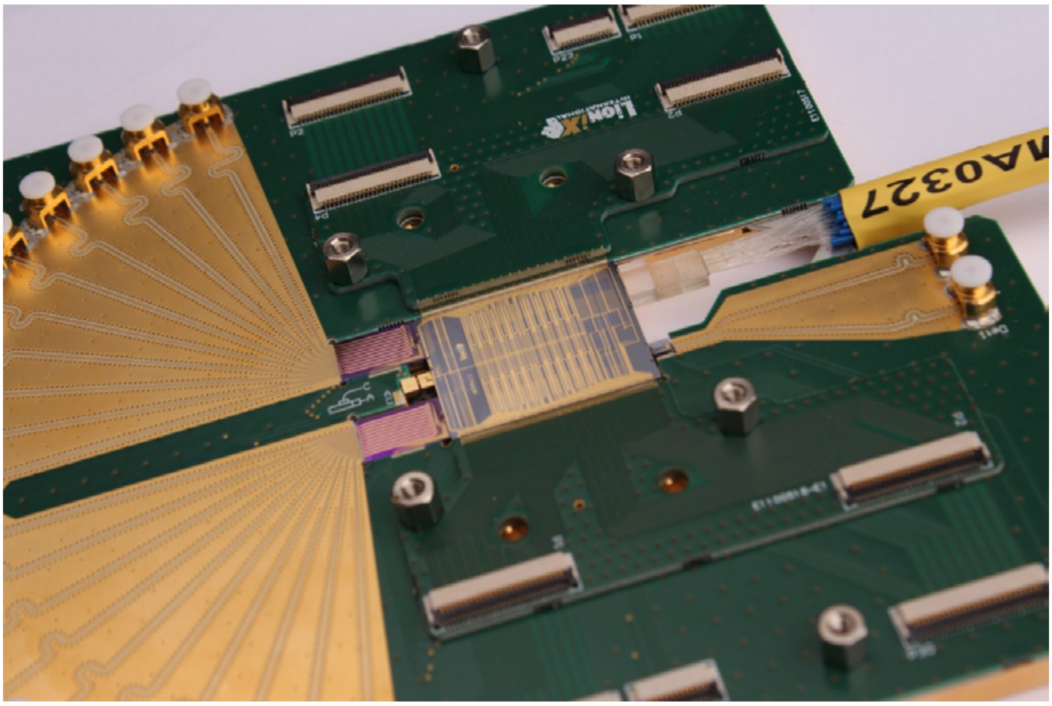


Figure 9: LioniX International's vertically integrated PIC module using TriPleX® silicon nitride waveguides. The design features ultra-low-loss passive waveguides (below ~0.1 dB/cm for the workhorse double-stripe and down to ~0.1 dB/m in single-stripe for visible/IR), efficient fibre coupling (≤ 0.5 dB/facet via spot-size converters), hybrid integration with active components (e.g. InP gain sections), and on-chip actuation (thermo-optic and stress-optic) – demonstrating a compact, high-performance module suited for telecom, sensing, quantum and microwave photonics applications.[11] (image credit: LioniX International)

Indium phosphide

Advantages

Indium phosphide (InP) is a direct-bandgap semiconductor, making it highly efficient for light generation and detection — a key distinction from silicon. It is transparent across 1050–1600 nm, covering the crucial 1550 nm telecom wavelength that underpins fibre-optic communications.[5]

Because it can emit light, InP supports the integration of lasers, modulators and photodetectors on the same chip. This allows both monolithic PICs and heterogeneous platforms, where InP is bonded with silicon photonics to combine active and passive components. Such integration yields compact, high-performance systems with low passive loss, efficient photodetection and integrated laser sources — reducing overall size, power, and cost.

Technology landscape

Applications

Although first developed for telecommunications, InP PICs are now used in a broad range of areas:[12]

- Fibre and free-space communications: compact high-power transmitters deliver long-range links while maintaining low cost, size, weight and power.
- LiDAR: InP-based beam-steering transceivers with sampled grating distributed Bragg reflector (SGDBR)[ii] lasers support two-dimensional scanning and frequency-modulated continuous-wave (FMCW) operation when combined with silicon photonic phased arrays.
- Microwave photonics: InP enables high-speed, high-linearity photodetectors and modulators for optical beamforming in millimetre-wave (mmW) wireless and phased-array systems.
- Other uses: remote sensing and advanced optical front-ends.

Limitations

InP has a narrower transparency window than silicon or silicon nitride[13] and suffers from higher optical absorption losses. It is also significantly more expensive, with wafer costs ranging from $1,000 to $2,000, and is typically manufactured on smaller 75 mm wafers compared to silicon's 300 mm wafers. This limits scalability. Integration with silicon is further complicated by lattice mismatch and thermal expansion differences,[14] which can cause defects and stress-induced cracking at high temperatures.

Despite these drawbacks, InP remains indispensable for photonic functions that silicon cannot provide, particularly in high-speed communications and other applications requiring efficient light sources.

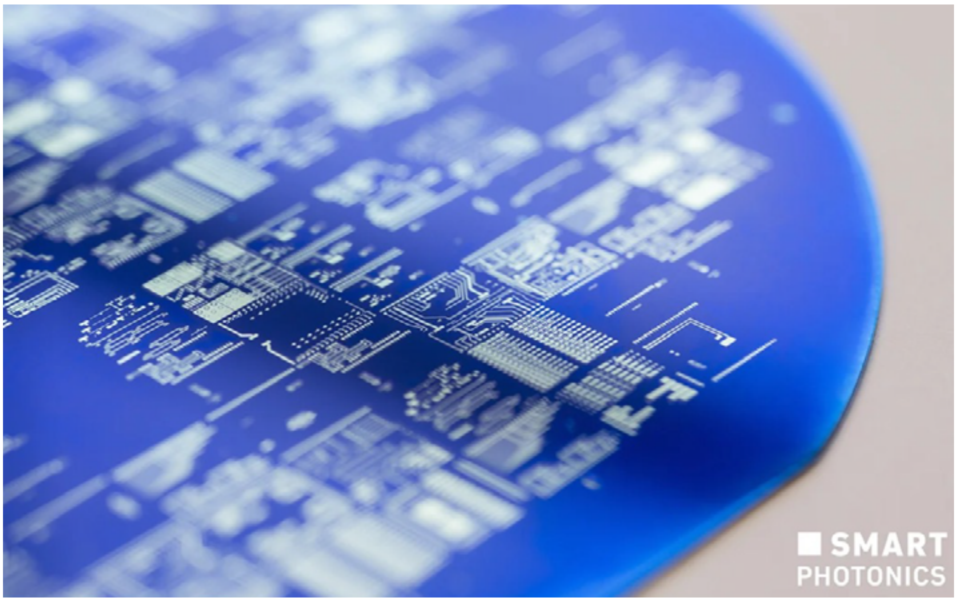


Figure 10: InP wafer with multiple chips printed, from SMART Photonics. The SMART Photonics' foundry is scaling from 3-inch to 4-inch InP wafer production, doubling output capacity and enabling higher volumes of photonic chips to meet growing demand in telecom, data-centres, LiDAR and quantum applications.[15] (image credit: Photon Delta)

[ii] SGDBR lasers, or sampled grating distributed Bragg reflector lasers, are widely tunable semiconductor lasers that use sampled gratings and multiple electrically controlled sections to achieve broad wavelength tuning for optical communication systems.

Technology landscape

Thin-film lithium niobate

Advantages

Thin-film lithium niobate (TFLN) has become one of the most promising material platforms for integrated photonics, thanks to its exceptional electro-optic, nonlinear and acousto-optic properties. Derived from bulk lithium niobate ($LiNbO_3$), TFLN combines the material's well-known optical qualities with the benefits of modern nanofabrication, enabled by wafer bonding and ion-slicing techniques.

It offers a wide transparency window from 350 nm to 5 µm, a high refractive index (~2.2), and a strong electro-optic (Pockels) coefficient ($r_{33} \approx 30.9$ pm/V). Together, these features make TFLN particularly well-suited for high-speed, low-voltage optical modulators and a broad range of advanced photonic functions.

Applications

The versatility of TFLN is reflected in its growing application base:

- Communications and data centres: high-performance electro-optic modulators for high-speed, energy-efficient optical links.
- Nonlinear and quantum optics: second-harmonic generation, quantum photon-pair production and frequency comb generation.
- Quantum transduction: conversion between microwave and optical signals.
- Acousto-optics: simultaneous guidance of light and acoustic waves enables integrated acousto-optic devices and piezo-optomechanical systems.

Limitations

Despite its strengths, TFLN faces several technical hurdles. Dry etching of lithium niobate is challenging, with sidewall roughness and redeposition degrading waveguide performance. The strong index contrast that enables compact routing complicates fibre-to-chip coupling, often requiring advanced tapering or grating couplers. Photorefractive effects and charge carrier drift can also cause instability, particularly under high optical power or low-frequency operation. Finally, electrode design is critical: while necessary for high-speed modulation, poorly optimised layouts can increase microwave losses.

Even with these challenges, TFLN's unique combination of fast modulation, low optical loss and wide spectral compatibility makes it one of the most important emerging PIC platforms. Its continued development is expected to expand its role in high-performance optical communications, quantum technologies and integrated microwave-optical systems.[16,17]

Technology landscape

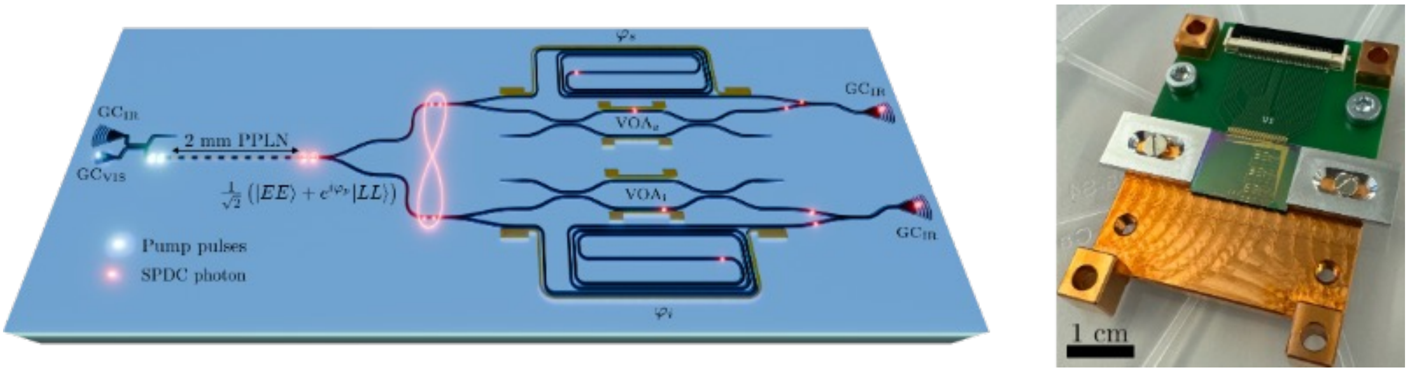


Figure 11: TFLN PIC developed at ETH Zurich for quantum communication. The device generates entangled photon pairs suitable for transmission over optical fibres, representing a key step towards ultra-secure communication networks.[18] (image credit: ETH Zurich)

Table 2: Summary of key PIC material platforms, comparing their main advantages, application areas, limitations and overall outlook.

Platform	Advantages	Applications	Limitations	Outlook
SOI / SiPh	Low cost, CMOS-compatible, scalable	Data/telecom links, LiDAR, HPC, sensing	No native lasers, moderate modulator efficiency, packaging complexity	Workhorse platform, strong industry adoption
SiN	Ultra-low loss, broad spectrum, high power handling	Biosensing, quantum, AR/VR, LiDAR	No active devices, higher cost than SOI	Niche but vital for low-loss and visible-spectrum uses
InP	Direct bandgap, efficient light sources	Telecoms, free-space optics, LiDAR, microwave photonics	Expensive, small wafers, higher losses, integration issues	Indispensable for lasers and high-speed comms
TFLN	Strong electro-optic effect, wide transparency, fast modulators	High-speed links, quantum optics, acousto-optics	Challenging fabrication, coupling, stability issues	Rapidly emerging in comms and quantum tech

Technology landscape

Emerging PIC material platforms

Apart from the main material platforms driving the PIC industry, several other materials are gaining traction for their unique electro-optic and integration properties. These emerging materials could play an increasingly important role in specialised applications, such as quantum technologies, high-speed modulation and optical amplification.

Among these, organic polymers on silicon combine strong Pockels-effect modulation with CMOS compatibility, achieving ultra-fast, low-voltage operation and compact device footprints, with demonstrations reaching data rates up to 200 Gb/s. Barium titanate (BTO), with its exceptionally high electro-optic coefficient, enables ultra-fast, low-power modulators when integrated epitaxially on silicon, and is being advanced by companies like PsiQuantum for optical switches and AI-focused interconnects.[19] Rare-earth-doped materials, including erbium, ytterbium and praseodymium, are being developed for temperature-stable, low-noise optical amplification within PICs, while aluminium oxide offers a wide transparency range and potential for visible and UV photonic applications, such as quantum sensing. Although still in early development, these material platforms are poised to play a crucial role in the evolution of high-performance, application-specific PIC technologies.[5,6]

PIC market forecast by material platform

The global PIC market remains dominated by hybrid silicon-based platforms, which account for over 92% of the market in 2024. These platforms, combining SOI, SiN, and III-V materials, continue to lead due to their maturity, scalability and compatibility with existing CMOS manufacturing infrastructure. However, by 2035, their market share is projected to decline to around 67%, reflecting growing diversification in material adoption.

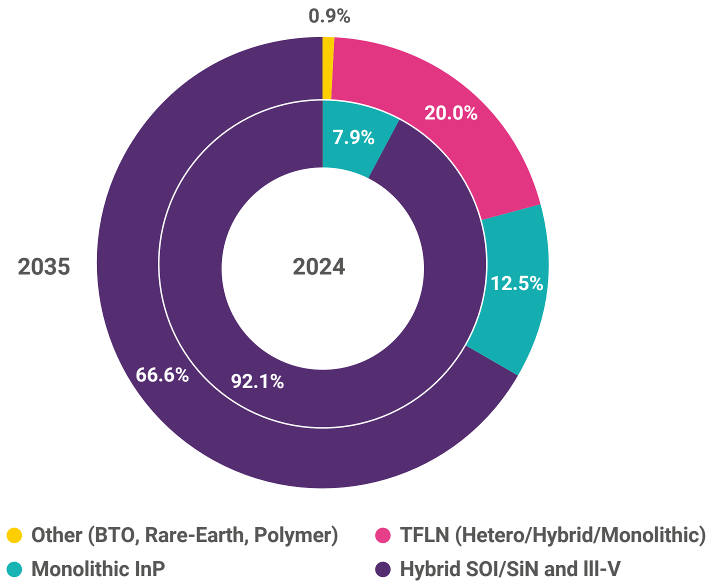


Figure 12: Global PICs market by material platforms. (source: IDTechEx 2025)

TFLN is expected to capture 20% of the market by 2035, driven by rapid advances in electro-optic modulation and heterogeneous integration. Monolithic InP platforms will hold about 12.5%, sustaining a key role in high-performance telecom and datacom applications. Meanwhile, emerging materials such as BTO, rare-earth-doped materials and polymers, which currently account for less than 1%, are projected to gain traction as enabling technologies for optical amplification, quantum applications and ultra-fast modulators.

Technology landscape

Overall, the data highlights a clear trend toward material diversification and heterogeneous integration, signalling a shift from silicon dominance to a more balanced ecosystem of high-performance photonic materials by 2035.

With the technological and material foundations in place, the next step is to examine how these platforms are being applied across sectors such as telecommunications, data centres, sensing and quantum technologies.

PICs in 5G, 6G, and future communication networks

PICs in 5G, 6G, and future communication networks

The need for advanced infrastructure

PICs are increasingly recognised as fundamental to the advancement of 5G and the development of future communication networks, including 6G and beyond. The rapid growth of data generation and consumption, driven by artificial intelligence, mobile connectivity and digitalisation, is placing immense pressure on existing communication infrastructure. Current systems are struggling to keep up with demands for higher bandwidth and lower latency. PICs offer an effective solution, supporting technologies such as coherent transmission[iii] and wavelength division multiplexing (WDM)[iv], both of which are essential for scaling next-generation networks.

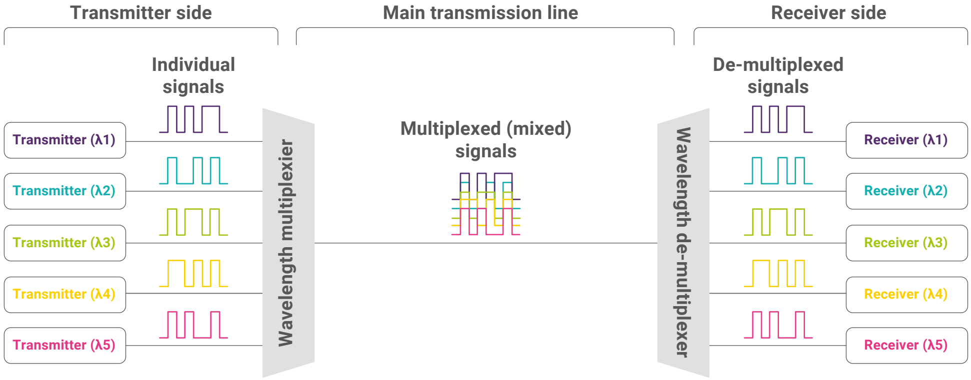


Figure 13: Diagram illustrating wavelength division multiplexing, where multiple optical signals at different wavelengths (λ1–λ5) are combined by a wavelength multiplexer, transmitted together over a single optical fibre, and then separated by a wavelength de-multiplexer at the receiver side to recover the original individual signals. (credit: FiberLabs Inc.)

iii Coherent transmission is a method of data transmission that encodes information in the intensity, phase and polarisation of a light wave, enabling greater data capacity and improved noise tolerance compared to traditional intensity-only methods.

iv Wavelength division multiplexing – a technology used in fibre-optic communications that allows multiple optical signals to be transmitted simultaneously on a single optical fibre by using different wavelengths (or colours) of laser light, increasing the capacity of the network.

PICs in 5G, 6G, and future communication networks

The emergence of terahertz technologies in 6G

Looking ahead, terahertz (THz) frequency bands are expected to play a central role in enabling ultra-high-speed wireless links with terabit-per-second (Tbps) data rates. With vast spectral bandwidth and highly directional "pencil beams", THz waves allow secure, low-latency, high-capacity communications and advanced applications such as 3D positioning[v].[20] PICs provide compact, CMOS-compatible platforms for THz signal generation, modulation and processing.

A major breakthrough in this space was demonstrated through the development of phototunable silicon topological photonic chips, capable of supporting on-chip THz communications. Key features include a 160 Gbit/s single-channel link, a high-Q topological cavity for demultiplexing 40 Gbit/s signals, and real-time HD video streaming. The system leverages topological protection and valley photonic crystals (VPCs) for robust, broadband THz waveguiding, switching and modulation. The platform also supports dynamic tuning and could be enhanced using deep reinforcement learning. This innovation lays the groundwork for compact, energy-efficient THz integrated circuits essential for next-generation wireless technologies and advanced photonic applications.[21]

Integrated THz transceivers: the TERAWAY project

The EU-funded TERAWAY project is advancing PICs for high-speed wireless communications beyond 5G. It demonstrated a fully integrated photonics-enabled transceiver using multi-platform photonic integration. The system combined InP-based photodiodes and photoconductive antennas (PCAs) for THz signal up- and down-conversion, including a novel waveguide-fed PCA receiver with on-chip optical amplification that reduced input power needs by 15 dB. The receiver also showed a flat frequency response across 92–322 GHz.

A real-time wireless link was tested across millimetre-wave (W-), D- and THz bands, processing 1.6 GBaud QPSK signals (3.2 Gb/s throughput) with real-time DSP. Results confirmed theoretical predictions, achieving error-free operation from 90–310 GHz.[22]

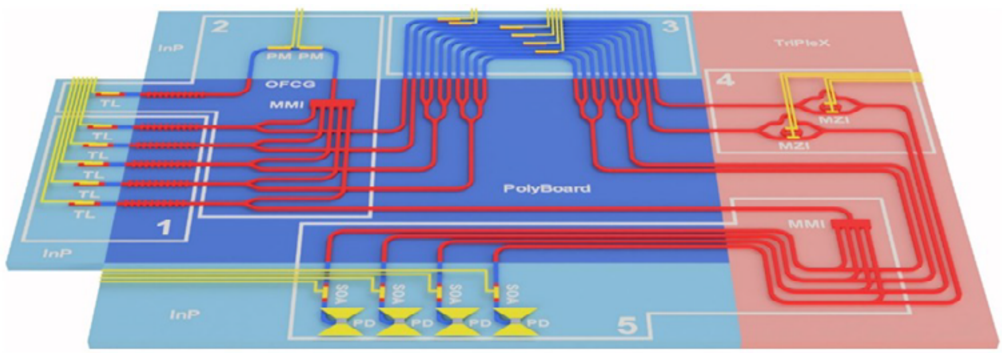


Figure 14: An artistic depiction of the hybrid photonics-enabled platform for generating W/D and THz signals. (1) optical carrier generation unit, (2) optical phase locking unit, (3) optical modulation unit, (4) optical filtering unit, and (5) optical amplification, up-conversion and wireless transmission unit. (image credit: Fraunhofer)

[v] 3D positioning refers to the use of THz wireless signals for precise localisation of objects or users in three dimensions (x, y and z), not just horizontal location, but also height or depth.

PICs in 5G, 6G, and future communication networks

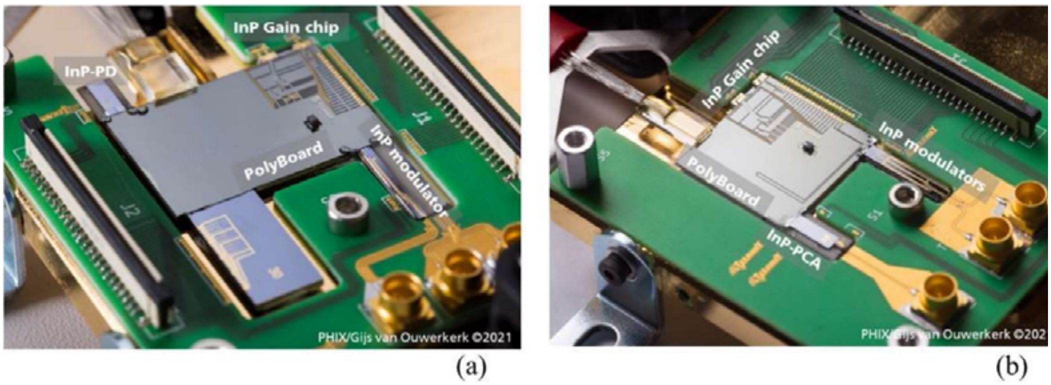


Figure 15: Hybrid photonic integrated circuits of the (a) transmitter and (b) receiver modules, integrating InP gain chips, modulators, photodiodes and photoconductive antennas with a polymer-based photonic mainboard. (image credit: ICT Teraway)

Commercial trials and industry adoption

The commercial potential of PICs in live 5G environments is also being explored. EFFECT Photonics is trialling tunable optical transceivers with integrated photonic chips in a live 5G network in the Netherlands. These smart transceivers can automatically detect and tune to the correct wavelength, simplifying deployment and reducing inventory needs. While current speeds reach 10 Gbps, the platform is designed for scalability and cost efficiency, laying the groundwork for more advanced future networks.[23]

Several other companies are at the forefront of developing PICs to support 5G and next-generation communication networks. SCINTIL Photonics is advancing high-speed silicon PICs with integrated lasers for 5G infrastructure,[24] while Sivers Semiconductors develops both silicon and III-V photonics modules tailored for 5G, 6G, and satellite communications.[25] PHIX Photonics Assembly supports the sector by offering high-volume packaging and integration of PICs into telecom-grade systems,[26] and SMART Photonics acts as a foundry, producing application-specific PICs for data and telecom markets.[27] Together, these companies are enabling scalable, low-latency, and high-bandwidth optical solutions that meet the demanding requirements of modern and future wireless networks.

Integrated photonics in data centres: enabling high-speed, sustainable infrastructure

Integrated photonics in data centres: enabling high-speed, sustainable infrastructure

The evolving demands on data centres

Data centres are the backbone of modern information technology, serving as critical hubs for storing, processing and managing vast volumes of digital data. At the heart of their operation lies a robust communication infrastructure that ensures seamless data flow between servers, storage units and networking equipment. High-speed, reliable communication protocols, enabled by Ethernet and fibre optics, are essential for maintaining fast and efficient operation. As data volumes continue to rise, driven by applications in the Internet of Things (IoT), Big Data and AI, the demand for faster and more energy-efficient data handling grows rapidly.

Transitioning from electrical to optical interconnects

As copper-based interconnects reach their limits in speed and efficiency, PICs are reshaping the data centre landscape. Silicon photonics, already widely adopted in pluggable transceivers, deliver high data rates with lower energy use. Intel shipped over 1.7 million silicon photonics-based 100 Gb/s transceivers in 2023, and the industry is progressing toward 800 Gb/s modules, with 1.6 Tb/s and 3.2 Tb/s devices expected by 2026, according to IDTechEx.[28]

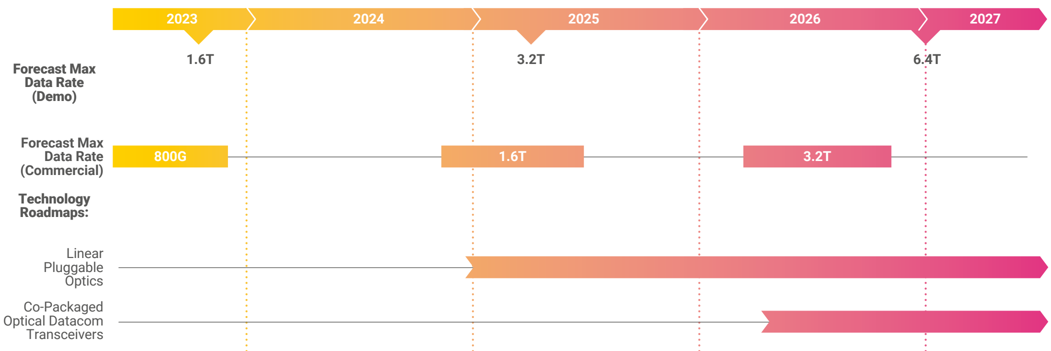


Figure 16: IDTechEx's roadmap for PIC-based pluggable transceivers. (source: IDTechEx)

Integrated photonics in data centres: enabling high-speed, sustainable infrastructure

Enhancing sustainability through photonic processing

The transition to photonics is not just about speed; it is also a response to energy and environmental pressures. Data centres are becoming increasingly energy-intensive, and their cooling systems often consume vast amounts of water. Photonics addresses both challenges. Optical signals travel with less resistance and generate less heat than electrical ones, significantly improving efficiency over distances beyond two metres. This makes PICs particularly attractive for high-density interconnects within and between data centre racks.[28,29] Additionally, photonics can enable a shift to more passive components, further reducing power draw and simplifying thermal management in future architectures.

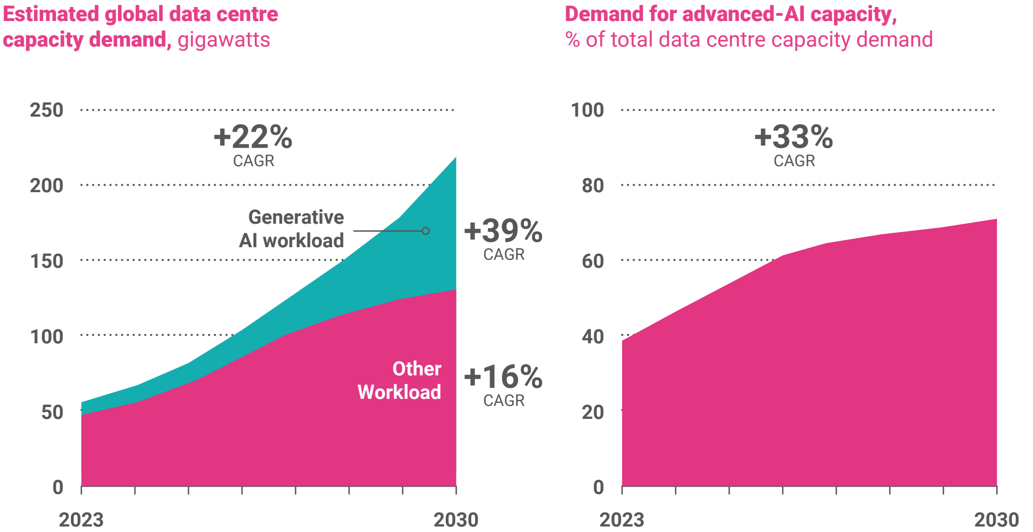


Figure 17: Projected growth in global data centre capacity demand (2023–2030), showing overall capacity expansion driven by generative AI workloads (39% CAGR) compared with other workloads (16% CAGR). The right-hand graph highlights the rising share of advanced AI capacity, expected to grow at a 33% CAGR and reach nearly 70% of total demand by 2030.[30]

The sustainability case is strengthened by evidence that photonic processors can lower cooling needs and water consumption. Companies such as Lightmatter and Q.ANT are developing chips that emit less heat and require far less water for cooling compared to conventional silicon-based processors.[31]

Industry innovations and market dynamics

STMicroelectronics has recently unveiled the PIC100, a new photonics chip developed in collaboration with Amazon Web Services, designed to support upcoming 800 Gbps and 1.6 Tbps optical interconnects for data centres, particularly AI workloads. The PIC100 is the first in ST's new PIC product line, combining silicon photonics and BiCMOS technologies on a 300 mm silicon platform. Manufacturing will take place at the company's fab in Crolles, France.[32]

The IDTechEx slide highlights the competitive landscape of the datacom PIC-based transceiver market, where demand is being driven strongly by data centre expansion and AI workloads. The market is led by Intel/Jabil, which holds the largest share, indicating a dominant position in supplying silicon photonics-based transceivers. Coherent follows closely behind, also demonstrating strong market penetration with a broad portfolio that includes SiPh, electro-absorption modulated laser (EML), and directly modulated laser (DML)-based solutions.

Innolight, a major Chinese player, has emerged as a key contender, benefiting from surging AI-related demand and establishing itself firmly among the top three. Cisco also maintains a significant market presence, underpinned by its manufacturing of high-end SiPh-based transceivers.

Integrated photonics in data centres: enabling high-speed, sustainable infrastructure

Nvidia, although holding a smaller portion of the market, is experiencing the fastest growth, driven by the integration of its transceivers with DGX servers and a strategic partnership with Cisco. This positions Nvidia as a likely future leader in AI-optimised transceiver technology. The remainder of the market is made up of smaller players, collectively contributing a modest share. Overall, the market is currently dominated by a few large suppliers, with hybrid silicon photonics platforms proving critical in meeting high-speed, low-power requirements for modern data centres.[5]

PIC datacom transceiver market forecast

The revenue outlook for PIC datacom transceivers indicates a steady shift toward higher data rates over the next decade. Growth is led by the 800 G segment, which is expanding faster than any other category. Emerging ultra-high-speed segments, such as 3200 G and 6400 G, are expected to gain significant market traction despite being absent today. Mid-range transceivers, such as 1600 G, are set to grow at a more moderate pace, while lower-speed categories like 400 G and 200 G are showing signs of maturity, with only limited expansion. Overall, the forecast highlights a clear market transition from legacy speeds to next-generation, higher-capacity solutions.[5]

PICs in quantum computing: applications, advantages and industry landscape

PICs in quantum computing: applications, advantages and industry landscape

The need and applications of quantum computing

Quantum computing has the potential to transform industries by solving problems that classical systems cannot handle efficiently. In logistics and transport, it can optimise planning and scheduling in real time; in energy, it can improve the management of power grids and traffic networks. Its computational power can accelerate research and development, for example, by simulating aircraft components to shorten design and testing cycles. In healthcare, it offers new approaches to drug discovery by analysing vast combinations of compounds, while in AI, it can boost the accuracy and speed of machine-learning models.

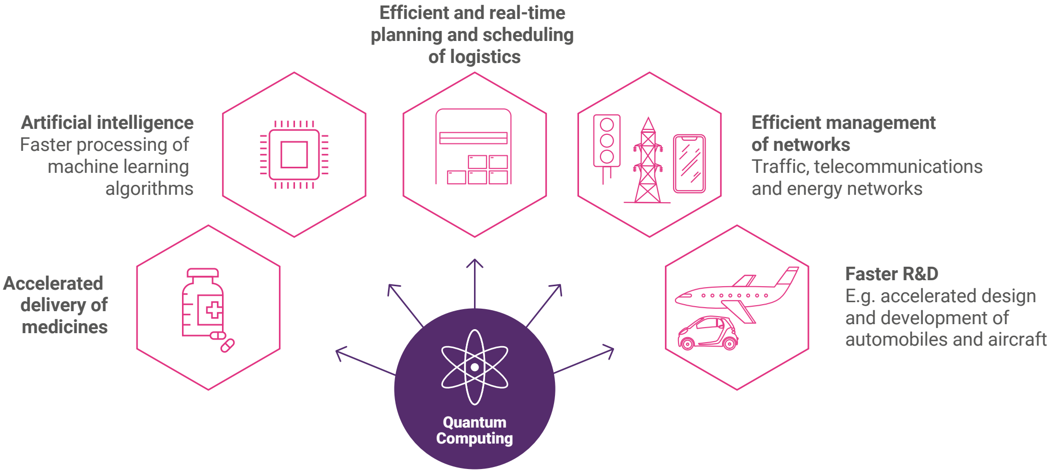


Figure 18: Potential applications of quantum computing across diverse domains.

Advantages of photonic processors

Realising these benefits requires scalable hardware, and photonics provides a compelling route for building quantum computers. Photons travel at the speed of light, enabling ultra-fast information transfer, while their resilience to noise ensures stable coherence. Photonic processors are energy-efficient, operate at room temperature, and support high-fidelity quantum gate operations needed for error correction. They are also naturally compatible with existing optical communication and data transmission systems, making integration into current infrastructure easier and providing both short- and long-term advantages.[33]

PICs in quantum computing: applications, advantages and industry landscape

Quantum algorithms for complex problems

Advanced algorithms are being developed to unlock the potential of quantum hardware, particularly when implemented on quantum PICs. These processors provide the physical platform for running optimisation approaches such as QUBO[vi], PUBO[vii], and Coherent Ising Machines[viii], which can address challenges like flight scheduling, factory workflows, and supply chain planning. In chemistry, methods including the Variational Quantum Eigensolver (VQE) and Gaussian Boson Sampling (GBS)[ix] help model reaction mechanisms and molecular behaviour. GBS also supports tasks such as molecular docking, subgraph detection and data mining, where it can complement classical techniques. By focusing on the algorithmic layer, these methods show how photonic quantum processors can translate mathematical problems into real-world industrial applications.[32]

Key players in photonic quantum computing

A growing number of companies are developing quantum computers using PICs, recognising the scalability and efficiency advantages of light-based platforms. Leading efforts include PsiQuantum, which is building a silicon photonic quantum computer in partnership with semiconductor foundries,[34] and Xanadu, which offers cloud-accessible photonic quantum processors.[35]

Quantum Computing Inc. is advancing integrated photonics through its thin-film lithium niobate chip foundry,[36] while Pasqal strengthened its photonics capability by acquiring AEPONYX.[37] Other innovators such as Photonic Inc., Ephos, ORCA Computing, Quandela, QuiX Quantum, Aegiq, Nu Quantum, Q.ANT, Oxford Ionics (now part of IonQ) and Quside are pursuing diverse approaches, from glass-based photonic chips to photon sources and modular architectures.

Together, these companies are shaping the photonic quantum ecosystem by combining scalable hardware platforms with practical applications in optimisation, chemistry, data science and secure communications.

[vi] QUBO (Quadratic Unconstrained Binary Optimisation): This is a common method to represent complex, real-world combinatorial optimisation problems. It involves finding optimal binary (0 or 1) values to minimise a quadratic function.

[vii] PUBO (Polynomial Unconstrained Binary Optimisation): A generalisation of QUBO, allowing for polynomial objective functions, rather than just quadratic ones.

[viii] Coherent Ising Machines are specialised quantum-inspired systems that map such optimisation problems onto the Ising model, allowing efficient solutions to tasks like scheduling and resource allocation.

[ix] The Variational Quantum Eigensolver (VQE) is a hybrid quantum-classical algorithm used to estimate the ground-state energy of molecules, making it valuable in quantum chemistry. Gaussian Boson Sampling (GBS) is a quantum algorithm that uses squeezed light states to perform complex sampling tasks efficiently, with applications in molecular docking, graph problems and data analysis.

PICs for secure communications: quantum cryptography

PICs for secure communications: quantum cryptography

The strategic importance of quantum key distribution

Quantum Key Distribution (QKD) is one of the most impactful applications of PICs, enabling ultra-secure communication through quantum-entangled photons that are inherently resistant to eavesdropping. In today's digital environment, this capability is particularly relevant for health, government, banking, finance and critical infrastructure, all of which require long-term data protection against emerging threats such as quantum computers capable of breaking classical cryptographic systems.[38]

Silicon photonics for quantum integration

PICs, especially those fabricated using silicon photonics, offer several advantages for realising QKD systems. These include miniaturisation, cost-effective device manufacturing, and compatibility with existing CMOS microelectronics. However, a longstanding limitation has been the difficulty of achieving high-speed modulation of quantum states on standard silicon platforms.[39] Recent advances have addressed this by using a hybrid modulation approach that combines slower but reliable thermo-optic phase modulators (TOPMs)[x] with faster carrier-depletion modulators (CDMs)[xi], which, despite their imperfections, enable high-speed operation.[40]

This hybrid modulation technique has demonstrated significant performance improvements. Experiments using PIC-based QKD systems achieved a modulation bandwidth of 10 GHz, quantum bit error rates (QBERs)[xii] as low as 1.01%, and asymptotic secret key rates of up to 916 kbps over a 20 km fibre link. These implementations included various QKD protocols such as chip-to-chip coherent one-way (COW)[xiii] QKD, polarisation-encoded BB84, and time-bin encoded BB84.[xiv] These results not only validate the technical feasibility of integrating high-speed QKD circuits into standard silicon photonic manufacturing but also pave the way for their commercial and infrastructural deployment.

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[x] Thermo-optic phase modulators (TOPMs): devices that change the phase of light by locally heating the waveguide, offering stability but limited speed.

[xi] Carrier-depletion modulators (CDMs): high-speed modulators that alter the refractive index of silicon by depleting charge carriers, though with higher loss.

[xii] Quantum Bit Error Rate (QBER): the fraction of bits that differ between sender and receiver in a QKD system, used to assess system security and performance.

[xiii] Coherent One-Way protocol (COW): a quantum key distribution method using weak coherent pulses and time-bin encoding.

[xiv] BB84: one of the earliest and most widely used QKD protocols, employing different polarisation or time-bin states to encode quantum bits.

PICs for secure communications: quantum cryptography

Scalability, integration and network deployment

Although commercial QKD systems have been available for some time, ongoing research aims to make them smaller, more affordable, and better suited for long-distance deployment. PICs are central to this evolution, as they enable the integration of multiple quantum photonic components on a single chip. However, integrating QKD into existing communication networks remains a complex undertaking. It requires the collaboration of a broad ecosystem, including telecom equipment vendors, infrastructure providers, network operators, QKD developers and cybersecurity experts.

Companies developing PICs for quantum cryptography

A growing number of companies are developing PICs to make quantum cryptography commercially viable. In the UK, KETS Quantum Security is producing on-chip QKD devices using standard foundries, offering low size, weight and power for telecom and data-centre applications.[41] ID Quantique in Switzerland has demonstrated integrated silicon photonics QKD systems aimed at compact, scalable key distribution.[42] In China, QuantumCTek has commercialised QKD terminals, leading the field in deployable quantum communication infrastructure.[43] Toshiba's Cambridge Research Laboratory is advancing PICs that integrate quantum random number generators, QKD transmitters and receivers with drive electronics on a single chip, achieving the first fully functional, chip-based QKD system using commercial fabrication.[44]

In addition, companies such as Quantum Dice, Arqit and Exail are contributing to the broader photonic ecosystem for quantum cryptography through innovations in secure key generation, quantum-safe encryption platforms and advanced photonic components, supporting the scalability and industrialisation of quantum-secure communication networks.

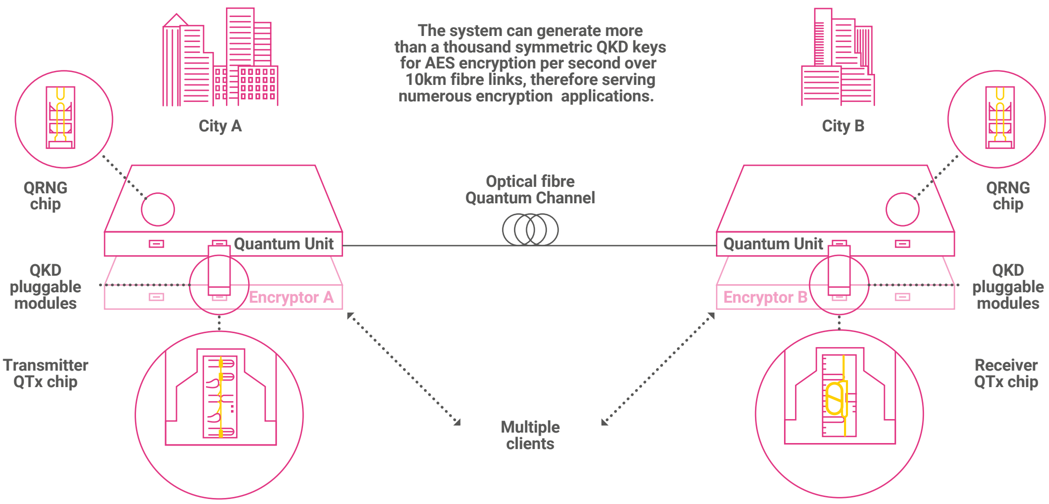
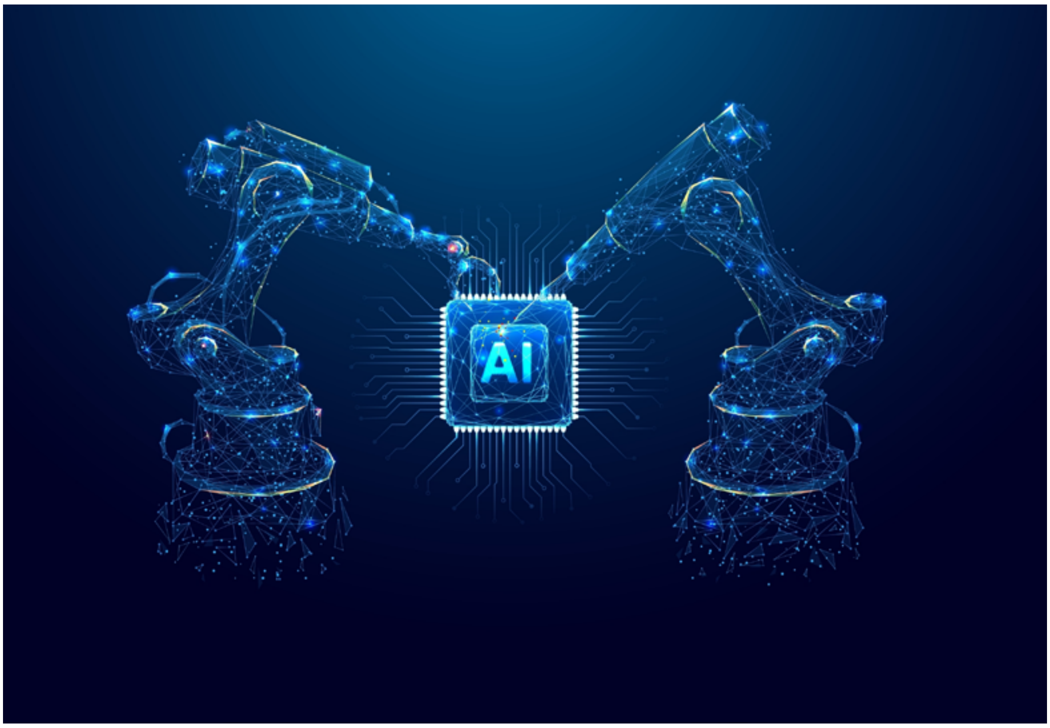


Figure 19: The diagram illustrates a quantum communication link between City A and City B using PIC technology. Each end hosts a quantum unit containing a quantum random number generator (QRNG) chip, QKD pluggable modules and integrated transmitter (QTx) or receiver (QRx) chips. These units exchange quantum keys over an optical fibre quantum channel, generating more than a thousand symmetric AES encryption keys per second over 10 km fibre links. The generated keys are then distributed via encryptors (A and B) to multiple client systems, enabling secure end-to-end data encryption based on quantum key distribution principles.[44] (image credit: Toshiba)

PICs in the AI revolution: photonic AI accelerators and neuromorphic computing

PICs in the AI revolution: photonic AI accelerators and neuromorphic computing



Neural networks and computational bottleneck

Neural networks are machine learning models that mimic how the human brain processes information. They consist of layers of connected "neurons" that adjust parameters, or weights,[xv] as they learn from data.[45] Their ability to make predictions and improve through training underpins AI applications such as image classification, speech recognition and natural language processing. However, as networks grow more complex and data volumes surge, conventional electronic hardware struggles to keep pace, particularly in speed, energy efficiency and data movement.

Photonic neural networks and optical computing

Photonic neural networks (PNNs), also called optical neural networks (ONNs), use light instead of electrical signals to perform computations. By exploiting light–matter interactions, they can execute matrix multiplications[xvi], a core operation in AI, with sub-nanosecond latency, minimal heat and parallelism across many channels.[46] This makes them well-suited for real-time inference and large-scale deep learning, both at the edge and in data centres, while overcoming the inherent limits of electronic processors.

PICs as enablers of photonic AI systems

PICs provide a hardware foundation for scalable, on-chip optical computing systems. They address key limitations of electronic hardware in artificial neural networks (ANNs), particularly the inefficiency of moving large volumes of data between components. By using light instead of electricity, PICs enable low-loss, low-latency data transmission and support high-speed, parallel computation through techniques such as WDM. They can implement core neural network operations, including weighted inputs and nonlinear activations, while making matrix multiplication significantly faster and more energy efficient.[47]

[xv] "Weights" are the adjustable parameters that determine how strongly one neuron's output affects another's input.

[xvi] "Matrix multiplication" is a way for a neural network to mix inputs with weights to figure out what the output should be. It's like combining numbers from the input with special importance values (called weights) to help the network make decisions. In photonic neural networks, this is done using light instead of electricity, making it faster and more efficient.

PICs in the AI revolution: photonic AI accelerators and neuromorphic computing

PICs have also enabled the development of photonic accelerators for electronic ANNs and are proving especially useful in edge computing and neuromorphic applications. Technologies like silicon photonics show strong promise for scalable, on-chip photonic neural networks, thanks to their tunable components (e.g. phase shifters and Mach-Zehnder interferometers) and compatibility with existing fabrication methods.[42]

Industry innovation and emerging technologies

Recent research has demonstrated major progress in applying photonic integrated circuits to AI workloads. A large-scale photonic accelerator with more than 16,000 integrated optical components has achieved high-speed matrix multiply-accumulate (MAC) operations with very low latency, enabled by hybrid electronics-photonics packaging.[48] In neuromorphic computing, a silicon-compatible spiking photonic chip capable of in-situ learning and gigahertz spike dynamics has brought brain-inspired processing closer to reality.[49]

In the industry, companies are rapidly moving from prototypes to manufacturable platforms. Q.ANT has begun pilot production of photonic AI accelerators on a converted CMOS line in Stuttgart, offering a Native Processing Server (NPS) aimed at high-efficiency AI computing.[50] Lightmatter continues scaling its architecture with the Passage photonic interconnect and high-integration processors exceeding 16,000 optical components.[51] Startups such as Arago (France) are pursuing hybrid photonic-electronic accelerators for inference.[52]

These developments underline a broader trend: PICs are emerging as a foundation for scalable, energy-efficient AI hardware across both research and industry.

PICs in LiDAR systems for automotive and agricultural applications

PICs in LiDAR systems for automotive and agricultural applications

Transforming sensing in autonomous mobility

PICs are central to the advancement of autonomous vehicle (AV) technologies through their integration into next-generation Light Detection and Ranging (LiDAR) systems. By miniaturising and integrating photonic components, they deliver accurate, high-speed and reliable obstacle detection, while also supporting intra-vehicle optical communication for real-time coordination of subsystems and sensors. This dual role is essential for safe and efficient autonomous operation.

Silicon photonics and LiDAR-on-chip solutions

Silicon photonics provides a scalable, cost-effective platform for LiDAR by integrating lasers, modulators and detectors onto a single chip, enabling compact solid-state LiDAR-on-chip designs. Frequency-Modulated Continuous-Wave (FMCW) LiDAR is particularly promising due to its energy efficiency, robustness against environmental interference, and elimination of bulky optical fibres. Compared to time-of-flight systems, FMCW LiDAR delivers more reliable sensing performance in variable and dynamic environments such as dense urban areas and agricultural fields.[38,53,54]

Integration, packaging and industry momentum

Advances in packaging, including flip-chip bonding and 3D stacking, are allowing PICs to be closely integrated with electronics, forming compact optoelectronic modules suitable for automotive and industrial use. Scantinel Photonics exemplifies this trend with its CMOS-fabricated FMCW LiDAR-on-chip architecture, which integrates the photonic engine, hybrid-integrated tunable laser, and detection on a PIC platform, while enabling solid-state beam steering through its Optical Enhanced Array technology. This design achieves coherent 1550 nm ranging beyond 300 m and per-pixel velocity detection, while reducing power consumption and supporting high pixel throughput.[55] At the same time, Luminar Technologies, a major LiDAR player, is expanding its chip business through acquisitions; it purchased Gooch & Housego’s laser module unit to bolster its in-house photonics capabilities, integrating lasers, detectors and related components.[56]

PICs in LiDAR systems for automotive and agricultural applications

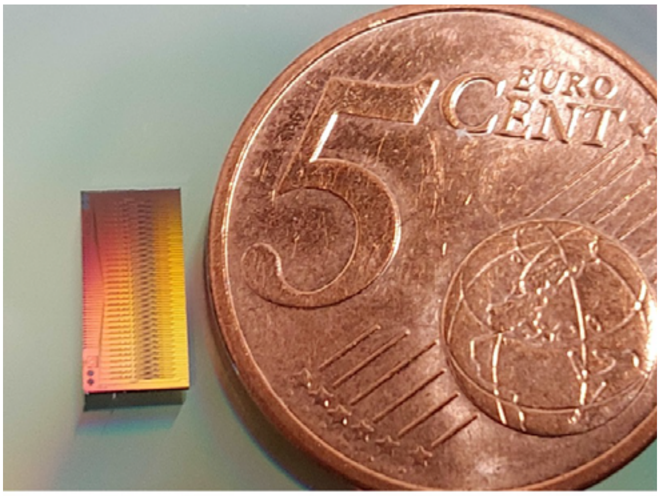


Figure 20: Scantinel Photonics' 2nd generation FMCW LiDAR silicon chip. (image credit: scantinel.com)

In agricultural settings, LiDAR adoption is advancing, too. For example, John Deere's autonomous orchard tractors are being outfitted with LiDAR sensors for real-time 3D imaging to navigate dense canopies and supplement vision systems.[57] These developments suggest that photonic LiDAR may soon support precision farming and autonomous operations in both road and off-road environments.

PICs in biosensing and environmental monitoring

PICs in biosensing and environmental monitoring

The role of PICs in modern healthcare

PICs have the potential to become foundational in the development of advanced biosensing technologies and medical diagnostics. Their small footprint, high sensitivity and compatibility with semiconductor manufacturing make them ideal for applications demanding speed, precision and portability. These strengths support decentralised and point-of-care (PoC) diagnostics, enabling rapid biomolecular detection outside traditional laboratories.

Silicon photonics and lab-on-chip platforms

A key driver of this progress is silicon photonics, which enables scalable lab-on-chip technologies using established microelectronics processes. Optical sensing platforms such as micro-resonators, diffractive waveguides, porous silicon and plasmonic structures detect changes in light properties caused by molecular interactions, often via evanescent field sensing. By integrating active and passive optical elements on a single substrate, PICs deliver robust and energy-efficient sensors that can be mass-produced at low cost. These systems now achieve sensitivities comparable to centralised laboratory instruments, supporting real-time, label-free analysis at the point of care.[58]

PIC-based biosensors for disease detection

PICs can be engineered to detect diverse biomarkers, including proteins, pathogens and genetic material. Integrated lab-on-chip systems combine sample handling, detection and processing within compact packages.[59] One example is an aptamer-based impedance biosensor fabricated with standard photolithography for early cancer detection. The device identified A549 lung carcinoma cells via electrochemical impedance spectroscopy, showing a strong linear correlation between cell concentration and capacitance changes ($R^2 > 99\%$) and a detection limit of $\sim 1.5 \times 10^4$ cells/mL.[38] These results demonstrate the feasibility of producing cost-effective, label-free, and highly specific biosensors using integrated photonics for clinical deployment.

Integration with microfluidics and wearables

There is growing momentum toward integrating PICs with microfluidic platforms, enabling automated sample manipulation and multi-analyte detection within a single device. These hybrid systems increase diagnostic throughput while reducing human error. PICs are also being applied in wearable devices for real-time monitoring of physiological parameters, such as temperature, pH and biomarker levels.

PICs in biosensing and environmental monitoring

Environmental and agricultural monitoring

Beyond healthcare, PIC-based biosensors are also gaining traction in environmental and agricultural monitoring. By leveraging light-based detection mechanisms, these sensors can assess parameters such as water purity, air quality, soil composition and crop health with high precision. Technologies like TriPleX™ waveguides and multichannel fluorescence detection enable parallel analysis of multiple analytes with remarkable accuracy and reusability, making them valuable tools for sustainable agriculture and pollution control. Their compatibility with IoT systems further enhances their deployment in remote or distributed monitoring scenarios.[38]

Fabrication and material advancements

PICs for medical and biosensing applications are typically fabricated using platforms such as SiN, InP and SOI. These materials offer low optical losses, biocompatibility, and the ability to integrate light sources and detectors on a single chip. Recent developments focus on scaling up manufacturing processes while maintaining device sensitivity and reproducibility.[60]

Across fields as diverse as quantum communications, LiDAR, biosensing and AI, PICs are demonstrating their versatility and transformative potential. The next stage lies in scaling these advances into the digital infrastructure that powers data centres and high-performance computing. This shift is driving interest in co-packaged optics, a technology poised to redefine the convergence of photonics and electronics.

Co-packaged optics

Co-packaged optics

Co-packaged optics (CPO) is a technology that brings optical components, such as PICs, closer to electrical components. CPO is especially useful for handling the massive amounts of data in modern applications like AI, cloud computing and 5G networks. Traditionally, optics are separate from the electronic chips connected by electrical cables. This setup can be bulky, power-hungry and slow, due to the distance signals must travel. In CPO, the optical components are integrated directly onto the same package or substrate as the electronic chips. This reduces the distance signals need to travel, which improves speed, reduces power consumption, and saves space. Integrating photonic and electronic components can be accomplished through several methods, each offering distinct benefits and facing particular challenges.

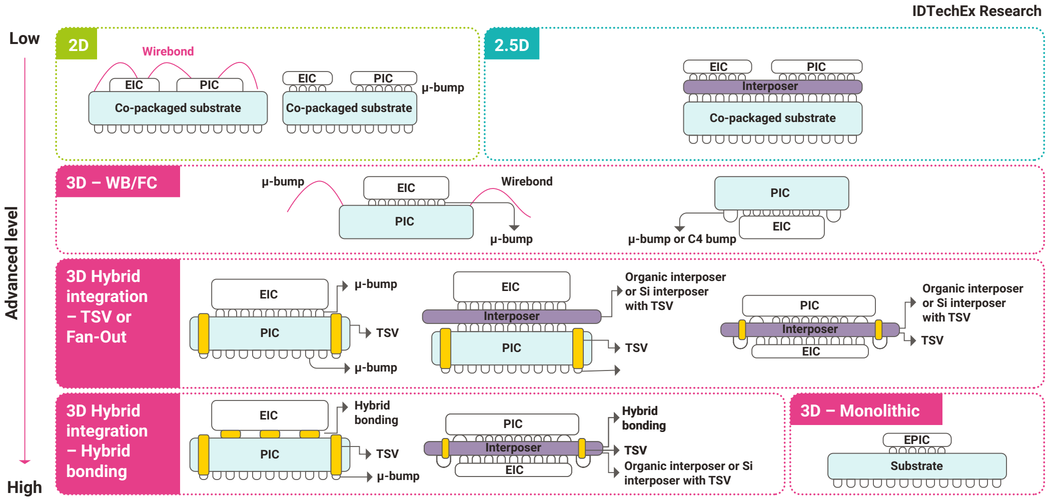


Figure 21: 2D to 3D EIC/PIC integration options.

2D Integration

PIC and electronic IC components side by side on a printed circuit board (PCB). It's cost-effective and simple but suffers from high parasitic inductance, signal integrity issues and limited bandwidth, making it unsuitable for high-performance applications.

2.5D Integration

Uses an interposer with through-silicon vias (TSVs) to connect PIC and EIC, reducing parasitics and enabling higher I/O connections. However, it has higher fabrication costs and still faces parasitic challenges compared to 3D integration.

3D Integration

Stacks EIC on top of PIC using advanced techniques like TSV or Cu-Cu hybrid bonding, minimising parasitics and improving performance. Challenges include heat dissipation and higher complexity, but it offers superior integration efficiency.

3D Monolithic Integration

Embeds photonic components within electronic process nodes, reducing parasitics and simplifying packaging. However, it often uses older CMOS nodes, leading to suboptimal photonic performance and higher energy consumption. It remains under development.

CPO requires advanced manufacturing techniques and materials to integrate optical and electrical components within the same package and must overcome significant thermal management and mechanical reliability challenges, including alignment stability. Cost remains a critical factor for scaling the technology for mass-market applications. Within the next ten years, CPO is expected to mature and become gradually integrated into data centres. As data rates continue to increase beyond 800G and 1.6T, the energy efficiency and performance benefits of CPO are likely to drive its broader integration into AI and high-performance computing infrastructures.

Co-packaged optics

Technology development highlights

Broadcom's co-packaged optics

Broadcom has advanced CPO as a solution by integrating optical engines directly with switch ASICs, improving efficiency and scalability.

Its CPO journey began with a 100 G/lane prototype proving the concept, followed by a second generation that improved manufacturability and thermal design. In 2025, Broadcom launched its third generation at 200 G/lane with the Bailly platform, a 51.2 Tb/s Ethernet switch. Bailly demonstrated around 70% lower power use for optical interconnects compared with pluggable solutions while increasing bandwidth density.

Challenges remain in thermal management, optical alignment and yield optimisation. Broadcom is now developing a fourth generation at 400 G/lane, aiming to further boost bandwidth and efficiency for large-scale AI data centres.[61,62]

Advanced Packaging for CPO
Broadcom's Optical Engine Platform

Ethernet Switch with CPO
Broadcom's Ethernet Switching for Scale-Out Networking

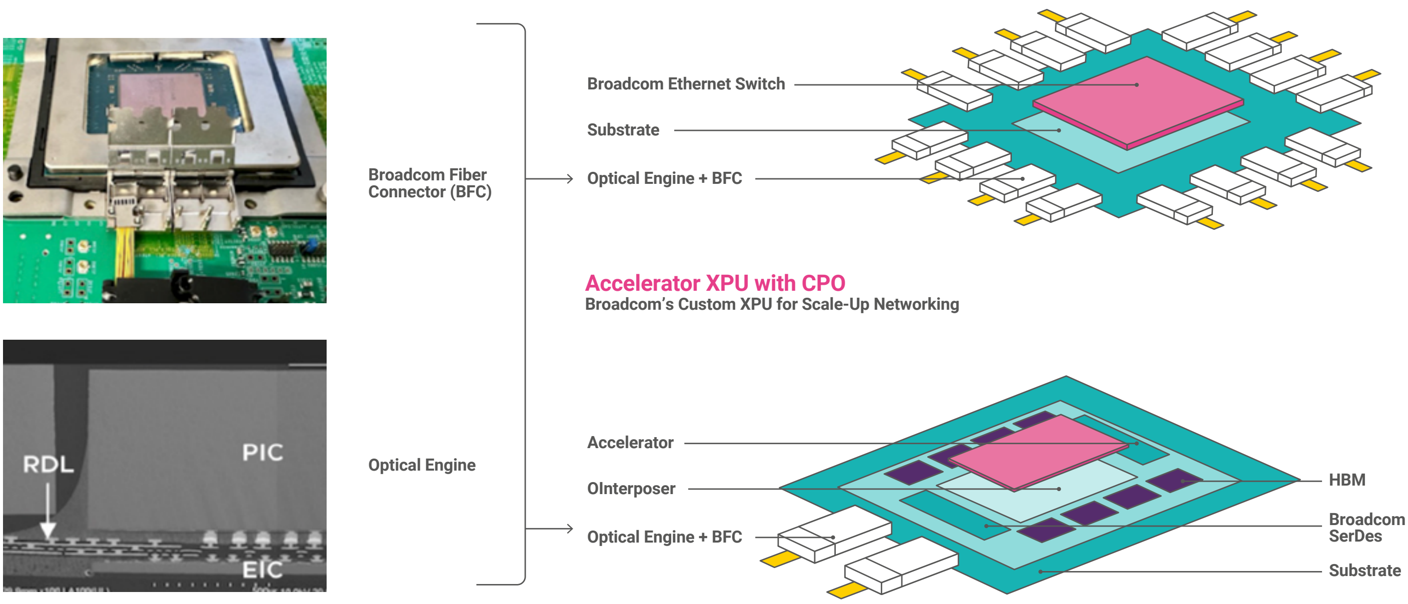


Figure 22: Left: Broadcom's fibre connector and optical engine (PIC+ EIC). Right: system-level examples, with CPO applied to Ethernet switches for scale-out networking and XPUs for scale-up networking.

Intel's integrated optical I/O chiplet

Intel has introduced its first Optical Compute Interconnect (OCI) chiplet, demonstrated alongside an Intel CPU. The device integrates a PIC with on-chip lasers and optical amplifiers, enabling direct optical I/O within a compact package.

The chiplet supports 64 bidirectional channels at 32 Gbps each, delivering up to 4 Tbps throughput over ~100 m of single-mode fibre. It is also compatible with PCIe Gen5, showing its potential for high-performance system interconnects.

A key feature is its low energy use: about 5 pJ/bit, compared with ~15 pJ/bit for typical pluggable optics. This efficiency, combined with co-integration of photonics and electronics, lowers latency and increases bandwidth density.

The OCI design employs dense wavelength division multiplexing (DWDM) with eight wavelengths per fibre pair, and integrates both transmitter and receiver functions. Demonstrated signal integrity confirms the stability and performance of this approach at scale.[63]

Challenges

Challenges

While PICs show strong market growth and technical promise, several barriers still limit their scalability and adoption. These span materials, design, packaging and system integration, and need to be addressed for PICs to reach their full commercial potential.

Silicon's indirect bandgap nature

Silicon, the dominant material in electronic integrated circuits, has an indirect bandgap, meaning it is highly inefficient at emitting light. This property makes it extremely difficult to fabricate efficient light sources, such as lasers, directly on silicon. As a result, silicon-based PICs often require hybrid integration with other materials (like III-V semiconductors) for light generation. This complicates fabrication processes and increases the overall system complexity and cost, while also pushing the industry towards alternative photonic materials and platforms that are less mature and less standardised.

Design challenges

PIC design faces several key challenges. Conventional electronic design automation (EDA)[xvii] tools struggle with curvilinear layouts required for waveguides and lack robust support for complex, bidirectional optical signal modelling. The absence of standardised simulators and mature photonic process design kits (PDKs)[xviii] often forces manual component creation, while fragmented design environments lead to duplicated effort and increased errors. Verification methods like design rule checking (DRC)[xix] and layout versus schematic (LVS)[xx] are less effective for photonics, and the co-design of electronic-photonic systems remains poorly supported. Developing accurate compact models also demands significant calibration. These issues highlight the urgent need for dedicated design tools to streamline PIC design.[64]

Packaging challenges

PIC packaging presents several key challenges that limit commercial scalability. It remains costly, often more than the PIC itself, due to expensive materials and the technical complexity of integrating fibres, lasers and micro-optics in non-standard formats. Much of the cost arises from housing and casing rather than assembly. The lack of high-volume production prevents economies of scale, resulting in higher prices.

Relative immaturity of the PIC ecosystem

Compared to the well-established and highly optimised ecosystem for electronic ICs, the field of PICs is still relatively young. Standardised design libraries, packaging solutions and volume manufacturing processes are still evolving. This immaturity limits scalability, hampers design reuse, and increases reliance on custom, project-specific development, which slows down innovation and raises time-to-market.

[xvii] Electronic design automation (EDA): a category of software tools used to design, simulate and verify electronic circuits and systems, from individual transistors up to complete integrated circuits.

[xviii] Process Design Kit (PDK): a collection of files, models and design rules provided by a semiconductor foundry that allows designers to accurately create and simulate circuits compatible with a specific manufacturing process.

[xix] Design rule checking (DRC): an automated process that verifies whether a circuit layout complies with the manufacturing rules set by the fabrication foundry.

[xx] Layout versus schematic (LVS): a verification method that checks whether the physical layout of a circuit matches its intended schematic design.

Challenges

High initial costs for prototyping and development

Developing PICs often requires access to specialised fabrication facilities, which can be expensive and limited in availability. The lack of widely accessible multi-project wafer (MPW) services compared to electronics further increases the cost barrier for initial prototyping. Additionally, the design tools for PICs are not yet as mature or as user-friendly as their electronic counterparts, adding further cost and complexity to development efforts. Development cycles can also be lengthy due to foundry lead times, particularly for emerging materials such as TFLN, which further slows iteration and increases overall development cost.

Conversion between electrical and optical domains

In most practical systems, PICs must interface with conventional electronic circuits. This necessitates frequent conversions between electrical and optical signals using components like modulators and photodetectors. These conversions can introduce latency, increase chip area, and lead to inefficiencies in power consumption, especially when high-speed, high-density interconnects are required.

Thermal management of active components

Certain photonic components, particularly active elements such as on-chip lasers, amplifiers and modulators, can generate significant heat during operation. Managing this thermal load is challenging, especially as PICs scale in complexity and density. Effective thermal control is essential to maintain performance and ensure device reliability, but it adds another layer of design and packaging complexity.

UK leadership and CSA Catapult's role

UK leadership and CSA Catapult's role

Photonics in the UK[65]

The UK photonics sector is a major contributor to the economy, generating £18.5 billion in revenues in 2024 and adding £8.6 billion in gross value each year. It employs 84,800 people across more than 1,400 companies, with productivity of £101,000 per employee, making it one of the most productive UK manufacturing sectors. Output has increased by over 20% in two years, significantly outpacing the broader manufacturing average.

Internationally, the UK is the second largest photonics producer in Europe and the ninth globally, accounting for around 2.25% of a £850 billion global market. Most UK firms export more than half of their output, and foreign investment continues to flow into the sector due to its reputation for innovation and skills.

Photonics underpins many critical industries in the UK. It enables advanced manufacturing through lasers and machine vision, supports defence with surveillance and targeting systems, underpins data and AI with fibre optics, and drives clean energy, healthcare, life sciences, space and quantum technologies. PICs, as previously discussed, are vital for low-latency data centres, AI accelerators, quantum technologies, 5G/6G networks and healthcare diagnostics. The UK's expertise in compound semiconductors and strong academic base position it well to lead in this fast-growing area.

The industry benefits from strong links with over 40 universities and research organisations, with high levels of industrial collaboration and R&D investment. Regional clusters exist across the UK, with major centres in South Wales, Scotland, Northern Ireland, the South Coast, Cambridge, Durham, Manchester and the Midlands.

To capture more value domestically, the sector must scale production, strengthen system-level integration and expand its skilled workforce. With the proper support, photonics, and PICs in particular, can continue to drive growth, resilience and innovation across the UK economy.

The UK's AI Action Plan

The UK Government's AI Opportunities Action Plan[66] emphasises the need for a long-term compute infrastructure strategy, including a ten-year roadmap, the creation of a Living Benchmarks Library to assess AI systems against real-world workloads, and stronger international collaboration to access diverse architectures. These priorities align with the advantages of PICs, which deliver high-bandwidth, low-latency, and energy-efficient optical interconnects essential for scaling AI compute sustainably. The benchmarking initiative provides a route for PIC-based accelerators to demonstrate their capabilities against practical AI workloads, while international partnerships create opportunities for development, validation and integration into national infrastructure. Together, these measures highlight significant opportunities for PICs to contribute to the UK's ambition of building resilient, efficient and future-proof AI systems.

Opportunities for PICs in the UK's quantum strategy

The UK Parliament's report[67] on quantum technologies highlights several areas that connect closely with the advantages and opportunities of PICs. It stresses the importance of building advanced infrastructure to support quantum research and commercialisation, including scalable hardware platforms and strong links between research and industry. A key theme is the need for energy-efficient, high-performance computing and communication systems, particularly as quantum technologies increasingly converge with AI, secure communications and sensing. This directly aligns with the strengths of PICs, which can integrate multiple optical functions on a single chip to deliver compact, low-latency and scalable solutions.

UK leadership and CSA Catapult's role

The report also underlines the UK's ambition to lead internationally in quantum computing, sensing and secure communications. PICs have a central role to play in these domains, enabling integrated sources, detectors and circuits for quantum communication, compact platforms for quantum sensing, and scalable photonic architectures for quantum computing. The emphasis on collaboration between academia, industry and government creates strong opportunities for PIC innovation to be validated, scaled and embedded into national programmes. In this way, the parliamentary strategy points to a future where PICs are not just an enabling technology but a driver of the UK's competitive advantage in quantum and AI-enabled systems.

CSA Catapult

CSA Catapult is the UK's authority on compound semiconductor applications and commercialisation.

We work with start-ups, SMEs, large organisations and academia to de-risk commercialisation, eliminate barriers to market and accelerate compound semiconductor technologies.

As a not-for-profit research and technology organisation, funded by Innovate UK, we're a trusted neutral convener in a range of industry sectors.

Our state-of-the-art facilities are home to a world-leading team of experts with significant know-how, experience and track records in developing and commercialising compound semiconductor technologies and applications.

Our Innovation Centre in Newport is home to cutting-edge testing, validation, characterisation and packaging technologies that are wholly unique to the UK. Our facilities span four areas: power electronics, photonics, radio frequency and microwave communications, and advanced packaging technology.

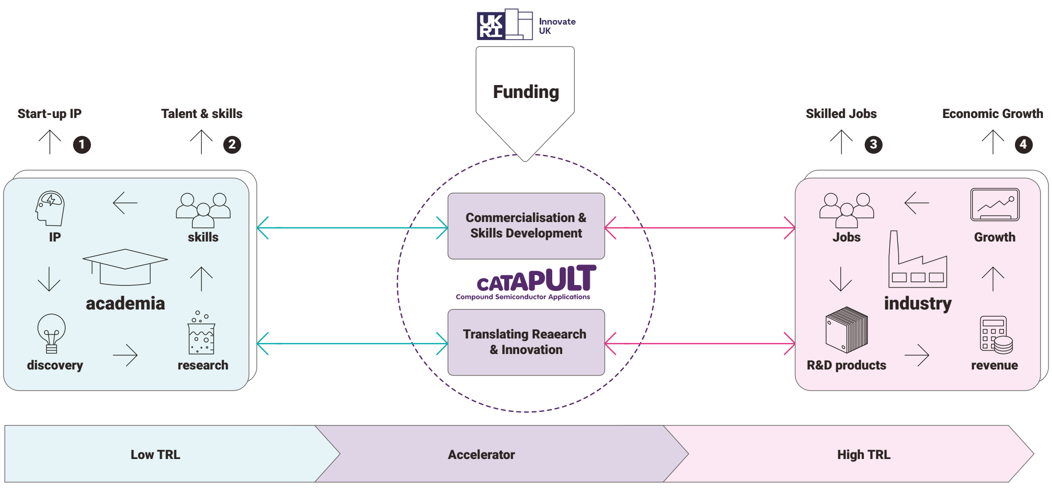


Figure 23: CSA Catapult's role in bridging the gap between academia and industry.

CSA Catapult also has a Future Telecoms Hub based at the Bristol and Bath Science Park, which is a translational research facility specialising in telecoms hardware and technology platforms. Work at the Future Telecoms Hub focuses on improving the speed, energy efficiency and security of future telecoms networks.

UK leadership and CSA Catapult's role

CSA Catapult's leadership in PICs

Our differentiator: design and integration under one roof

At CSA Catapult, we focus on design and integration challenges under one roof by offering optimised IP blocks. This approach overcomes the cost and complexity bottlenecks in PIC development by optimising efficiency and scalability of hardware for AI data centres, quantum systems, and high-performance computing. Key hardware includes CPOs, optical engines, optical switches, quantum sources and processing chips.

Prototype platform for early validation

Our central objective is to create a PIC co-design and co-packaging prototype platform aimed at delivering a minimum viable product (MVP). This platform enables early-stage validation and helps bridge the gap between research concepts and manufacturable technologies.

Full design and integration capabilities

Our capabilities span the complete design and integration chain:

- Component level – process design kits (PDKs)
- Device and circuit level – reusable intellectual property (IP) blocks
- Assembly and testing – application design kits (ADKs), plus validation and control
- Scalable integration – support for high-yield manufacturing and convergence between PICs and RF systems

Strengthening the UK supply chain

By combining design expertise with integrated prototyping services, we are positioning ourselves as a key enabler of the UK's photonics supply chain. Our focus on manufacturability, scalability, and convergence ensures that emerging PIC technologies can transition more effectively from research to industrial deployment.

UK leadership and CSA Catapult's role

Recommendations for the UK to lead PICs

1. **Invest in scale-up and manufacturing capacity**
   The UK should establish pilot and production facilities to enable PIC technologies to transition from research prototypes to high-volume industrial production. CSA Catapult can play a central role by providing a bridge between research and manufacturing, offering prototyping platforms, and supporting scalable integration and packaging processes that prepare technologies for industrial deployment.

2. **Embed PICs within national AI and quantum strategies**
   The UK should position PICs as a core enabler in its ten-year compute roadmap, the Living Benchmarks Library, and national quantum programmes in sensing, secure communications and computing. CSA Catapult can help deliver this by running demonstrator projects that validate PICs in AI accelerators, quantum platforms and data centre interconnects, ensuring alignment with national strategic goals.

3. **Strengthen integration and prototyping capabilities**
   The UK should expand co-design, packaging and validation services that help reduce the time and risk for companies adopting PICs. CSA Catapult is already addressing these needs through its co-design and co-packaging platforms, reusable IP libraries, and design-for-testing frameworks. Scaling these services would allow Catapult to act as a national integration hub, supporting SMEs, start-ups and larger firms alike.

4. **Develop specialist talent pipelines**
   The UK should expand training programmes, apprenticeships and fellowships in photonic design, packaging and testing to build the skilled workforce required for a competitive PIC sector.

   CSA Catapult addresses the UK's need for skilled engineers in the compound semiconductor sector through our dedicated Skills Academy. Collaborating with schools, universities, industry, government, charities and parents, the Academy aims to inspire and train the next generation of scientists and engineers. Initiatives include early STEM engagement, internship programmes via the UK Electronics Skills Foundation, support for doctoral training centres, and projects like "Spark their imagination; power their future", which offers bursaries to students pursuing relevant degrees.

5. **Promote cross-sector adoption and international collaboration**
   The UK should showcase PIC applications across data centres, telecoms and healthcare, to accelerate adoption and secure a stronger global position. CSA Catapult can act as a neutral demonstration and collaboration platform, supporting multi-sector pilot projects, engaging international partners, and promoting UK-developed PIC solutions into global markets.

Conclusions

Conclusions

Photonic integrated circuits are moving steadily from research into widespread commercial use. The analysis in this report shows that their impact is not confined to one sector but spans communications, data centres, healthcare, automotive, quantum technologies and defence. The common thread across all of these areas is the need for faster data handling, lower energy consumption, and more compact, integrated systems — needs that conventional electronic approaches alone can no longer meet.

Several cross-cutting points emerge. Energy efficiency is now a primary driver of adoption. Data centres, AI workloads and mobile networks all face rising power demands, and PICs offer a way to decouple growth from energy use. Integration is another key theme: progress depends on scalable packaging, reliable co-design tools, and supply chains that effectively integrate photonics and electronics. Finally, the ecosystem remains immature compared to that of electronics. Skills shortages, limited access to multi-project wafer runs, and high packaging costs continue to slow the pace of adoption.

For the UK, the opportunities are clear. The domestic photonics sector is already highly productive, contributing £18.5 billion annually and employing over 84,000 people. With recognised strengths in compound semiconductors, research excellence, and a growing base of innovative companies, the UK is well-positioned to capture a greater share of this market. However, international competitors are moving quickly, supported by coordinated national programmes. Without similar commitment, the UK risks losing ground and becoming reliant on overseas suppliers.

The economic case extends beyond market share. PICs align directly with national priorities in AI, quantum, secure communications and clean growth. They can support long-term competitiveness, reduce reliance on energy-intensive infrastructure, and create high-value jobs. To achieve this, the UK will need to scale up manufacturing, strengthen packaging and prototyping capabilities, and invest in specialist training.

CSA Catapult has an important role in enabling this transition. By providing shared facilities for co-design, co-packaging and prototyping, the Catapult lowers barriers to entry and reduces risk for companies adopting PICs. By building links across industry, academia and government, it can help ensure that UK-developed technologies move beyond research and into deployment.

The message is straightforward: PICs are no longer optional or peripheral. They are becoming a critical part of modern digital infrastructure. If the UK acts now to build capability and capacity, it can secure long-term leadership.

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CSA CATAPULT

Innovation Centre
Imperial Park
Celtic Way
Newport NP10 8BE

collaboration@csa.catapult.org.uk
01633 373121

@CSACatapult

Compound Semiconductor
Applications (CSA) Catapult

CATAPULT Compound Semiconductor Applications

UKRI Innovate UK