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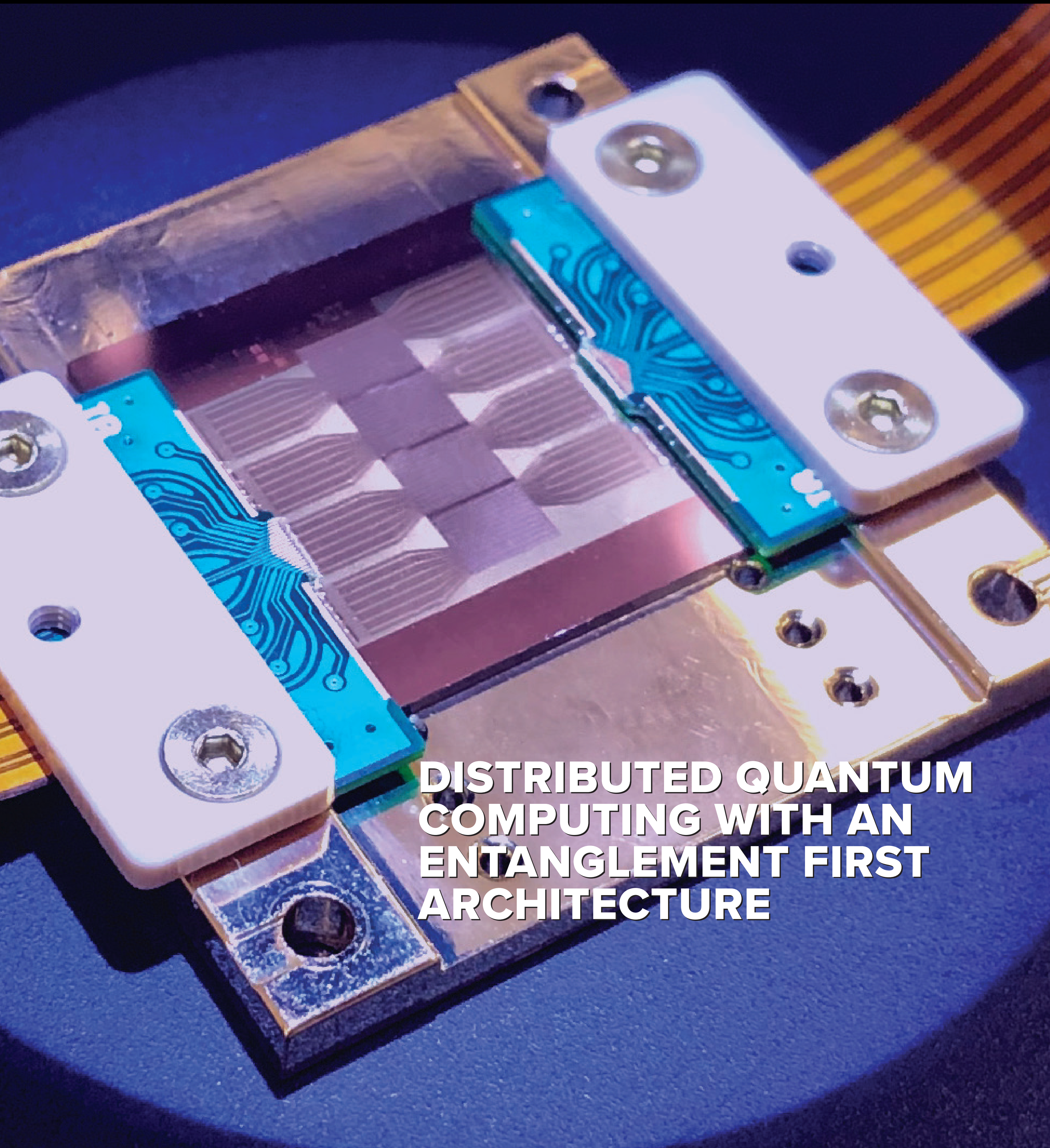

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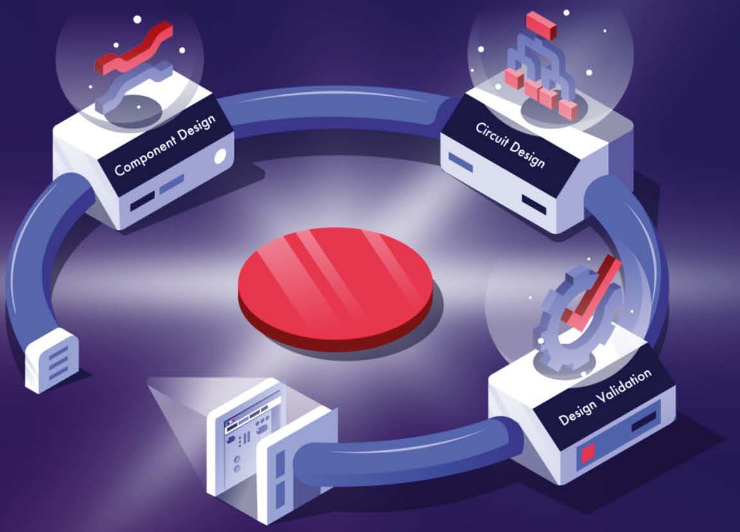

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VIEWPOINT

BY LAURA HISCOTT
EDITOR

A quantum inflection?

LAST YEAR, the UN announced it had designated 2025 the International Year of Quantum Science and Technology (IYQ) to celebrate a century of quantum mechanics. In the last 100 years, researchers have not only dramatically expanded their understanding of quantum phenomena, but have also made huge strides in harnessing them to create new kinds of technologies.

Several companies are now taking impressive steps towards achieving a universal fault-tolerant quantum computer – among the most eagerly awaited promises of the quantum revolution. Yet developing such sophisticated technologies is often, as one might expect, a long-term endeavour, and it can be difficult to stay in the public spotlight during that process.

In the last few years, quantum tech – whose name is almost synonymous with groundbreaking research – has perhaps fallen slightly into the shadow of AI. Since the advent of ChatGPT, it seems, this other futuristic technology has dominated the airwaves – not only in the public conversation, but also in the PIC industry.

It might have put a dampener on the start to IYQ, then, when Jensen Huang – whom I hardly need introduce as NVIDIA CEO – said in January that we are 15-30 years away from very useful quantum computers. That may be true. Indeed, many experts in the industry estimate similar timelines. But Huang's comments were interpreted somewhat negatively, reportedly causing stock prices of multiple quantum computing companies to nosedive.

But that was not the end of the story. In a surprise turnaround, reports emerged in May that NVIDIA was considering investing in PsiQuantum – one of the major companies in the quantum computing race. In early June, Huang appeared altogether more optimistic about the field, commenting at a conference for AI developers in Paris that "there's an inflection point happening in quantum computing" and that we might expect something similar to Moore's law to take off for logical qubits. Whatever it was that changed Huang's mind, it was a welcome remark for the quantum industry, whose shares duly soared soon after.

But this vote of confidence is also excellent news for PICs, which are a key enabling technology for multiple different quantum computing architectures. PsiQuantum itself uses photonic qubits and in February announced its quantum photonic chipset "purpose-built for utility-scale quantum computing". But companies pursuing other, non-photonic-centric qubit platforms are also likely to need integrated photonics to scale their systems. In just the last few months, both IonQ – which uses trapped ions – and Pasqal – which uses neutral atoms – have announced acquisitions of integrated photonics companies.

So, whichever qubit platform triumphs, it seems likely that the PIC industry will play a significant role in bringing quantum computers to fruition. With all the buzz in recent years, AI has frequently been touted as integrated photonics' "killer application". As quantum heats up, maybe another one is around the corner.

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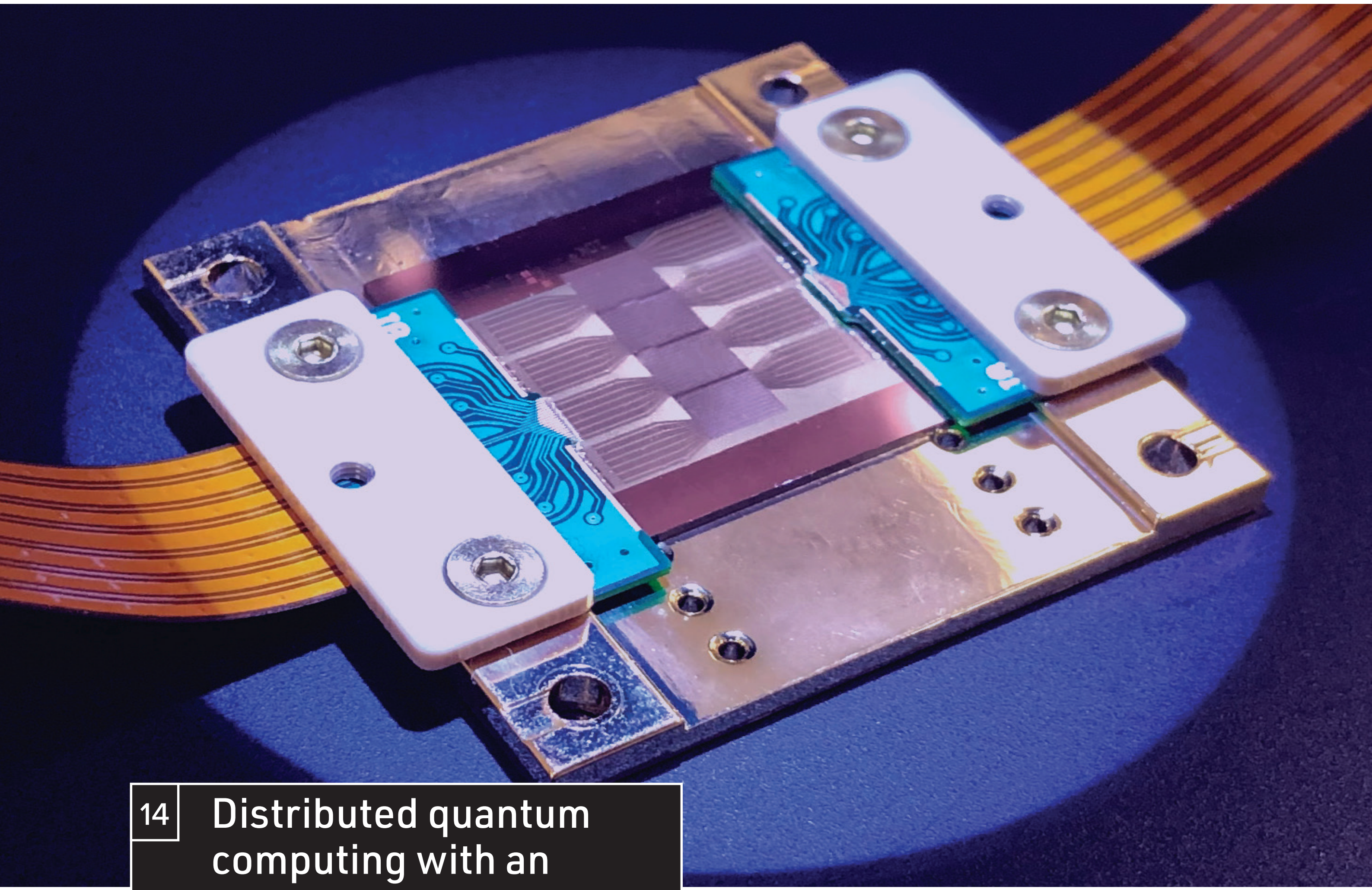

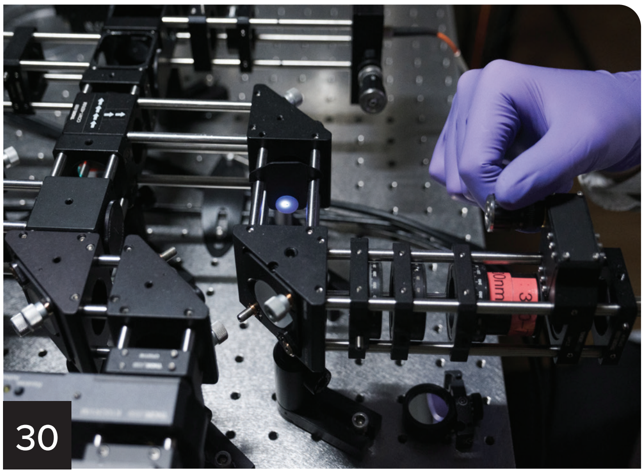

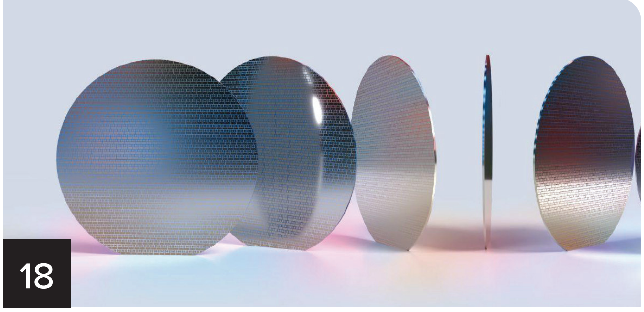
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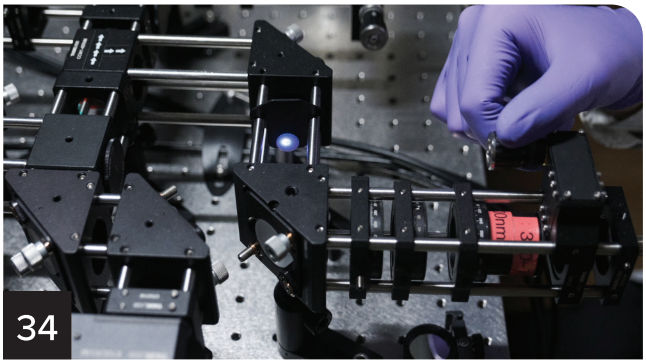
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NEWS


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Quantum photonic processor boosts machine learning

Using a quantum photonic circuit, researchers demonstrated that even small-sized quantum computers can outperform conventional systems, potentially inspiring the design of new algorithms that improve performance and reduce energy consumption

AN INTERNATIONAL TEAM of researchers of the University of Vienna has published an experimental study on a photonic quantum processor, reporting that small-scale quantum computers can boost the performance of machine learning algorithms.

The scientists say the work, which appears in *Nature Photonics*, shows promising new applications for optical quantum computers.

Machine learning and artificial intelligence have already revolutionised our lives from everyday tasks to scientific research, while quantum computing has emerged as a new paradigm of computation.

The combination of these two fields has opened up a new line of research: quantum machine learning. This field aims to find potential enhancements in the speed, efficiency, or accuracy of algorithms when they run on quantum platforms.

To this end, an international team of researchers designed a novel experiment carried out by scientists from the University of Vienna. The setup features a quantum photonic circuit built at the Politecnico di Milano (Italy), which runs a machine learning algorithm first proposed by researchers working at Quantinuum (UK).

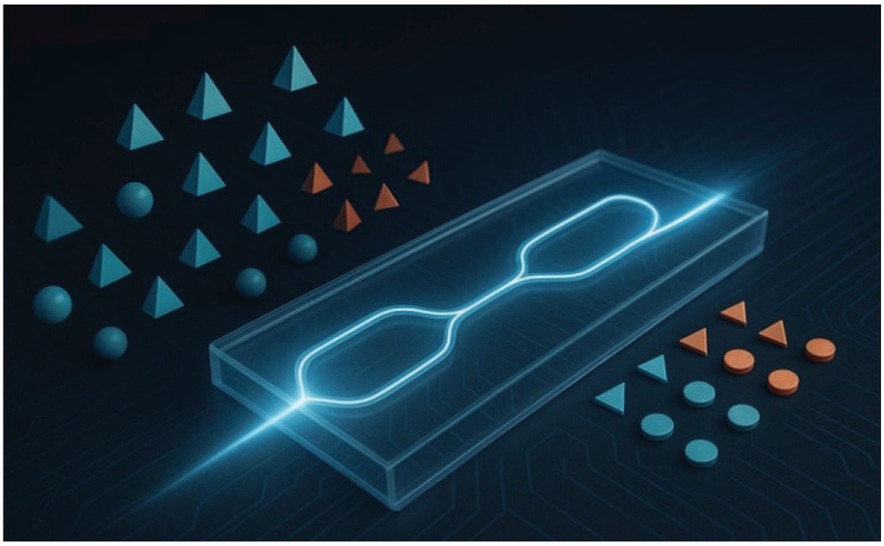

Image credit: Iris Agresti

The goal was to classify data points using a photonic quantum computer and single out the contribution of quantum effects, to understand the advantage with respect to classical computers.

According to the team, the experiment showed that even small-sized quantum processors can already perform better than conventional algorithms. “We found that for specific tasks our algorithm commits fewer errors than its classical counterpart,” explains Philip Walther from the University of Vienna, who led the project.

Zhenghao Yin, first author of the publication, added: “This implies that existing quantum computers can show good performances without necessarily going beyond the state-of-the-art technology.”

Another interesting aspect of the new research is that photonic platforms can consume less energy with respect to standard computers.

“This could prove crucial in the future, given that machine learning algorithms are becoming infeasible, due to the too high energy demands,” emphasises co-author Iris Agresti.

The researchers say their results have an impact both on quantum computation, since they identify tasks that benefit from quantum effects, and on standard computing. Indeed, the study could lead to the design of new algorithms inspired by quantum architectures that achieve better performance and reduce energy consumption.

Another interesting aspect of the new research is that photonic platforms can consume less energy with respect to standard computers. “This could prove crucial in the future, given that machine learning algorithms are becoming infeasible, due to the too high energy demands

Silicon Austria Labs joins PIXEurope

The research institute will focus on integrating high-performance electro-optic materials such as thin-film lithium niobate and aluminium nitride onto silicon and silicon nitride PIC platforms, enabling ultra-fast modulation, low-power photonic signal processing, and broadband operation

Image credit: Silicon Austria Labs

Coordinated by ICFO, the PIXEurope pilot line has officially kicked off in Barcelona, aiming to unite leading European research institutions to establish the world's first open-access PIC ecosystem.

Backed by the European Chips Act, the initiative will invest €400 million to accelerate the development and production of photonic chips in Europe, which are critical for next-generation applications in telecommunications, AI, mobility, imaging, and sensing.

By leveraging its expertise in integrated photonic and thin-film integration, Silicon Austria Labs (SAL) aims to contribute to developing scalable, high-performance fabrication processes and ensure smooth technology transfer to industrial partners.

A key focus for SAL will be the integration of high-performance electro-optic materials such as thin-film lithium niobate (TFLN) and aluminium nitride (AlN).

According to SAL, these materials will be integrated onto silicon and silicon nitride PIC platforms, enabling ultra-fast modulation, low-power photonic signal processing, and broadband operation. Such capabilities are essential to realising next-generation green and efficient photonic technologies.

"Research and technology are the driving forces behind Austria's productivity and competitiveness," said Peter Hanke, Austrian minister for innovation. "It is therefore important to me to make targeted investments in innovation, even in difficult budgetary times. The PIXEurope pilot line is another strategic milestone for Europe as a technology location. Through Silicon Austria Labs, Austria is once again making a strong contribution to accelerating technological progress, strengthening industrial performance and supporting the EU's goals in the area of digital and green transformation. In addition, the initiative will contribute to the creation of high-tech jobs and strengthen Europe's technological sovereignty."

Mohssen Moridi, senior director at SAL, commented: "We are proud to be a key player in this pilot line and collaborate with other major players in Europe. Our capabilities in integrating TFLN and AlN onto 200 mm wafer platforms – combined with advanced microfabrication – will unlock new application fields and strengthen Europe's position in photonic chip innovation."

PIXEurope aims to advance Europe's goal to lead in photonic chip development. By enabling faster prototyping, scalable production, and open access to the next generation of photonic technologies, the initiative aims to empower start-ups, SMEs, and established industry players alike to thrive in the fast-evolving digital economy.

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Xanadu reports on-chip generation of error-resistant photonic qubits

Describing its results as the first demonstration of such qubits on a chip, the company says the experiment generated specific quantum states that enable logic operations at room temperature and are suitable for networking with standard fibre connections

QUANTUM computing company Xanadu has announced it has achieved a significant milestone in the development of scalable quantum hardware by generating error-resistant photonic qubits on an integrated chip platform.

The company has published its results, which it describes as a foundational result in its roadmap and the first-ever demonstration of such qubits on a chip, in the journal *Nature*.

This development builds on Xanadu's recent announcement of the Aurora system, which it says demonstrated – for the first time – all key components required to build a modular, networked, and scalable photonic quantum computer.

The company says this latest demonstration further strengthens the scalability pillar of its architecture.

According to Xanadu, the quantum states produced in this experiment, known as GKP states, consist of superpositions of many photons to encode information in an error-resistant manner – an essential requirement for future fault-tolerant quantum computers.

The company reports that these states allow logic operations to be performed using deterministic, room-temperature-compatible techniques, and they are uniquely well-suited for networking across chips using standard fibre connections.

Xanadu says this demonstration of generating photonic qubits was enabled by a number of key technological achievements from its hardware team, including the development of photon-number-resolving detectors with detection efficiencies above 99 percent, the fabrication of customised ultra-low-loss silicon nitride waveguides on 300 mm wafer platforms, and the implementation of in-house state-of-the-art optical packaging.

"GKP states are, in a sense, the optimal photonic qubit, since they enable logic gates and error correction at room temperature and using relatively straightforward, deterministic operations," says Zachary Vernon, CTO of hardware at Xanadu.

"This demonstration is an important empirical milestone showing our recent successes in loss reduction and performance improvement across chip fabrication, component design, and detector efficiency."

The next hurdle towards a utility-scale photonic quantum computer, Xanadu says, is the further reduction of optical loss to allow for higher-quality GKP states suitable for fault-tolerance.

To this end the company plans to further optimise fabrication and photonics packaging processes to alleviate optical loss across its platform.

Ranovus and Drut partner on co-packaged optics for AI

By combining Drut's photonic fabric with Ranovus's CPO optical interconnect technology, the companies aim to address the demands for high bandwidth, low latency, and power efficiency in datacentres

RANOVUS, a provider of interconnect solutions, and Drut Technologies, a company focusing on software-defined photonic solutions for datacentres, have announced a new collaboration to enable infrastructure for AI, machine learning, and high-performance computing workloads.

Drut aims to deliver the system architecture and control plane to harness the benefits of an all-photonic fabric architecture for AI computing clusters.

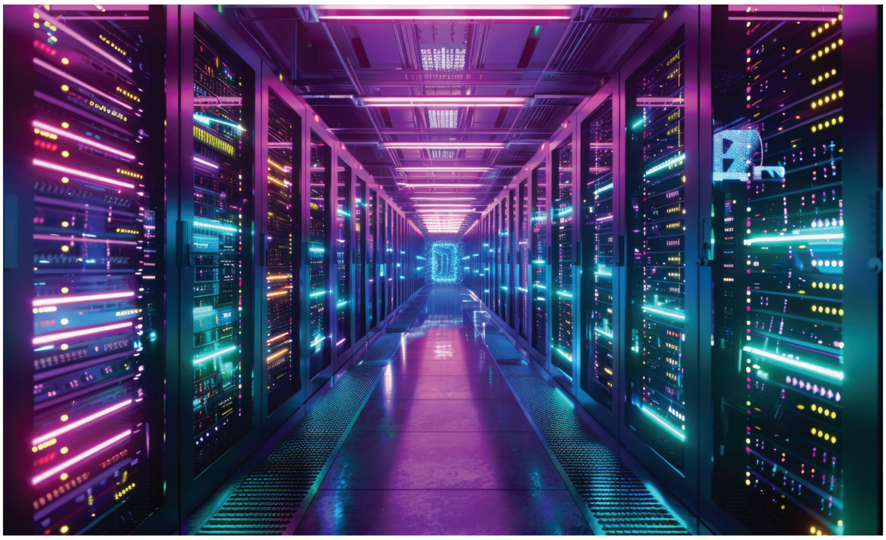
Drut says its 2500 series enables PCIe Gen 5 servers to be directly connected to photonic fabrics with full x16 line speed of 32G per serdes.

According to the companies, the integration of Ranovus's ODIN CPO optical interconnect technology further enhances this performance by addressing the critical bandwidth, density, and power consumption challenges associated with traditional high-speed electrical interconnects.

The 2500 series is one of the first commercially available solutions using the CPO technology, Drut adds.

"We are thrilled to partner with Drut to bring the transformative benefits of our CPO technology to their game-changing 2500 series," said Hojjat Salemi, chief business development officer at Ranovus. "Drut's unwavering focus on pushing the boundaries of network performance aligns perfectly with our mission to revolutionise datacentre interconnect."

"Together, we are empowering the next generation of AI and hyperscale infrastructure for PCIe Gen 5/Gen 6/Gen 7 and 100G and 200G ethernet connectivity."



William R. Koss, CEO and president of Drut Technologies, commented: "Ranovus's ODIN CPO technology is a true industry disruptor. Integrating their solution into our 2500 series allows us to deliver unparalleled levels of performance and density while significantly reducing power consumption and footprint. This partnership underscores our commitment to providing leading-edge networking solutions that anticipate and exceed the evolving needs of our customers."

This collaboration aims to address the increasing demand for higher bandwidth and lower latency in modern datacentres. As AI, machine learning, and other data-intensive applications become increasingly prevalent, the need for efficient, high-density, and scalable interconnect solutions continues to grow. Ranovus and Drut say their combined expertise offers a compelling solution to these challenges, enabling the creation of powerful and sustainable datacentre infrastructure.

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Aeluma and Thorlabs announce breakthrough for quantum PICs

The companies have collaborated to demonstrate wafer-scale integration of aluminium gallium arsenide – a nonlinear optical material that enables entangled photon pair generation – onto 200 mm CMOS silicon photonics wafers

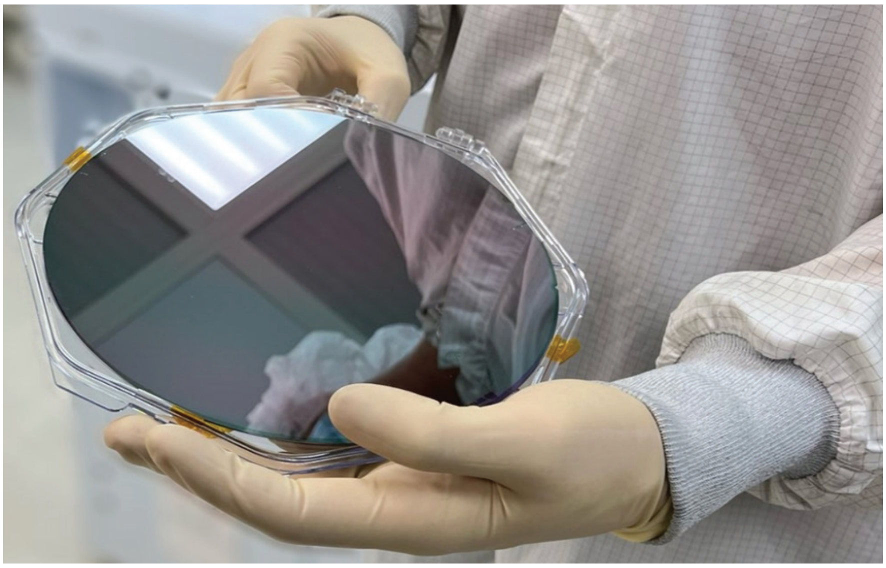
AELUMA, a semiconductor company focusing on high-performance, scalable technologies, together with Thorlabs, a vertically integrated photonics products manufacturer, has announced an advancement in silicon photonics that could accelerate adoption of quantum computing and communication at commercial scale.

According to Aeluma, its large-diameter wafer platform combines the performance of compound semiconductors with the scale of mainstream silicon manufacturing, enabling cost-effective solutions across high-growth markets including mobile, AI, defence and aerospace, automotive, and quantum computing.

Silicon photonics is a promising technology for quantum computing and communication. Aeluma says its ability to incorporate quantum dot sources and highly nonlinear electro-optic materials unlocks new high-performance functionality for this platform.

Collaborating with Thorlabs, and with support from the Office of Secretary of Defense, Aeluma has demonstrated wafer-scale integration of aluminium gallium arsenide, a nonlinear optical material, onto CMOS silicon photonics standard 200 mm diameter wafers, providing a potential path for scaling complex quantum photonic circuits.

The nonlinear optical material is designed to enable entangled photon pair generation and modulation, key building blocks for quantum photonic systems



The nonlinear optical material is designed to enable entangled photon pair generation and modulation, key building blocks for quantum photonic systems. Compared with other materials like silicon nitride or lithium niobate, Aeluma says that aluminium gallium arsenide offers significantly improved efficiency for next-generation quantum photonic circuits.

“Scalable photonic integration is essential to move quantum technologies out of the lab and into real-world systems,” said Matthew Dummer, director of technology at Aeluma. “By merging the performance of compound semiconductors with the scalability of silicon photonics, we are pushing the boundaries of what’s possible in quantum and AI.”

This combination of advanced materials and CMOS silicon substrates, using manufacturing methods compatible with mainstream fabs, marks a step towards volume production, which could move quantum technologies out of research labs and into mass-market products, the company adds.

“This successful collaboration was enabled by the large-area epitaxial growth capabilities of Aeluma and the direct wafer bonding expertise at Thorlabs,” added Garrett Cole, manager of Thorlabs Crystalline Solutions.

“The heterogeneous integration of compound semiconductor materials on silicon is broadly applicable and now shows significant promise for quantum photonics.”

Aeluma says the demonstration complements its work with quantum dot materials in 300 mm silicon photonics, aimed at optical interconnects for AI infrastructure and advanced sensing. It directly addresses a longstanding challenge in scaling quantum photonic systems and could provide a meaningful step forwards for quantum system integrators pursuing scalable, production-ready solutions.

Pasqal acquires AEPONYX to advance quantum computing with PICs

The company plans to integrate AEPONYX's photonic chips to provide the light needed to manipulate neutral atom qubits, a move it says will bring a new level of accuracy, robustness, and scalability to its quantum computing system

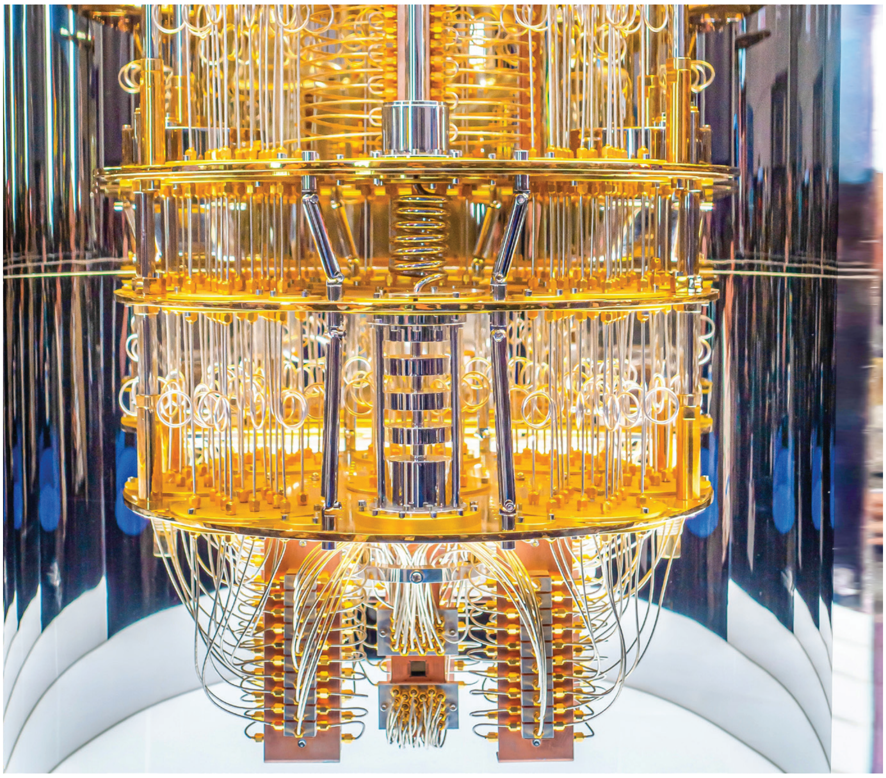
PASQAL, a company focusing on neutral-atom quantum computing, has announced the acquisition of AEPONYX, a Canadian company specialising in PICs.

The company says this strategic move strengthens its hardware platform and accelerates its roadmap to fault-tolerant quantum computing, a critical milestone towards unlocking quantum's full potential.

Pasqal's quantum computing platform uses neutral atoms, suspended in space using lasers, as quantum bits, or qubits, which store and process quantum information.

Controlling the light that manipulates these atoms requires extreme precision, more than traditional systems can provide. According to Pasqal, AEPONYX's PICs offer a compact, stable, and efficient way to generate and control the complex light fields required to trap, arrange, and entangle these atoms.

By embedding this technology directly into its processors, Pasqal aims to bring a new level of accuracy, robustness, and scalability to the complex optics needed to run a quantum computer.



"AEPONYX has built some of the most precise and scalable light-control chips available now," said Loïc Henriet, CEO of Pasqal. "By combining their technology with our neutral-atom architecture, we're tightening our control over a critical part of the hardware stack. This gives us a competitive edge in scalability, advanced individual control of qubits, and hardware stability – three main goals every quantum company must achieve to deliver value at scale." Pasqal says the integration of PICs will allow it to replace delicate optical setups with chip-scale photonic circuits that will dramatically increase the stability of atom control and the precision of individual qubit manipulation, while also simplifying scaling from hundreds to thousands of qubits.

"Quantum computing is crossing a threshold – from proof-of-concept to real, usable processors," said Philippe Babin, CEO of AEPONYX. "Joining Pasqal means our photonics will help power that leap. Together, we're not just making better quantum machines – we're building the foundation of a new computing era."

According to the two companies, the combination of neutral atom qubits and photonic chips delivers a unique technological edge: unmatched control fidelity, error resilience, and hardware stability. These are the critical ingredients in the next-generation digital fault-tolerant quantum computing – processors that detect and correct their own errors in real time.

With this acquisition, Pasqal says it is executing on its broader vision: to build the world's most practical and scalable quantum computer systems, moving quickly to enterprise-ready platforms.

"The future of computing will belong to the leading companies who can make quantum systems practical, reliable, and scalable," Henriet added. "With AEPONYX on board, we're a giant step closer to that future."

Perceptra wins PhotonDelta's global engineering contest

The start-up, which aims to build the first ultra-compact, PIC-based molecular analysers to transform the biotech industry, will receive €50,000 in services to advance the concept

PHOTONIC CHIP industry accelerator PhotonDelta has announced the winner of its global engineering contest. Perceptra was judged to be the submission with the best new application of photonic chips designed to tackle global challenges.

The start-up's entry focused on developing the first ultra-compact, low-cost PIC-based Raman analysers for real-time molecular monitoring in biomanufacturing and other process industries. Its technology aims to replace bulky dispersive spectrometers with on-chip tuneable lasers, which could transform the biotech industry and help bring lifesaving innovations to the market faster.

Perceptra will receive €50,000 worth of services to bring their concept to life and the opportunity to raise a favourable loan of up to €2 million with PhotonDelta to kick-start the company's growth. Having demonstrated proof-of-concept, Perceptra plans to use the funding to develop a first PIC-based version of the system.

To help launch Perceptra's solution, PhotonDelta will showcase this winning submission at the upcoming industry leading event PIC Summit Europe 2025, which brings together 700 industry experts from over 25 countries in Eindhoven, the Netherlands on 4 and 5 November.

Currently, bioprocessing and biomanufacturing practices have significant inefficiencies due to reliance on offline analytical testing to measure molecular concentrations in processing equipment like bioreactors. This limits access to real-time, high-quality data for R&D, delays time-to-market for critical life-saving products, and leads to poor process monitoring and control, ultimately contributing to high failure rates in biomanufacturing.

PhotonDelta and Wevolver launched the engineering contest to help drive the creation of innovative ideas for photonic chip-based solutions that address some of the world's most pressing societal and technical challenges, from combating climate change and advancing healthcare to addressing energy sustainability challenges.

The contest received 33 high-calibre entries from over 15 countries from all continents. In total, over 350 organisations engaged with the contest worldwide. Contest entries were judged on the level of innovation, technical and commercial feasibility, and how effectively the design addresses current industry challenges. Participants were required to submit detailed descriptions of their projects, including team information and supporting visuals or videos.

Other notable entries that PhotonDelta has highlighted include Linq with the Matrix Electro-Optic Modulator (M-EOM) – a PIC-solution designed to address scalability and precision challenges in neutral atom quantum computing – and FlowBeams with a laser-actuated, needle-free jet injector using microfluidics and PICs to revolutionise medical and cosmetic injections.

The contest was backed by a €60 million fund from PhotonDelta, set up to fund new start-ups and innovative applications in the photonic chip industry.

By offering favourable loans to companies, the fund aims to support entrepreneurs in turning their ideas into viable businesses.

The initiative's goal is to foster innovation at the earliest stages, encouraging the development of new technologies and applications that can shape the future of the PIC industry.

Distributed quantum computing with an Entanglement First architecture

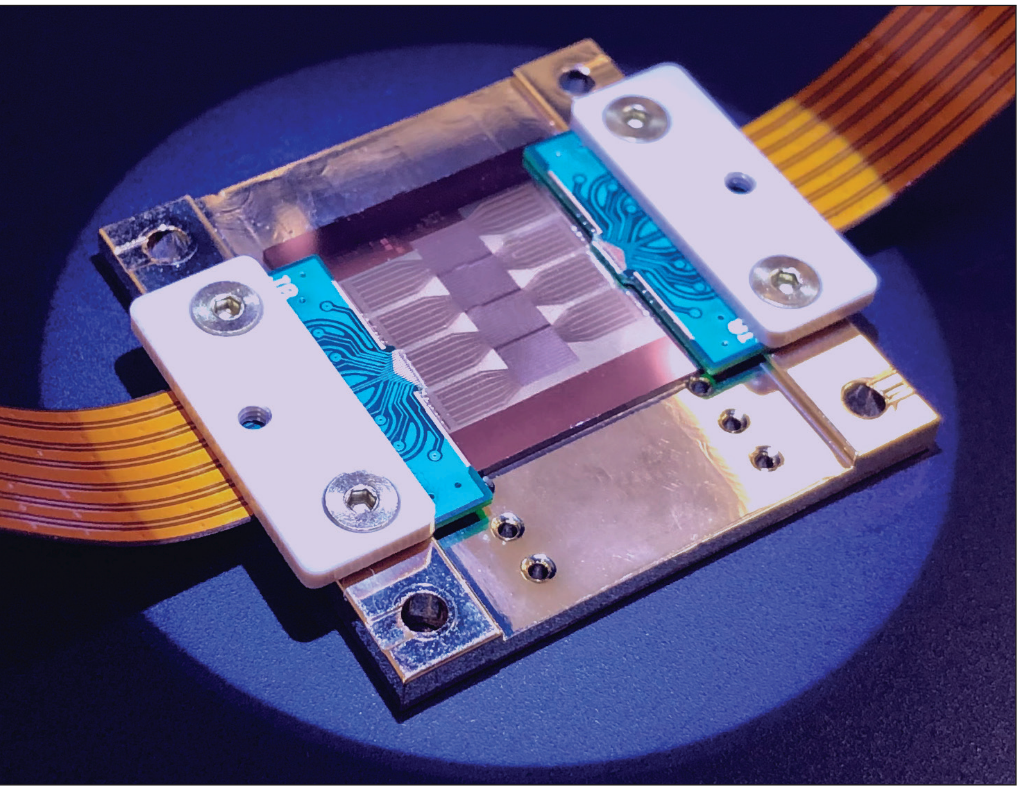
Photonic Inc. is harnessing silicon photonics to build a high-connectivity, modular system that solves the scalability challenge in quantum computing and paves the way for its use in commercially relevant applications.

BY KEVIN MORSE, SENIOR TECHNICAL PRODUCT MANAGER, PHOTONIC

TO REALISE the full potential of quantum computing in commercially relevant applications, including materials science, drug discovery, climate change, and security, we will need to build large-scale quantum computers. However, there is a well-known obstacle in scaling quantum technology: the difficulty of connecting individual systems to get beyond a single unit and perform distributed quantum computing across modules.

This feat demands the efficient creation and distribution of high-quality entanglement – a property that links two qubits (quantum bits) such that what affects one affects the other instantaneously, regardless of the distance between them. At a high level, we can think of entanglement as a critical resource for information transfer and operations in quantum computers. Any high-performance quantum computing system must therefore be able to efficiently generate, distribute, and consume entanglement.

There are two broad categories of techniques that quantum computers use to generate entanglement: direct coupling (proximity-based) and mediated interaction (for example via photons). In the former, the qubits are physically close enough to connect to one another. In photon-based mediated interaction approaches, photons interfere with one another and entangle the qubits, while the qubits themselves remain physically separated.

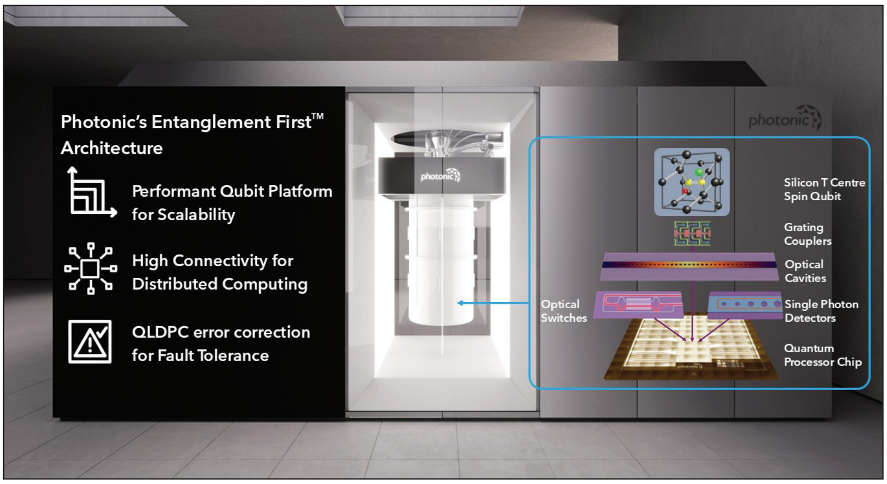


At Photonic Inc., we have developed a photon interference-based Entanglement First architecture, so named because it prioritises this key resource. Rather than using photons as the qubits, as some other companies do, we instead use colour centres in silicon as the qubit platform, while photons serve as the interconnects between them.

In Photonic's technology, a qubit emits telecom-wavelength photons that are spin-entangled, meaning that their quantum state is directly linked to a property of the qubit called its spin state. This entanglement is crucial for performing quantum operations both within and across modules, as well as for distributing entanglement across the network, and becomes increasingly complex as systems scale.

Telecom photons can enable high-connectivity links between systems, but they only do so efficiently if the system has been designed to interface with optical fibre without the need for signal frequency conversion between electrical and optical ranges (transduction). This is what Photonic's Entanglement First architecture is built to do, paving the way for large-scale quantum computing and networking [1].

Footnote: Entanglement First is a trademark of Photonic Inc.



➤ Figure 1. Entanglement First Architecture Overview: The architecture consists of silicon T centres embedded in optical cavities, photonic switches, and single-photon detectors, all cooled in a 1 K cryostat. These components are connected via telecom fibre to room-temperature photonic switch networks and control electronics. The setup allows for non-local connectivity, enabling both the expansion of computing power and the creation of long-distance quantum networks. The system is designed for integration into standard datacentre setups.

From the outset, we designed this approach to scale up, with continual increases in the quantity and density of components within a single unit, and to scale out, by adding units to a network.

Drawing inspiration from classical cloud computing, where networking has enabled massive compute power, Photonic focuses on integrating intermodular operations, a unique challenge for quantum technologies. To do this, we combine three powerful technologies.

First, we use a high-performing qubit platform carefully chosen to support scalability. Our low-cost, high-density silicon spin qubits have an optical interface to facilitate communication through photons. They also have long coherence times, meaning they can maintain their quantum states for a long time, an essential capability for commercial applications.

Second, we harness a switched optical architecture that incorporates silicon photonics and telecom fibre to enable on-demand entanglement both within and between modules. This feature makes for a high-connectivity system to facilitate distributed computing.

Such high connectivity also supports a specific technique for correcting computational errors called quantum low-density parity check (QLDPC) codes. Compared with other conventional methods, these codes are fast and efficient at addressing any errors that occur in the quantum computing operations, with a known instance requiring up to 20 times fewer qubits for this task.

This combination makes it possible to distribute and consume entanglement efficiently using any-to-any connectivity with telecom photons between qubits. This core capability puts Photonic's quantum system in prime position to reach commercial utility and datacentre deployment.

High-performance qubit platform

The basis of our high-performance qubit platform is the T centre in silicon, which occurs when a silicon atom is replaced with two carbon atoms, one hydrogen atom, and a free electron. These particles act as spin qubits – encoding information in their spin states and effectively serving as the compute and memory of the quantum processor.

A relatively new qubit modality, the T centre is Photonic's platform of choice due to its favourable properties for generating and distributing entanglement. First, while quantum states are inherently fragile, T centres have long coherence times, meaning they can maintain their quantum state over extended periods.

This is crucial for reliable quantum operations. Second, T centres emit telecom-wavelength photons, which are compatible with existing fibre-optic communication infrastructure, facilitating long-distance quantum communication. Finally, T centres are naturally compatible with silicon PICs, allowing for scalable fabrication using existing manufacturing techniques.

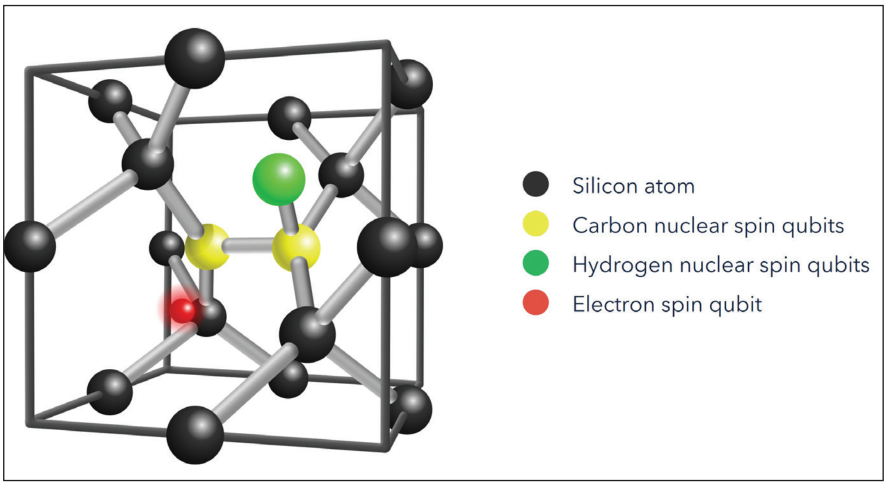
The telecom photons that are the primary carriers of quantum information are also foundational to Photonic's architecture. Emitted by the T centres, these photons establish entanglement between distant qubits connected by telecom fibres. The photons' inherent telecom wavelength is particularly advantageous because it does not require conversion into another form to travel. It also minimises loss in optical fibres, allowing for long-distance communication and any-to-any connectivity.

Photonic's system creates entanglement through methods such as the Barrett-Kok protocol [2]. This involves using an optical pulse to trigger two physically distant T centres to emit synchronised photons, each one spin-entangled with the T centre that emitted it. The two photons are then interfered on a beam splitter and directed to single-photon detectors.

If the photons are indistinguishable – meaning they are so similar it is not possible to determine which photon originated from which T centre – the entanglement will be detected when they exit the same branch of the beam splitter at the same time. The two entangled qubits are now what is called a Bell pair. This means that they have a shared state and can no longer be considered independent of each other.

Such state sharing is required before quantum information can be transferred between qubits using teleportation protocols. Last year, Photonic was the first to demonstrate distributed computing using entangled qubits in separate commercial systems using this approach [3].

As well as computation and communication of data, the computing system needs quantum memory. This is also fulfilled by the T centre spin qubits,



➤ Figure 2. Photonic's qubit platform, the T centre in silicon

which can hold a quantum state in memory and continue to emit photons until entanglement is successful. This protects the system's operation from errors if a photon is lost.

High-connectivity architecture

The T centre is rare among qubit platforms because of its direct telecom interface; it can interact efficiently with a pump laser pulse and emit a spin-entangled O-band photon. In our architecture, the T centre is embedded in a photonic cavity, which both isolates it from noise and enhances its emission rate of photons in the desired optical modes. The cavities are coupled to optical waveguides with well-defined modes so that spin-entangled photons can be accurately (and with low loss) routed to their destination, either through integrated photonic waveguides or by coupling into optical fibre. Optical fibres can then connect T centres on a single chip or across multiple chips, enabling an inherently modular and horizontally scalable design.

The use of integrated photonics is one of the most innovative aspects of this architecture, reducing losses and improving the overall performance of the quantum system. The optical cavities and photonic waveguides containing the T centres are fabricated on a silicon-on-insulator (SOI) platform, maximising photon collection efficiency and boosting the photon emission rate and quality through photonic engineering. Additionally, the SOI platform allows for high-density integration of qubits and photonic components, facilitating the creation of large-scale quantum systems. Among the essential integrated components are on-chip photonic switches, which enable the routing of photons between different T centres and other photonic components. They operate by dynamically changing the path of the photons based on control signals from room-temperature electronics.

Integrated switches reduce the overall loss and latency in the system by processing photons within the chip, minimising the number of interfaces and potential points of loss they encounter. The switches are designed to handle the high bandwidth and low loss requirements of telecom photons, ensuring that the entanglement distribution is efficient and reliable.

Single-photon detectors are another key integrated component, collecting individual photons and measuring their quantum state on-chip. Upon detecting a photon, these detectors generate a signal to confirm its transmission and reception, heralding successful entanglement events.

Specifically, Photonic's architecture employs superconducting nanowire single-photon detectors (SNSPDs), which are known for their high efficiency and low dark count rates; they catch a very high percentage of photons but rarely generate a false signal when a photon is not present. These detectors can detect single photons with high fidelity, ensuring an accurate and reliable entanglement distribution process.

The on-chip integration of SNSPDs further enhances the system's performance by reducing the overall loss and improving detection efficiency. Besides the integrated photonics, the architecture also employs off-chip, room-temperature photonic switch networks and control electronics. These are connected to the cryogenic quantum modules via telecom fibre. This setup allows for nonlocal connectivity, enabling both the expansion of computing power and the creation of long-distance quantum networks. Room-temperature components also increase the efficiency by reducing the energy and cooling requirements of the system.

A major advantage of Photonic's system is its modularity, made possible through high connectivity. In the Entanglement First architecture, each T centre is connected by an optical fibre to a switch, allowing for flexible and arbitrary routing. The system works the same way whether it is connecting qubits within systems or across modules. Instead of requiring ever-larger monolithic quantum supercomputers to increase the size of a system, this architecture can directly link multiple quantum modules across telecom fibres.

Other approaches that do not use telecom wavelength photon interference to generate entanglement require additional steps to transform to a telecom wavelength to get between modules, and then to transform back to perform operations. Photonic's approach to modularity not only simplifies scaling for quantum computers but also applies to scalable quantum networks.

Scaling fault-tolerant systems

There is still another factor to consider for building practical, large-scale quantum computers: fault tolerance. The quantum effects that underpin quantum technologies occur at a tiny, often subatomic scale, making them particularly susceptible to noise from their environment. Disruptions can lead to the loss of entangled or quantum states and to operational imperfections, resulting in computational errors.

Quantum computing systems usually handle this problem by forming logical qubits – groups of individual physical qubits that work together using error-correcting codes to detect and fix errors

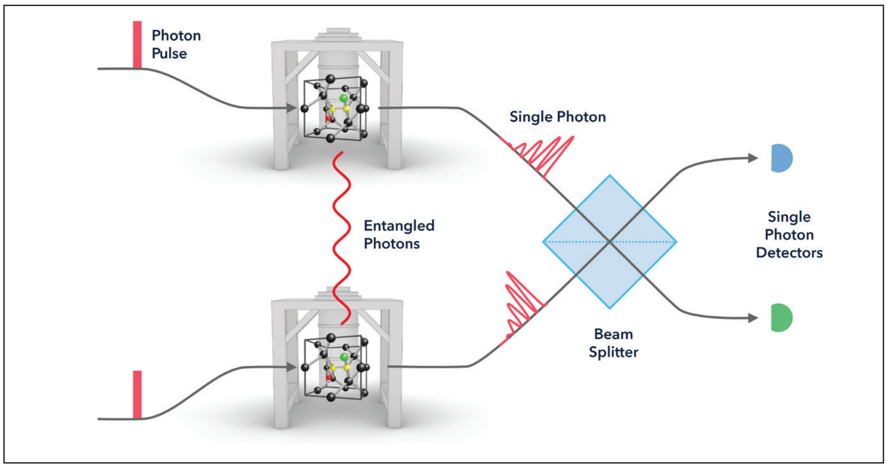


Figure 3. Photonic uses an interference-based approach to generate entanglement.

during computation. While individual qubits are notoriously unstable, groups are much more resilient to noise, enabling the system to complete operations and run algorithms reliably. Error-correction codes are therefore essential for achieving a fault-tolerant system, but there is a wide range of different codes, some of which require more physical qubits per logical qubit than others. A high-connectivity architecture offers a further benefit here: it allows more flexibility in the codes that can be used. Certain types of codes, called quantum low-density parity check (QLDPC) codes, require comparatively few physical qubits per logical qubit.

This means that a smaller system using QLDPC can achieve the same computational capacity as a larger system running a less efficient type of error-correction code. In February, Photonic introduced a new QLDPC code family, SHYPS [4], which is the first to unlock logic in this type of code [5]. This family requires up to 20 times fewer physical qubits per logical qubit than other conventional techniques.

However, QLDPC codes require a high-connectivity architecture; they are not universally implementable but are well suited to our Entanglement First system. By combining the high-performance physical architecture with these exceptionally efficient error-correction codes, Photonic is realising the true potential of large-scale, distributed, fault-tolerant systems for commercially relevant quantum computing applications. The Entanglement First system is designed to scale up and scale out, by optimising distributed computation with high connectivity and integrating key components on-chip.

The benefits of this approach are not just limited to quantum computers. The key characteristics of the architecture also meet the requirements for quantum repeaters for long-distance communication of quantum information and scalable quantum networks.

Photonic is defining the shortest path to accessible quantum services based on scalable quantum systems, accelerating the timelines to achieving the benefits of quantum technology.

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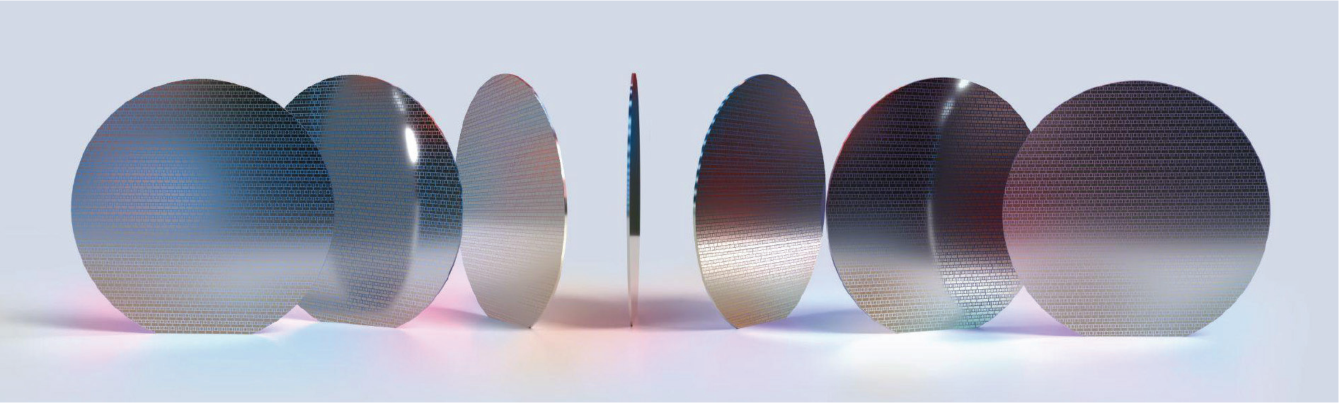


Enabling the future of integrated photonics with thin-film lithium niobate

As PICs become ubiquitous, they are ushering in a revolution in computing, communication, and sensing. Quantum Computing Inc. (QCi) recently built an agile foundry dedicated to fabricating TFLN devices, providing unprecedented access to rapid prototyping and process-informed PIC design.

BY MILAN BEGLIARBEKOV, COO, AND POUYA DIANAT, CRO, QUANTUM COMPUTING INC.

SINCE THE 1970s, Moore's law has dominated the global technological landscape, with the number of transistors on a chip doubling about every two years. However, as physical limitations and rising costs become constraining factors, it is no longer practical to increase computing capacity by shrinking transistors. Furthermore, it has long been acknowledged that other physical phenomena underpinning the meteoric growth of CMOS are coming to an end.

Dennard scaling, for instance, described how the power density is roughly constant for a given die size, meaning that power usage and waste heat would not be increased by packing more, smaller transistors into the same area. Recent experiments, however, have shown that making transistors even smaller no longer reduces power consumption, but can in fact increase it due to effects like current leakage. Meanwhile, Amdahl's law states that adding more processing cores can only reduce latency if the system is not bottlenecked by parts of a task that cannot run in parallel. This puts a limit on how much we can speed up processing simply by adding more components.

These seemingly disastrous obstacles to continued conventional CMOS scaling can only be overcome by a new paradigm of computing – a novel architecture that looks beyond the confines of von Neumann machines and embraces new materials to carry out computation. One solution looks towards integrated photonics, using light as the signal carrier and thus bypassing the physical limitations of electrical signals.

Using light opens up new possibilities for modulation, encoding, and data transmission by leveraging additional physical properties of photons. Unlike electrons travelling through copper wires, which usually only encode data in whether a current is flowing or not, light offers additional degrees of freedom; intensity, wavelength, polarisation, and even quantum properties like entanglement, can all carry information.

By harnessing these properties, we can significantly advance both classical and quantum computing, as well as usher in breakthroughs in AI, remote sensing, LiDAR, and biomedical sensing and imaging. Integrated photonics is rapidly building a new technological playground—one with the potential to revolutionise a wide range of fields through the development of next-generation photonic hardware.

The ultimate dream of integrated photonic engineers is to create a single chip that contains all four key elements necessary for computing with light: light sources, such as LEDs and lasers; passive components, which guide and route the light (such as waveguides and splitters); active components, which modulate or manipulate the light's properties (such as phase, amplitude, or polarisation); and detectors, such as photodiodes and superconducting single-photon detectors, which capture and convert the light into electrical signals. While offering multiple functional advantages over traditional electronic integrated circuits, integrated photonics still benefits from using the same semiconductor fabrication technologies as those used in silicon-based microelectronics, to create PICs that manipulate light instead of, or in addition to, electrical signals.

A key enabler of future photonic chips is thin-film lithium niobate (TFLN), a material that has gained significant traction in the telecommunications industry over the past decade due to advances in mechanical exfoliation and etching techniques. Lithium niobate itself is an established material with a proven 60-year history of utility as the active element in nonlinear optical components and in piezoelectric transducers, which transform mechanical energy into electrical energy and vice versa. But TFLN brings to the table even more exciting possibilities, since it overcomes the biggest limitation of the bulk material: the inability to tightly confine light.

TFLN PICs are the basis of optical engines in a new computing paradigm envisioned by Quantum Computing Inc. Currently, QCi has demonstrated this computing modality in our commercially available quantum optimisation machine, named Dirac-3, which is a unique quantum-hardware approach for tackling hard polynomial optimisation problems. Dirac-3 can solve problems with variables beyond binary (0,1), including non-negative integers, decimals, and sum-constrained continuous numbers (whose values must add up to a specific total).

The system consists of an optical-feedback loop that includes an optical amplifier, a photon-mode mixer/encoder, and a loss medium to implement both linear and nonlinear loss mechanisms. In particular, the core part of the system is a Mach-Zehnder mesh – an N x N grid of Mach-Zehnder interferometers – that requires high-performance modulators. Such components can be realised at scale and at a high level of functionality in a TFLN-based optical engine.

Why TFLN?

When selecting an ideal material for integrated photonics, PIC designers must consider three key factors: optical transparency, active device performance, and manufacturing compatibility.

First, the transparency window—the range of wavelengths a material can transmit with minimal absorption or scattering—is critical for passive components like waveguides that direct light across the chip. Ideally, this window should span from UV-VIS (400–750 nm) for remote sensing and imaging, to the O-band (1260–1360 nm) for short-reach, high-capacity telecom, and the C-band (1530–1565 nm) for long-haul fibre-optic communication.

Second, for high-performance active devices, the material should exhibit strong electro-optic and nonlinear optical properties. This includes a high Curie temperature, meaning the material will retain certain important properties and will still work well at high temperatures, the presence of free charge carriers to respond to electric fields, and a refractive index above 2.1 to enable light confinement. There should also be both high second-order (χ^2) and third-order (χ^3) nonlinear susceptibilities, meaning that certain interactions between light and the material depend on the square or cube of the light's intensity.

Additionally, the electro-optic coefficient, which defines how much the material's refractive index changes in the presence of an electric field, should be greater than 25 picometres per volt, to enable efficient periodic poling and modulation. Notably, such nonlinear properties are not equally achievable in silicon-based PICs as in TFLN.

Finally, from a manufacturing standpoint, the material must be compatible with existing high-volume production methodologies. This means it needs to possess thermal and mechanical stability, low insertion and propagation losses (< 0.1 dB per centimetre), and seamless integration with existing CMOS foundry processes.

Additionally, the material should have low switching voltages – the voltage change required for the optical modulator to switch the light signal between states – so that CMOS circuits can drive modulation directly. And on top of these qualities, the material should enable realistic paths to co-packaged optics and heterogeneous integration with other components and materials. For many materials that are being tested in academic labs, engineering them to fulfil these criteria remains a challenge.

Several emerging materials such as lithium niobate, lithium tantalate, and barium titanate are currently being considered for use in integrated photonics. However, among these, TFLN is the most mature, with a well-established supply chain and a strong track record of performance. TFLN is ideal for the datacom market since it enables high-speed modulation and dense signal encoding at a lower energy cost.

Specifically, TFLN devices have been shown to support ultra-fast switching

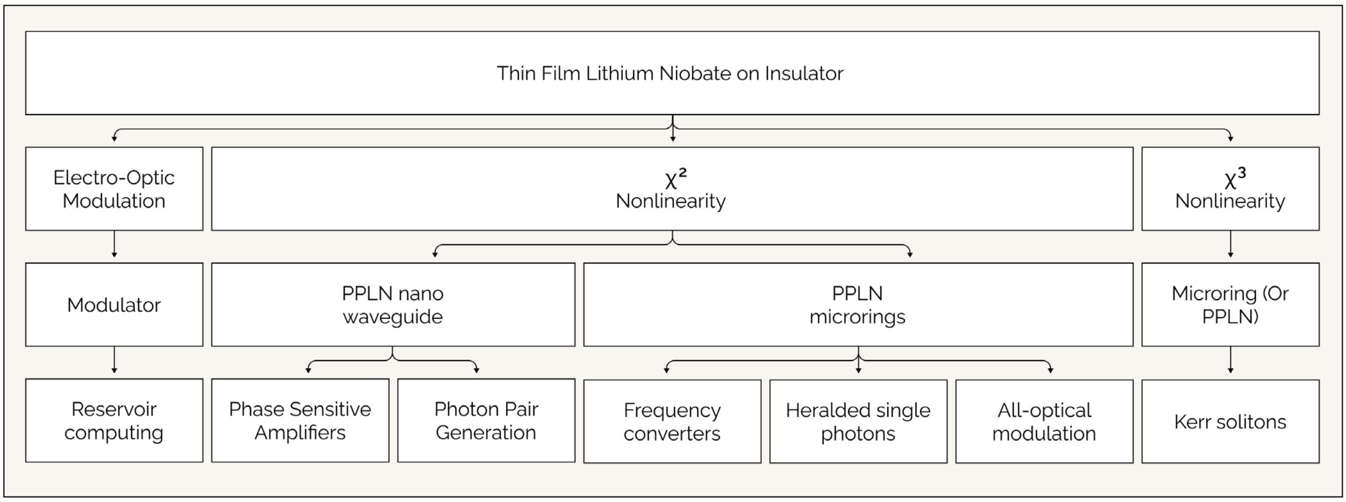


Figure 1. Key TFLN properties that enable QCi's innovative technologies and products.

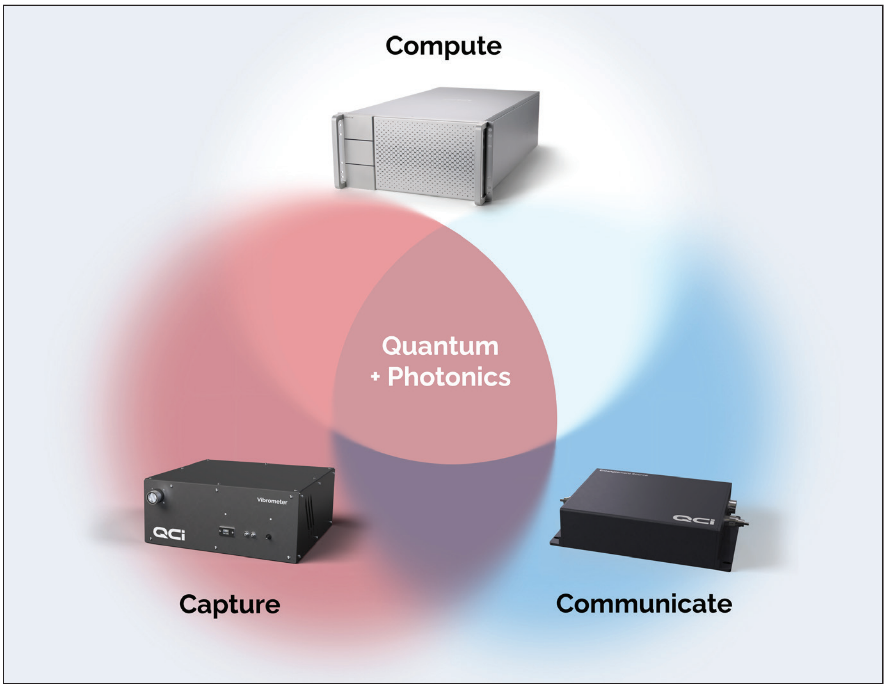
speeds exceeding 100 GHz, low driving voltages (< 1 V to shift the light's phase by half a wavelength), and large bandwidths. They are also CMOS-compatible, with exceptionally low insertion and operational losses (< 0.1 dB per centimetre). Compared to bulk lithium niobate, TFLN provides stronger light confinement, a high second-order (χ^2) nonlinearity, appreciable third-order (χ^3) effects, low propagation losses, and a large electro-optic response, supported by the presence of free charge carriers. These characteristics, summarised in Figure 1, make TFLN a highly versatile and high-performance platform, and an ideal choice of material for next-generation PICs.

Electro-optic and acousto-optic modulators are two devices where TFLN offers immediate and significant advantages over bulk lithium niobate. Traditionally, making bulk LN modulators involves a process of diffusing titanium into the LN to create a contrast in refractive index and thereby form optical waveguides to direct the light. However, this approach results in poor light confinement, as the optical mode tends to leak into the surrounding material – ultimately limiting modulation speed. TFLN overcomes this problem by tightly confining the optical mode within nanophotonic waveguides, allowing for much higher switching speeds. The enhanced confinement not only boosts performance but also enables compact, chip-scale devices – often just a few millimetres in length – making TFLN modulators ideal for high-speed, high-density photonic integration.

The QCi Foundry

QCi is a vertically integrated company providing accessible and affordable quantum machines that leverage quantum optics and integrated photonics to either capture data, compute, or support communication.

The key enabling material in our devices is lithium niobate, but for the reasons described above it is also a limiting factor for both the device footprint and performance specifications. To support continued improvements to our technology, the bulky LN components need to be replaced with TFLN PICs, which improve upon the performance and, more importantly, the stability of bulk LN, while miniaturising the size of the photonic circuits.



➤ Figure 2. QCi's core technologies use the quantum properties of light and photonics to capture, compute, and communicate data. A dedicated TFLN foundry provides a pathway to high-quality devices that optimise performance metrics with a compact footprint.

The QCi Foundry, which recently opened in Tempe, Arizona, was built to strategically support the manufacturing of TFLN PICs for our quantum machines. Over the last 12 years, the academic community has demonstrated the exceptional performance of TFLN PIC components and gained expertise in high-quality fabrication (for example, producing smooth side walls in the material) while working at university or shared-user cleanrooms.

However, our quantum machines have such stringent requirements that a dedicated TFLN foundry, where each fabrication step can be tailored to and meticulously controlled for processing TFLN, is the only path forward in optimising our performance metrics.

From a broader perspective, there is a growing consensus that TFLN will be a key enabler of next-generation optical modules for datacentres—specifically 1.6T and 3.2T—driving demand for reliable and scalable fabrication facilities. As the photonics industry moves towards higher bandwidth and more compact solutions, a dedicated foundry service for TFLN could play a crucial role in accelerating this progress.

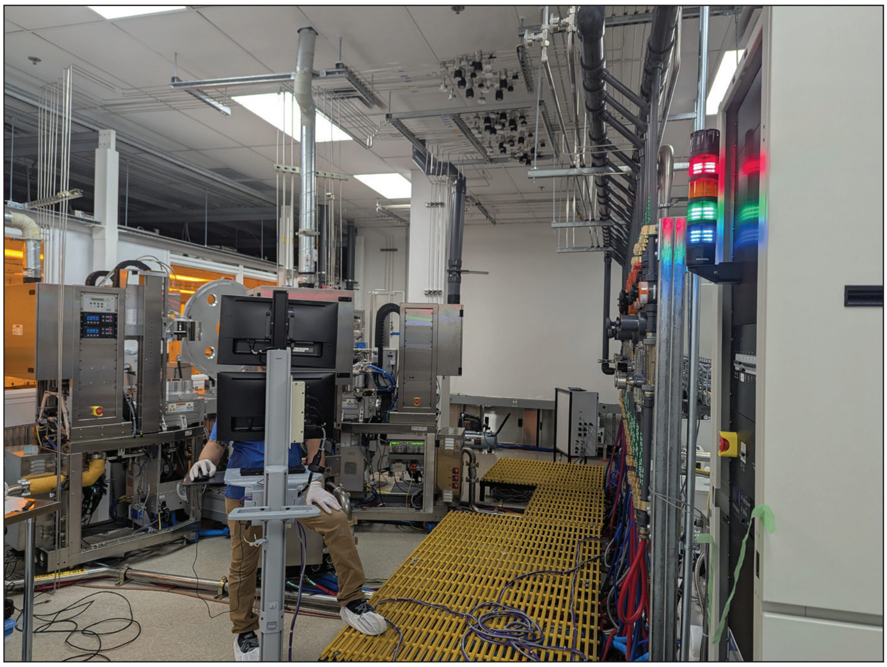
The QCi foundry's main focus is on passive and active components—the parts that steer and shape the light on the chip. For more complex elements like lasers and detectors, viable solutions include co-packaging and heterogeneous integration – smart ways to combine different technologies

> A key enabler of future photonic chips is thin-film lithium niobate (TFLN), a material that has gained significant traction in the telecommunications industry over the past decade due to advances in mechanical exfoliation and etching techniques

into one system. Another important focus area for our foundry is creating periodically poled TFLN (PPLN) devices. While it is extremely challenging to manufacture PPLN devices with high yields, having access to high-quality PPLN components and PDKs is crucial for servicing the quantum markets. We view PPLN as the gateway to nonlinear integrated photonics which will enable chip-scale quantum computing.

Currently, the QCi foundry is in its first phase, with the initial goal of being able to rapidly prototype devices and bring them to medium-volume production. The toolset was selected to suit the needs of rapid prototyping for six-inch wafers, which allows the foundry to offer both custom and multi-project wafer (MPW) runs. The foundry offers a comprehensive suite of services including design and simulation, frontend and backend fabrication, as well as optical, DC and RF testing. All these in-house capabilities mean we can support our customers for the duration of their projects. Our process design kit, which currently includes standard component libraries, layout rules, and design rule check files, is now available on the GDSFactory+ platform to help streamline the PIC design process.

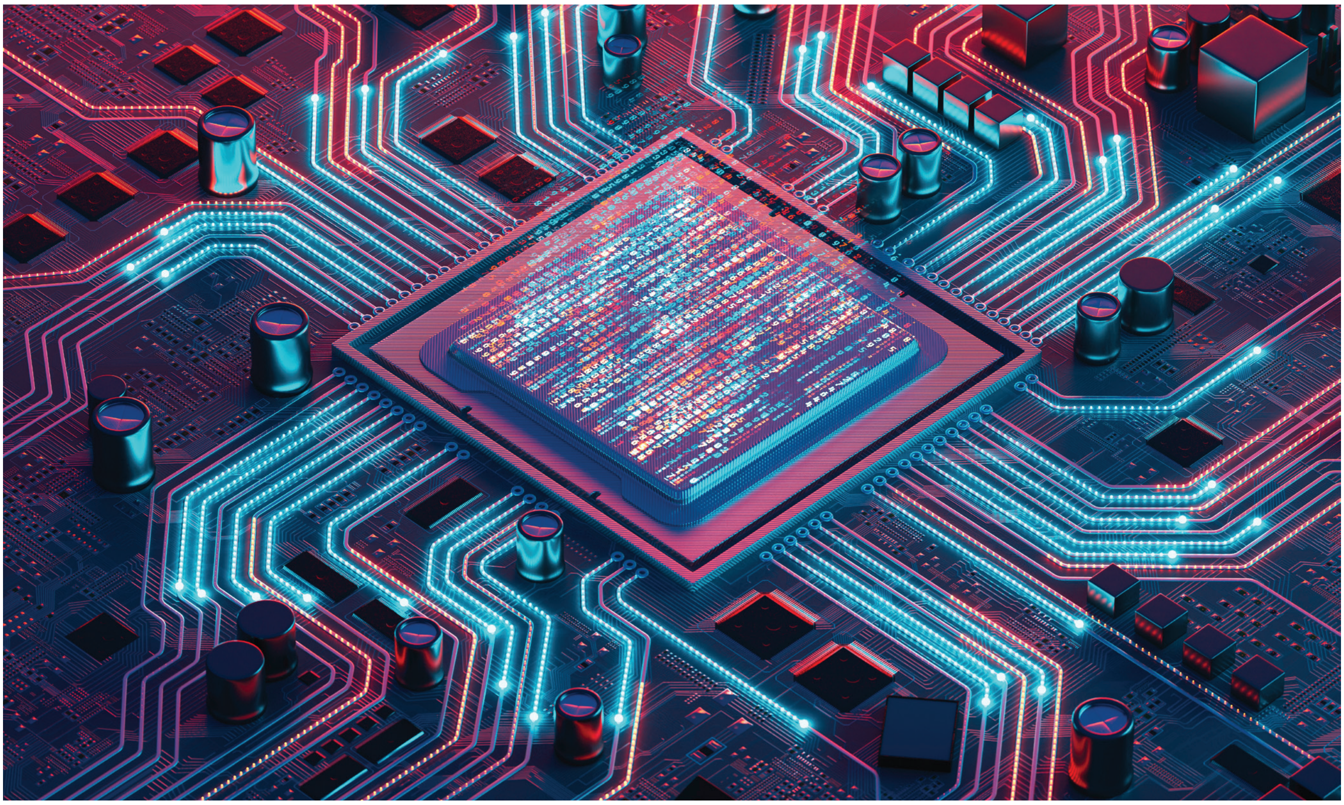
QCi's long-term goal is to commercialise an entirely new paradigm of computing that looks beyond von Neumann architectures and embraces all-optical computing in both classical and later quantum variants. These technologies require nonlinear optical methods to carry out the computation, and TFLN is the ideal material to do this. Its robust nonlinear and electro-active properties, coupled with high transparency required for quantum devices, are essential for the next generation of computing and optical AI fabrics. However, TFLN devices will need to meet highly rigorous specification demands to be suitable for quantum computing. This is why we have decided to build our own fab, where we can manufacture these devices to the highest standards. At this new facility, we will use the knowledge we gain from servicing the datacom and telecom industries as a stepping stone towards fully on-chip quantum devices.



➤ Figure 3. QCi's foundry was constructed specifically for processing TFLN.

FURTHER READING / REFERENCE

➤ https://quantumcomputinginc.com/foundry



Pure photonic CPUs: a future without electronics?

By using all-optical logic, memory, and multiplexing, Akhetonics is harnessing THz-frequency light on-chip, bypassing electronic speed limits and creating photonic processors that can advance AI inference, networking, and cryptography

BY MICHAEL KISSNER, CEO, AKHETONICS

"WHAT IS the difference between electronic computing and photonic computing?" This is a question that we at Akhetonics often get asked. The quick answer is that one uses electrical signals and the other optical. Yet under the hood, both are just electromagnetic (EM) wave processors. At first glance, an electronic chip and a PIC even look alike, until you inspect them under a microscope and notice that photonic waveguides are much larger.

The difference really comes down to frequency. At low frequencies (Hz to MHz), the EM wave's wavelength is enormous compared to chip features, so it makes sense to think of electrons shuttling through transistors instead of focusing on the wave. But once you move to the GHz domain, the wavelength is on the order of a millimetre – still much larger than most components, but it no longer covers the entire circuit in a single oscillation. Radio-frequency engineers must therefore think about guiding the wave as well, even if only in a fairly simple way.

When we increase the signal's frequency by another factor of 1000, we reach the hundreds of THz, and it is all about the EM wave travelling through the system. The wavelength, now around a micrometre, has the same order of magnitude as the components needed to guide and process it on a chip. And this is precisely when we start calling it photonic – instead of electronic – processing.

In short: electronic integrated circuits cram billions of tiny transistors running at GHz speeds with long wavelengths. PICs have fewer components – tens of thousands – but operate at much higher frequencies and shorter wavelengths, allowing for blazing signal rates. It therefore makes sense that any THz CPU would need to be photonic in nature – and this is exactly what Akhetonics does.

But creating THz CPUs – or, as we like to call them, pure photonic CPUs – is far from trivial. An easy cop-out might be to keep traditional electronic processing in the loop and reserve photonics for communication. Luckily, there are indeed ways to move between frequency domains; photodiodes and modulators, for example, can convert signals from GHz to THz or vice versa. But any such conversion would instantly result in a bottleneck. If parts of the computer process in the photonic THz domain and parts in the electronic GHz domain, the total system will essentially still be limited to GHz, without a massive increase in parallelisation. To avoid this altogether, it seems obvious to ask: why not remain in the photonic THz domain while processing?

Of course, there is a reason why we do not already have THz CPUs. For electronics, the problem is not the transistor itself, as those have proven capable of handling low THz speeds. Rather, the issue is the large electric field coupling to everything nearby and causing a combination of resistance, capacitance, and inductance effects – collectively known as parasitics – which slow everything down. On the photonics side, since the EM wave is short enough to fit into a waveguide, we do not have parasitic interactions. But that also means it is hard to get light to interact at all.

Rethinking CPUs

To control one light beam with another like a transistor – a process called all-optical switching – we need to facilitate the interaction with a nonlinear optical medium. This has been possible for decades. In fact, the renowned physicist John von Neumann was granted the first patent for such a design in 1957 [1]. But so far there have been too many downsides to make it practical. Two of the most prominent ways to achieve all-optical switching are to use semiconductor optical amplifiers – which consume a great deal of power in their idle state – or highly nonlinear fibres – which require very long interaction lengths.

Nonetheless, both can be used for all-optical switching in a pure photonic CPU. The devices must simply meet four fundamental criteria. They must be cascadable, meaning that one device's output can be fed as an input into another. They must also be fan-out, so that each device can drive the inputs of at least two others. Since we are computing with binary signals, we require logic-level restoration; the devices need to restore the highs and lows of the signal at each stage, so that the quality does not decline as the signal passes through the system. And finally, we need input-output isolation, meaning that the devices' inputs and outputs are separated to avoid crosstalk.

These conditions are called Miller's criteria for optical logic [2]. As long as they are satisfied, you can create any photonic binary logic circuit, including a CPU. However, using a slow, inefficient all-optical switch defeats the purpose of using light as the signal in the first place. To develop a high-performance all-optical switch, we need an optimal nonlinear optical material platform: one that offers strong nonlinear effects in compact structures, consumes little power, and can be integrated onto a PIC. No small feat, but two stand-out technologies are already on a path to commercialisation.

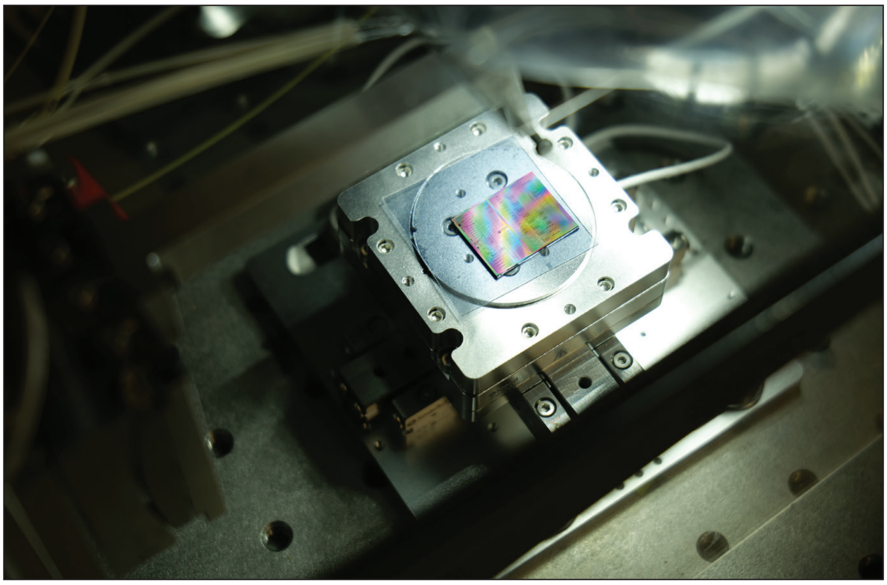
The first is a modified version of our trusted semiconductor optical amplifier in a III-V semiconductor platform, such as indium gallium arsenide phosphide (InGaAsP). While power hungry, they offer the most reliable operation of all methods of switching on a small scale. By carefully layering thin films of InGaAsP, engineers can finely tune how light interacts with the material to facilitate all-optical switching on a PIC. In our HAETAE project [3], together with the Aristotle University of Thessaloniki, imec, DGIST, and KAIST, we are exploring such a complete heterogeneous PIC platform for photonic computing.

The second promising technology harnesses 2D materials, which not only allow for THz speeds, but also extremely compact devices. Here our GATEPOST [4] and 2D Pilot Line [5] consortia seek to commercialise this novel material class for nonlinear photonics.

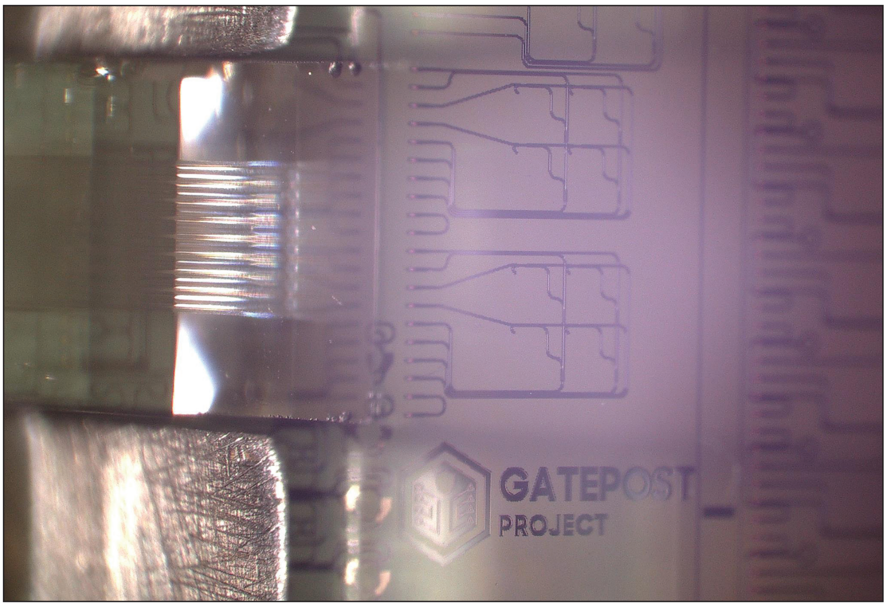
But even with these promising avenues for all-optical switching, a question remains. An electronic CPU has billions of transistors – how could we fit billions of micrometre- and millimetre-sized all-optical switches on a PIC? The answer is, we don't. We are still years away from fitting millions of devices on a PIC, let alone billions. But we don't necessarily need to. Instead, we must completely rethink our understanding of CPUs to design a photonic version.

Looking at electronic CPUs, they seemed to do just fine with thousands of transistors in the 70s and 80s. The MOS Technology 6502 microprocessor, introduced in 1975, has slightly more than 3,000 transistors and yet we still see it in use today, running fan favourite games, such as Super Mario Bros. Intel's x86-series debuted in 1978 with just shy of 30,000 transistors, running the first version of an instruction set that is still used by almost all desktop computers and laptops today.

We must recognise that the move from thousands to billions of transistors was for performance reasons, not fundamental capability. Then we can start using photonic computing's inherent THz speeds, building architectures more akin to those of



➤ Figure 1. A pure photonic processor on a test bench, ready to process its first THz signals. (Image by Akhetonics)



➤ Figure 2. The GATEPOST project aims to use 2D materials to enable ultra-fast computing on a PIC. (Image by Akhetonics)

the 70s and seeing how they would compare to modern electronic CPUs.

As it turns out, running a photonic CPU with a mere thousand all-optical switches using a simple reduced instruction set computer (RISC) architecture, but at speeds a million times higher than its electronic predecessor, is very much within reach, at least on the processing side.

Memory and multiplexing

The problem now boils down to accessing memory, which is about 100 times slower than processing data. Modern electronic CPUs spend more than 99.9 percent of their transistor count not on actual computation tasks, but on working around this inherent memory bottleneck through tricks such as introducing cache, branch prediction, pipeline re-ordering, special instructions, and more. If photonic CPUs can't solve this issue either, all our efforts would be futile.

The first component to look at is the interconnect between the CPU and memory. Linking the two electronically severely limits bandwidth; even advanced memory standards, such as DDR5, have not reached 10 giga transfers per second. And with round-trip latencies well beyond 10 nanoseconds on average, and peaking at 50-100 nanoseconds, this is simply not good enough for THz computing. It would mean, just as we see in electronics today, either a lot of idle time waiting for memory, or introducing all the complex optimisation structures we are trying to avoid.

Instead, photonic computing requires its own memory. But how do you slow light down to a standstill and call upon it at will? While that might not be feasible, we can use resonant structures to store an optical signal, while pumping or amplifying it, and manipulate the structure to store a new bit or release an old one. Integrated ring resonators, nanocavities, and even a flip-flop arrangement of all-optical switches can be used in this way. Related to this is delay-line memory, which was first used in electronic computing, and is used to manipulate optical signals in some contexts today.

But beyond storing light itself, we can also encode the signal in some other way, such as material transitions. Phase-change materials have been tried and proven as optical memories, for instance in DVDs or BluRays, and they are perfectly suited to integration on a PIC. The beauty of this solution is that the materials are non-volatile, so they can store data without a continuous power supply. In fact, reading them comes nearly for free, inducing minimal loss and, most importantly, happens instantaneously. Although we are not yet at the point of creating terabytes of volatile storage, researchers have gone beyond that on the read-only memory side, with projects such as 5D Optical Storage and Project Silica demonstrating petabyte storage capabilities.

As well as solving the issue of memory, we also need to consider how we can achieve efficient processing with far fewer components than an electronic CPU. Here, photonics has a superpower: its potential for multiplexing. Two, ten, or even hundreds of optical signals of different wavelengths can travel inside a single waveguide without affecting each other significantly. This capability has driven an industry-wide adoption of optical networking, enabling the transmission of terabits of data per second over a single strand of fibre.

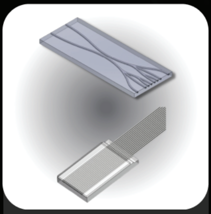
But this multiplexing does not have to be restricted to optical communication; we can use it for photonic computing as well, effectively making a multi-core processor out of a single physical core. Furthermore, since photonics does not induce parasitics, we can also use dense time multiplexing within the processor or introduce multiplexing based on phase and polarisation.

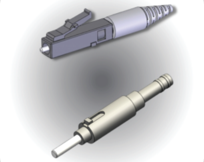
The parallelisation options are almost limitless, with one goal: minimise the number of physical components and instead add more multiplexing for performance. Quality over quantity.

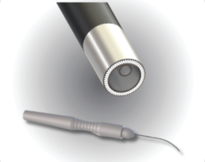
Processors for purposes

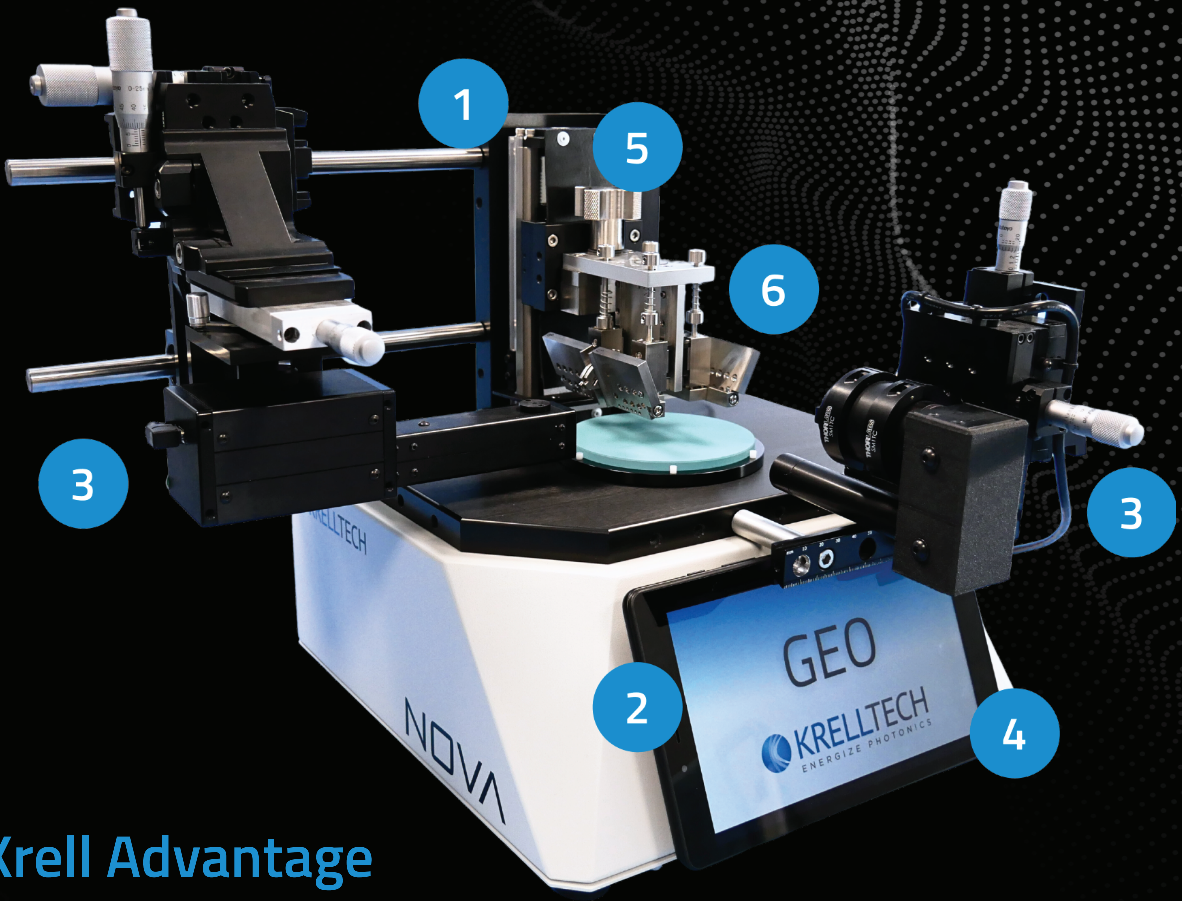
With photonic all-optical switching, all-optical memory, and multiplexing strategies in place, what can we build? We can create logic circuits that integrate on the order of 10,000 all-optical switches, and we have a limited amount of volatile optical memory and plenty of read-only memory. This may not be a great starting point to run an operating system like Linux, but perhaps L4.

Interestingly, it's very similar to what a GPU looks like. GPUs have numerous smaller cores, called shader units, that run lock-step in groups, performing the same operation on different bits of data. This massively parallel computation enables fast, efficient processing. But it also means GPUs work best if they treat most memory as read-only. Otherwise, any write-induced race condition, in which multiple cores try to write to the same piece of memory at the same time, would kill performance.





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And for the purpose for which they were designed, this is exactly how GPUs are used. 3D renderings or complex graphics games treat their assets as static resources that do not change in-memory, but rather are "shaded". Through computational steps, the static asset is fed through a pipeline of shaders and transformed and animated for a specific situation in a game, or setting in a 3D render. Incidentally, these shaders are often computing how light interacts with its environment. It would seem only fitting to actually use light to do those calculations in a pure photonic processor.

But we aren't focusing on running games – at least not yet. A very similar application is AI inference. Current AI hardware treats the model as largely static once trained, allowing it to reside in read-only memory. Neural network layers, in many ways, resemble shaders, and could be similarly handled in our photonic CPU. While the majority of processing is linear algebra, we must not underestimate the amount of branching ("if-then"-statements) and nonlinear arithmetic such as activation functions. These demands are addressed by the design of our pure photonic arithmetic and logic unit within the CPU.

Of course, we will always need some working memory. Luckily, we have our photonic memory available, and this is truly what sets the binary photonic CPU apart from its analogue cousin. Analogue computing is great for mathematics, but struggles with branching operations and has essentially no solution for memory. It therefore requires interactions with electronic processors, which kill its performance and efficiency by constantly moving between the electronic and photonic domains. This is why almost all companies in the analogue photonic computing space, such as Lightmatter, Ayar Labs, and Celestial AI, have decided to move to interconnecting electronic chips using their technology as a photonic interposer instead.

Another advantage of pure photonic computing chips is that their relatively large structures make them compatible with mature semiconductor nodes using 90 nm, 130 nm, and even 250 nm processes. This could open the door to production at a wide range of foundries globally, potentially shifting the balance from a TSMC-Intel-Samsung-centric landscape for high-performance fabrication to a much more open environment, significantly reducing supply chain risks. What's more, these mature processes are typically more cost-effective and environmentally friendly than leading-edge processes for advanced electronics.

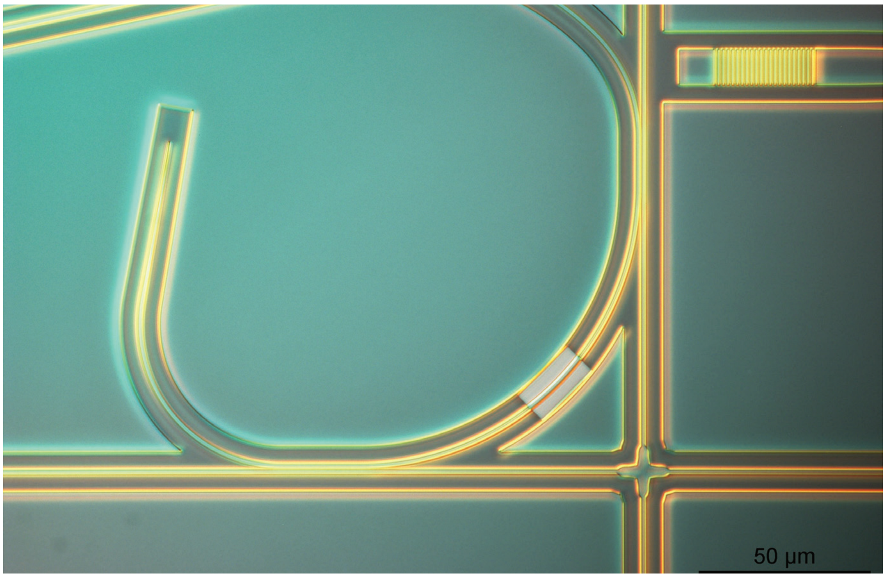

Figure 3. PICs enable the integration of a variety of optical materials for computing and memory, such as phase change materials (PCM) seen here covering a waveguide. (Image by Akhetonics)

But even if our pure photonic computing approach solves a lot of issues that have plagued electronic or electro-optical hybrid computers, it is not ideal for every use case. AI training, for example, which requires terabytes of volatile storage, will simply not benefit from photonic computing in the near future. Photonic computing must pick its early priorities, and the most promising are centred around AI inference, graphics processing, networking, cryptography, and real-time systems. This is where the pure photonic approach really shines, although it will likely be another two or three years before we see the first commercial devices in the wild.

So no, pure photonic computing does not mean a future without electronics. Even if we could run everything using light, different applications would still need to process different frequencies throughout the EM spectrum. From Hz to THz, the specific use case dictates which processing capabilities we need. That said, where high performance is key, we are sure to see much more photonics on the horizon.

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Enabling secure quantum communications with photonic components and integrated circuits

Fraunhofer HHI is advancing quantum key distribution systems by developing photonic components such as single-photon detectors and transmitters based on InP, and creating hybrid PICs that can generate photon pairs and control their polarisation states

BY NINO WALENTA, PATRICK RUNGE AND MORITZ KLEINERT, FRAUNHOFER HHI

IN AN ERA marked by growing concerns over cybersecurity and data privacy, quantum communication is emerging as a promising solution for secure information exchange. Although classical encryption methods have so far been robust, they are increasingly vulnerable to advances in computing – especially the anticipated capabilities of quantum computers.

Quantum communication systems aim to ensure information-theoretic security – meaning it cannot be broken even with unlimited computational resources and time. These systems leverage principles such as quantum entanglement, which links pairs of particles, and the no-cloning theorem, which prevents quantum information from being perfectly copied. Such principles can be seen at work in quantum key distribution (QKD), a well-known cryptographic task that enables two parties to share encryption keys with security rooted in the laws of physics.

However, realising practical quantum networks requires more than just theoretical foundations; it depends critically on scalable, stable, and high-performance photonic systems. Photons are ideal quantum information carriers, since they do not interact much with the environment and they are compatible with existing optical fibre networks. To support quantum communication, advanced photonic components such as low-loss waveguides, integrated sources of entangled photons, and high-speed single-photon detectors are vital. Moreover, PICs enable the miniaturisation and mass production of quantum devices, paving the way for cost-effective deployment. This synergy between quantum principles and photonic technologies will form

the backbone of next-generation communication infrastructure.

Photonic components

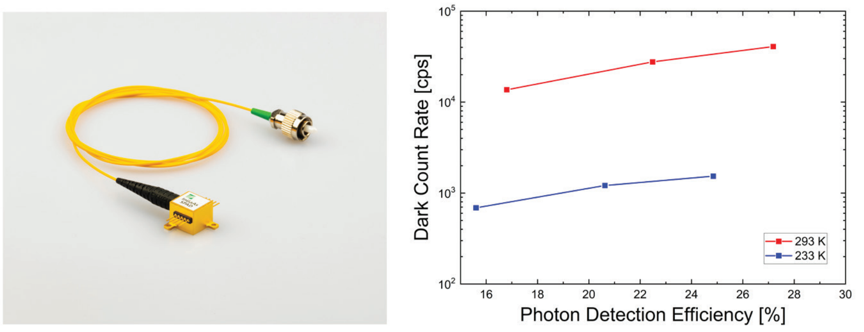
One of the main challenges in the quantum industry is detecting photons in the short-wave infrared (SWIR) wavelength range (1000-1600 nm). For shorter wavelengths up to 900 nm, single-photon avalanche diodes (SPADs) fabricated on silicon material platforms work well. However, when targeting the use of low-loss single-mode fibres for QKD applications, detectors must operate at telecom-wavelengths from the O- to L-band. In this case, indium phosphide (InP) is the material platform of choice.

For quantum applications requiring detectors that can pick up just a few photons, there are photodiodes available with high detection efficiencies of 99 percent [1]. This is sufficient for certain applications, such as those using squeezed light. However, other applications require yet higher-sensitivity detectors that can even catch individual photons with high accuracy.

To achieve this performance, systems need to incorporate either internal amplification to boost the detection signal, or superconductivity to reduce background noise from electrical resistance. A drawback of the latter is its need for cryogenic cooling, which is impractical for most non-academic settings.

SPADs are a preferred choice for industrial applications, thanks to their compact size, high reliability, and low power consumption. However, these devices suffer from dark counts, meaning they occasionally generate a false detection signal when no photon is present. Since dark count rates (DCR) can significantly impact the system performance, for example by reducing the signal-to-noise ratio and decreasing the secret key rate, the system design must consider this parameter. However, moderate cooling with a thermoelectric cooler (TEC) reduces the DCR significantly, meaning that the SPAD's packaging becomes as important as the design of the chip itself.

Figure 1 shows a fibre-coupled SPAD module with a system application-oriented housing (fibre in-plane with printed circuit board (PCB)) and its measurement results [2]. Besides the excellent photon detection efficiency (PDE) and DCR, the module performs well on several other characteristics. It has an afterpulsing probability – or likelihood of generating a false secondary signal shortly after a genuine detection – of under 0.5 percent. This is measured at a hold-off time of 10 µs, during which it is intentionally switched off to "reset" after a detection.



➤ Figure 1. SPAD module with the key performance parameters measured at 1550 nm wavelength for room temperature and internally TEC cooled operation.

Additionally, the timing jitter, or uncertainty about precisely when each photon triggers the detection signal, is just 162 picoseconds.

The SPAD module also has a compact footprint of less than a thumbnail and includes a TEC that can cool the device to 70 degrees C below the temperature of its environment. With this cooling, the module can achieve a DCR of 1500 counts per second and 25 percent PDE, which represents state-of-the-art performance at 1550 nm. Besides the SPAD design itself, the fabrication technology, including the high-quality epitaxial growth of the semiconductor layer stack, contributes to its excellent performance.

Since the SPAD operates by triggering an electrical current when it detects a photon, it also needs an inbuilt process to stop this current, "resetting" it so it is ready for the next photon. This is called quenching and there are multiple ways of achieving it.

Typically, QKD systems use one of two techniques: high-speed gating or free-running passive quenching. In the former setup, a voltage source sets the SPAD above the breakdown voltage – the threshold value at which the voltage is high enough to set the photodetector to single-photon detection mode. The voltage source repeatedly drops below this value and returns to it at a defined time interval, continually turning the SPAD off and resetting it.

Meanwhile, the other quenching technique sets the SPAD into a free-running passive quenching mode, in which the voltage source remains constantly above the breakdown voltage. If a detection event generates a photocurrent, an internal resistor reduces the voltage, which drops across the SPAD, until the current stops. The voltage then recovers so the SPAD can detect another photon. SPADs with internal resistors are called negative feedback avalanche diodes.

On the transmitter side, InP-based PICs are excellent candidates for QKD signal generation, since they enable monolithic integration of lasers and electro-absorption modulators. Moreover, InP PICs are already a mature technology, thanks to well established component manufacturing for the telecom industry. With a few minor design changes, telecom PICs can be readily adapted for QKD transmitters.

Since QKD systems rely on single-photon interactions, the PIC design needs to include variable optical attenuation, to reduce the emitted light intensity. Additionally, to provide the random numbers that QKD systems use to ensure secure encryption, the design incorporates quantum random number generators built to introduce non-deterministic processes such as laser beating or laser switching.

Researchers have already demonstrated high-performance transmitter QKD components on InP PICs, showing the potential of this approach [3] [4]. As a cost-efficient low entry level for InP PIC development, engineers can use multi-project wafers to get experience with PIC design and characterisation.

Hybrid PICs

While monolithic integration of photonic functionalities in a single material platform, namely InP, is advantageous for some quantum applications, others have stringent specifications that cannot all be fulfilled by a single material. Often these specifications set conditions on various characteristics, from waveguide losses and spectral operating range to the handling of the polarisation and the use of nonlinear processes.

This is where hybrid integration of chips from two or more material platforms comes into play. Through hybrid integration, engineers can combine low-loss passive waveguide platforms, such as silicon nitride or polymers, with a broad spectral transparency from the visible to the infrared, and active semiconductor components individually optimised for their respective functionality.

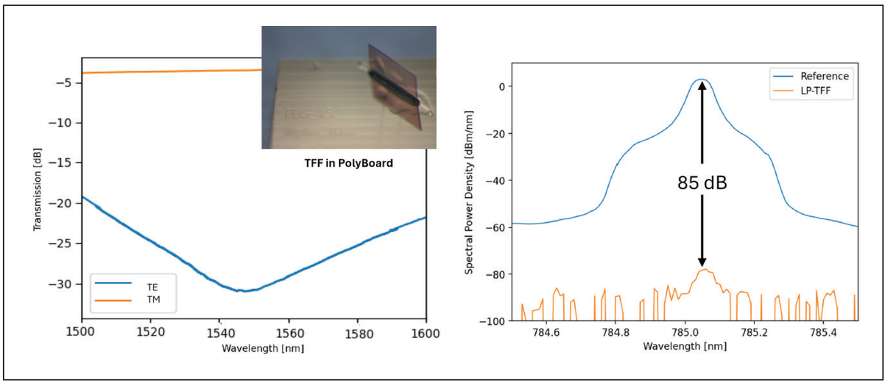
Over the past decade, Fraunhofer HHI has developed its hybrid photonic integration platform PolyBoard, which uses passive polymers as a waveguiding platform. In contrast to dielectric or crystalline materials, which are deposited by epitaxial methods, PolyBoard is made of polymer films, which are fabricated by subsequent spin coating and curing steps. This allows for great flexibility in the layer stacks, so each device can be tailored to its target application and wavelength. The material is easily structured by dry etching, allowing for deeply etched slots and grooves on the chip.

The precise etching in the PolyBoard platform enables the efficient on-chip integration of micro-optical elements, such as thin-film filters (TFFs), for example. TFFs consist of a micrometre-thin polymer film and a dielectric layer stack deposited on top, and they offer a solution to a pressing issue in photonic integration for quantum communications: efficient filtering and light conditioning.

When TFFs are inserted into etched slots on the chip perpendicularly to the waveguide layer, it is the dielectric layer stack, not the waveguides, that determines the filter characteristic. This approach allows PICs to benefit from highly efficient dielectric filters, which are already employed in free-space optics.

Figure 2 shows two examples of TFFs used in quantum communications applications. On the left is the transmission spectrum of a TFF used as a polarising beam splitter/combiner. The right-hand side presents a filter for the suppression of pump light for the nonlinear generation of photon pairs. Here, we observe an extinction of 85 dB of the 785 nm pump light. As well as being highly efficient, the TFF-based filtering has the advantage that it does not require phase or temperature stabilisation, making it ideally suited for applications outside of laboratory settings.

In the context of quantum communications, being able to efficiently handle the polarisation of light is especially important for QKD transmitters that encode qubits in this property. Figure 3 shows such a transmitter realised in the PolyBoard platform. It uses four individual tuneable lasers, emitting transverse electric (TE)-polarised pulses in the C band. The two inner waveguides pass through a TFF serving as a half-wave plate, which rotates the polarisation from TE to transverse magnetic (TM).



➤ Figure 2. Thin-film filter as a polarising beam splitter/combiner (left) and as a pump light suppression filter (right).

Subsequently, these TM-carrying waveguides are recombined with the outer TE-carrying waveguides by TFFs acting as polarising beam combiners. One of these arms is then rotated once more by another TFF half-wave plate. This results in one arm carrying light in a state of diagonal polarisation, and the other carrying light in a state of antidiagonal polarisation. Finally, the two waveguides are combined and fed into a variable optical attenuator, which attenuates the pulses down to the single-photon level.

By selecting the input laser from the laser array and carefully controlling its light pulses, we can choose the polarisation state of the output, whether it is in the horizontal/vertical basis or the diagonal/antidiagonal basis. In this way, the TFFs allow for passive on-chip handling of the polarisation to create qubits with a maximum deviation of less than 6 degrees from the ideal polarisation states. This fulfils the requirement of QKD implementation to be able to send photons in specific polarisation states.

While many QKD transmitters can use attenuated lasers as photon sources, some quantum applications require true single photons or photon pairs. One common way of generating single photons and photon pairs is via spontaneous parametric down conversion. In this process, a high-energy, short-wavelength photon is directed into a nonlinear crystal, stimulating the emission of two lower-energy, longer-wavelength photons.

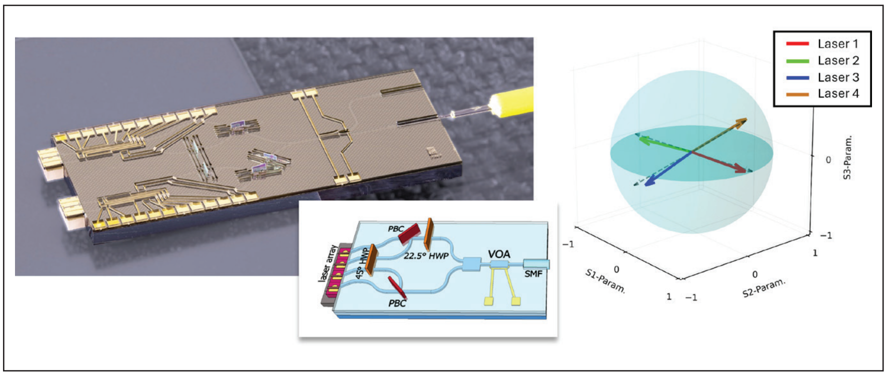
The main challenges in miniaturising these photon sources are the difficulty of integrating nonlinear crystals onto a PIC and the on-chip suppression of the pump light. The PolyBoard platform offers a way of overcoming both obstacles. The module shown in Figure 4 is an integrated photon pair source, in which a nonlinear periodically poled KTP crystal from Raicol Crystals is integrated into an on-chip free-space section. In this section, gradient refractive index (GRIN) lenses form a collimated beam profile,

enabling the integration of micro-optical elements that are on the order of a few millimetres long.

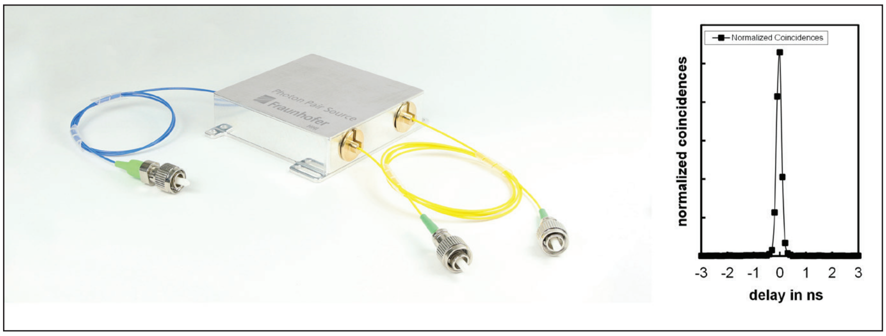
The 785 nm pump light is coupled into the chip through a polarisation-maintaining fibre. Once in the chip, the pump light causes the integrated crystal to generate photon pairs, which are collected by a second GRIN lens and coupled into the on-chip waveguides.

After the crystal, a chip-integrated TFF as presented on the right-hand side of Figure 2 suppresses the 785 nm pump light by 85 dB, so that only the 1550 nm photons are emitted at the chip output. Subsequently, the photons are separated by polarisation with a TFF polarising beam splitter, and the single photons are finally coupled into single-mode fibres where they are readily available for transmission.

The two hybrid PICs presented here for use in quantum communications exemplify the versatility of hybrid photonic integration, especially for emerging applications.



➤ Figure 3. Polarisation-encoded BB84 DV-QKD transmitter (left) with resulting polarisation states (right).



➤ Figure 4. Photon pair source module relying on the micro-optical bench in the PolyBoard platform.

System integration

The integration of high-performance photonic components in PICs is pivotal in transitioning quantum communication from laboratory research to real-world applications. These technologies enable the development of compact, scalable, and robust quantum communication systems, facilitating the deployment of QKD in practical settings.

Fraunhofer HHI has developed a high-speed QKD system that illustrates this integration. The system is based on the BB84 QKD protocol, and encodes the data in the photons according to the time interval they arrive in and their phase relative to a reference (time-phase encoding). It also uses a single decoy-state method, sending additional non-qubit photons to increase security, operating at a qubit frequency of 625 MHz.

The system features instant optical switching and routing capabilities for the quantum channel, without the need for a separate dedicated channel to establish synchronisation between the sender and receiver.

Its design allows for fast automatic startup and continuous operation over both fibre and free-space optical links, and is compatible with various single-photon detectors, enhancing its adaptability to different operational environments.

A quantum random number generator serves as the primary source of randomness, ensuring the unpredictability of the generated keys, and thus the security of the encryption. The synergy between advanced photonic components, PICs, and standardised protocols underscores the feasibility of establishing secure quantum networks.

By leveraging these technologies, we can implement QKD systems that are not only secure, but also practical for widespread adoption, marking a significant step towards realising quantum communication networks.

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Ultra-thin devices light the way to miniaturised entangled photon sources

Stacked layers of very thin materials offer a novel way of creating entangled photon pairs that could be integrated into future PICs, paving the way for quantum computing at a much more compact scale

BY LEEVI KALLIONIEMI, PHD STUDENT, AND XIAODAN LYU, RESEARCH FELLOW, NANYANG TECHNOLOGICAL UNIVERSITY, SINGAPORE

QUANTUM ENTANGLEMENT has astounded and divided physicists since it was first conceived last century. One of many counterintuitive effects predicted by quantum mechanics, the phenomenon involves two particles becoming linked, or entangled, meaning that a change in one particle's state will inevitably and immediately change the state of the other, even if they are infinitely far apart. Many pioneers of quantum theory initially rejected this idea. Most famously, Albert Einstein described it as "spooky action at a distance," highlighting how nonsensical it seemed.

However, quantum theory has held up to scientific scrutiny; experiments conducted in the past century have repeatedly confirmed its predictions, and quantum entanglement has been demonstrated with many particles, including pairs of electrons and pairs of photons.

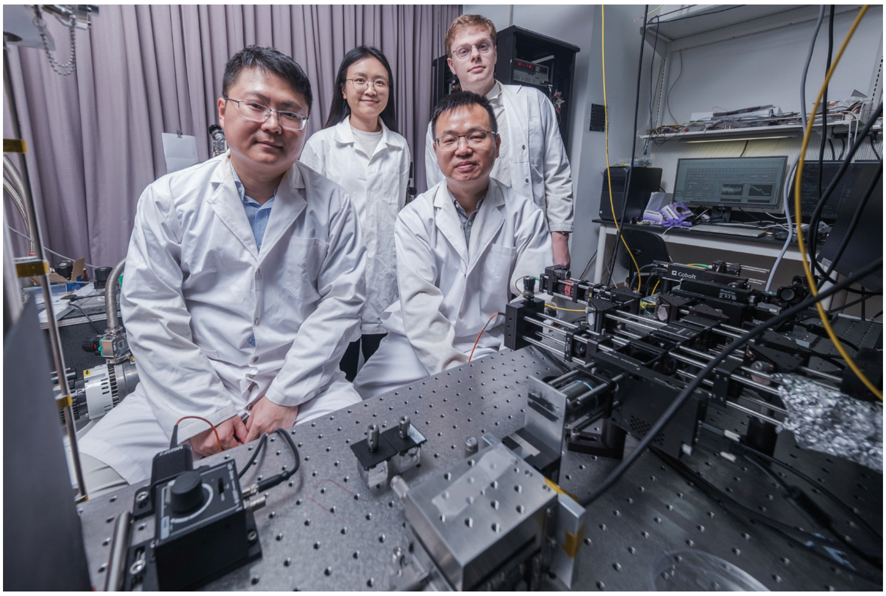
Not only has the phenomenon been verified, but it is also now vital to quantum computing. This field of research aims to create powerful computers that could supercharge efforts to tackle all kinds of complex problems, from drug discovery to climate change. Yet the technology is still developing, and researchers face many hurdles in realising its potential benefits.

Now, our team at Nanyang Technological University, Singapore (NTU Singapore) has made an advancement that could pave the way for significant progress in quantum computing, by offering an innovative method of creating entangled photons.

While many kinds of particles can be entangled, photons have the advantages that they are stable and naturally tend to travel across distances, lending themselves to signal transmission. For a pair of photons to be entangled, both must vibrate in sync when produced. Entangling two particles of light can be a relatively simple process in a modern laboratory.

Conventionally, researchers create entangled photons at room temperature by shining a laser on crystals that are a few millimetres thick. The crystals interact with photons from the laser and then produce pairs of lower-energy photons, a process called spontaneous parametric down conversion. Scientists then use optical gear to ensure the generated photons in a pair remain linked. But for quantum applications that may need to manipulate these particles in small devices, such a set-up is too large. Optical equipment can also be cumbersome to align and adds further bulk and complexity to the set-up.

However, our research team, led by Gao Weibo, a professor in NTU's School of Electrical & Electronic Engineering and School of Physical & Mathematical Sciences, has made a discovery that addresses this problem. We have produced entangled photons from crystalline materials that are 1000 times thinner than the crystals used in current state-of-the art devices. This means that devices for quantum applications, such as those for quantum information and photonic quantum computing, could get simpler and more compact in the future.



(From left) Gao Weibo, Lyu Xiaodan, Liu Zheng and Leevi Kallioniemi are part of the NTU Singapore team that found a new way to produce entangled pairs of photons with very thin materials. (Credit: NTU Singapore)

The best of both worlds

This is not the first time that scientists have sought to replace bulky crystal sources of entangled photons with thinner materials. But making sources of linked photons smaller comes up against a major issue: as the materials get thinner, they produce photons at a lower rate. In fact, the rate falls so much that these thin materials become far less useful for computing applications.

A new crystalline material called niobium oxide dichloride ($NbOCl_2$) has the potential to resolve this. Exhibiting unique optical and electrical properties, recent research suggests that even when this material is very thin, it can produce photon pairs efficiently. But there is still another problem: the pairs of photons generated by a single flake of $NbOCl_2$ are not entangled by default, so they cannot be used for quantum applications.

Gao's idea for a solution to this was inspired by a longstanding method published in 1999 for producing linked photons using thick and bulky crystalline materials. The technique involves stacking two flakes of thick crystals, aligned so that their crystalline grains are perpendicular to each other.

Shining a laser at the crystals stimulates the production of photons in each flake, but in different polarisations, due to the different alignments of the flakes. This results in the photon pairs being entangled in terms of their polarisation; determining the polarisation of one particle will immediately determine that of the other.

Gao hypothesised that the same process would produce entangled photon pairs from $NbOCl_2$ flakes. If it worked, this would dramatically scale down the core components of the set-up; the $NbOCl_2$ flakes have a combined thickness of just 1.2 micrometres – 80 times thinner than a strand of hair, and around 1000 times thinner than the bulky, millimetres-thick crystals traditionally used.

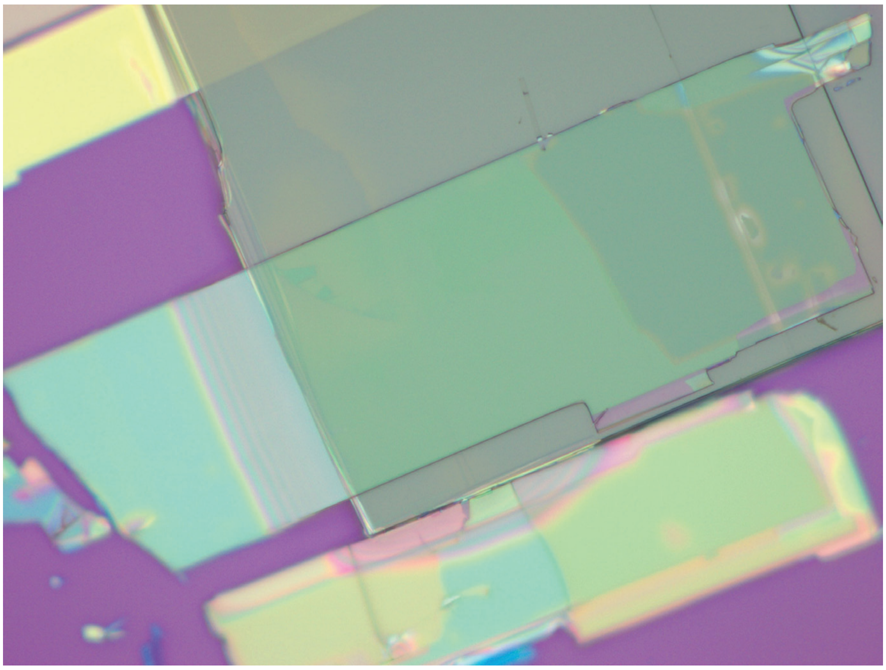
To achieve this set-up with $NbOCl_2$ flakes, Gao drew on a technique called van der Waals engineering, which involves stacking thin sheets of materials. These sheets are held together by weak natural interactions called van der Waals forces, which act between the thin layers. Researchers can harness these weak forces to stack multiple thin layers of the materials at different angles relative to each other to alter their optical properties and create new ones.

Besides shrinking the size of the crystals themselves, this substitution also eliminates the need for external optical equipment. After photons are created in a pair in the traditional set-up, the way they travel inside the thick crystal flakes can cause them to vibrate out of sync. Extra optical instruments are therefore needed to keep the particles synchronised and ensure the pair remain linked.

But Gao realised that, since the $NbOCl_2$ crystal flakes used would be much thinner than the bulkier crystals from previous studies, the photon pairs generated would travel a smaller distance inside the $NbOCl_2$ flakes. As a result, the photons would be more likely to remain in sync with each other, and additional optical equipment would no longer be needed, helping to simplify and reduce the bulk of the set-up.

To test his hypothesis, Gao collaborated with Liu Zheng, a professor from NTU's School of Materials Science & Engineering, and led a research team to conduct a series of experiments.

The results proved Gao's theory, finding that the stacked $NbOCl_2$ flakes produced photon pairs that behaved very similarly to perfectly entangled photons; observations showed that they had a fidelity – a measurement of how closely they resemble an ideal entangled state – of 86 percent. In future, these entangled photons could be used as photonic quantum bits, or qubits, for quantum computing.



Two thin flakes of niobium oxide dichloride stacked on each other and photographed under a light microscope. One flake's crystalline grain (grey flake) is positioned perpendicularly to the grain of the other flake (green flake). (Credit: NTU Singapore)

Potential for quantum computing

Quantum computers promise to make complex calculations and discern patterns in large sets of data much more quickly than conventional computers. They could take just minutes to complete computations that would take today's supercomputers millions of years.

Such processing capabilities have the potential to transform how we tackle many pressing challenges facing humanity and accelerate the discovery of solutions. For example, we could harness this computing power to make better sense of complex weather phenomena and find new antibiotics much faster than before.

According to theory, quantum computers should be able to do this because they can perform multiple calculations at once, instead of working through them one at a time like standard computers. This ability is thanks to tiny switches called qubits, which are quantum entangled particles that can be in both the on and off positions simultaneously. Standard computers, by contrast, have switches that can only be in either the on or off state at any time, but not both.

Currently, many approaches to building quantum computers use electrons as qubits. But for this to work, the electrons need ultra-low temperatures approaching the coldness of outer space. Maintaining such conditions requires a lot of energy and resources, making these efforts costly, more complex, and less accessible.

Photons are promising alternative options for qubits. Since they can be produced in entangled pairs at room temperature instead of needing extreme conditions, photonic qubits could make quantum computing cheaper, more energy efficient, and more practical.

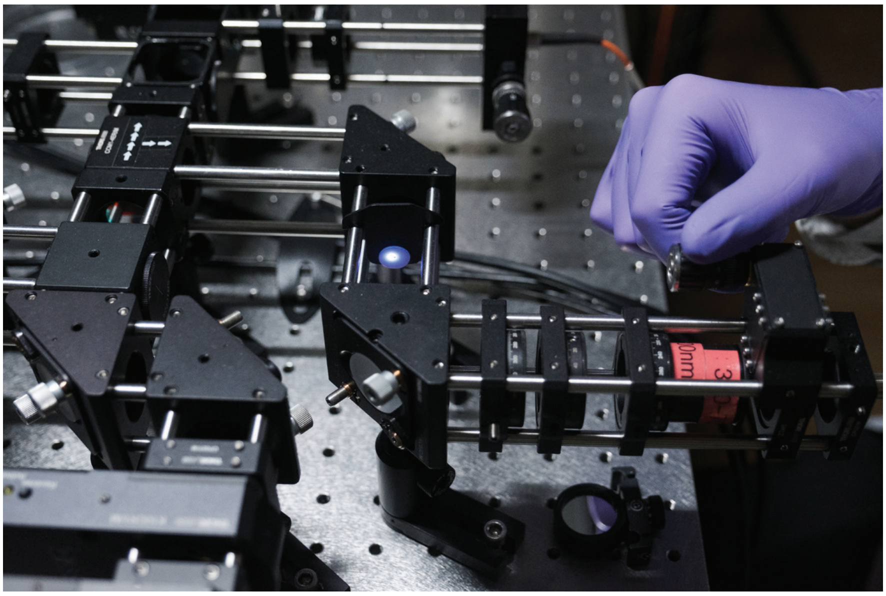
Photonics specialist Sun Zhipei, a professor at Finland's Aalto University and co-principal investigator at the Research Council of Finland's Center of Excellence in Quantum Technology, said the new technique for producing entangled photons "is a major advancement, potentially enabling the miniaturisation and integration of quantum technologies."

Sun, who was not involved with the research, added: "This development has potential in advancing quantum computing and secure communication, as it allows for more compact, scalable and efficient quantum systems."

Furthermore, entangled photons could enable instant communication, since these particles of light are like synchronised clocks that show the same time regardless of the distance between them.

Future directions

Although our advancement is a significant step towards using photons as qubits, more breakthroughs are needed before we can realise its potential in photonic quantum



A blue laser set-up for generating entangled pairs of photons in NTU Singapore's experiments. (Credit: NTU Singapore)

> Although our advancement is a significant step towards using photons as qubits, more breakthroughs are needed before we can realise its potential in photonic quantum computing devices

computing devices. For one thing, the technologies to integrate very thin crystalline materials into photonic quantum computer chips need to be developed. Our current method of producing linked photons must also be improved to a level that is suitable for practical applications.

Going forward, our team at NTU is planning to optimise the set-up so that it can create entangled photons at a faster rate than we have achieved so far, in order to make it useful for quantum computing. Boosting the rate of production will likely improve the fidelity of the light particles too, so that they behave even more closely to ideally entangled photons.

We are exploring whether we can increase the number of entangled photons generated by etching small patterns and grooves on the surface of the $NbOCl_2$ crystal flakes. The team is also considering stacking other materials with the flakes, such as 3R-phase transition metal dichalcogenides, which are emerging materials reported to be capable of generating photon pairs efficiently. We could also improve the fidelity of the entangled photons by further adjusting our set-up, for example by changing the thickness of the flakes. Another factor we are planning to investigate is how much the flakes' crystalline grains line up with the direction of the laser light's polarisation.

While there is more work to be done, this discovery sets out an exciting vision for miniaturised, room-temperature sources of high-quality, entangled photon pairs that could underpin the quantum computers of the future.

FURTHER READING / REFERENCE

➤ L. Kallioniemi, X. Lyu, R. He, A. Rasmita, R. Duan, Z. Liu and W. Gao, "Van der Waals engineering for quantum-entangled photon generation", Nature Photonics, 2024. DOI: 10.1038/s41566-024-01545-5

10th PIC International explores the future of quantum photonics

The conference held a session dedicated to quantum applications, with discussions of how PICs can underpin secure communications and enable the scaling of quantum computing, as well as a broad overview of the quantum industry's trajectory for the coming years

BY LAURA HISCOTT, EDITOR, PIC MAGAZINE

IN APRIL this year, the 10th PIC International conference took place in Brussels, marking a decade full of innovation and industry growth since the event began. But this year is not only a major milestone for the conference; it's also a special year for quantum, with the UN having designated 2025 the International Year of Quantum Science and Technology.

In recognition of this global spotlight on the growing significance of quantum technologies, PIC International hosted a dedicated session covering multiple aspects of the sector and the role that integrated photonics plays in its development. From secure communications networks to new computing architectures, PIC technologies are poised to help realise many of the promises of the quantum revolution.

Opening the session was Taofiq Paraïso from Toshiba's quantum information group, which is developing new cryptography systems. Describing the motivation for this research, Paraïso explained the vulnerabilities of current methods for securing data; signals can be relatively easily intercepted in public channels without the sender or receiver noticing, and the cryptographic keys rely on solutions to very difficult mathematical problems that could be broken by more powerful computing systems. This has given rise to "harvest now, decrypt later" attacks, in which people steal and store encrypted information, waiting for future computers – including quantum computers – that could decode it.

One solution to this is quantum key distribution (QKD), which involves encoding each bit of data into a single photon. Thanks to quantum effects, the photons cannot be intercepted without introducing detectable noise, guaranteeing that any eavesdropping would be discovered. Additionally, since the keys generated are based on truly random quantum effects, they cannot be deduced even by very powerful computers.

While quantum applications are often thought of as futuristic technologies, QKD systems already exist today. Paraïso highlighted that Toshiba started the first commercial QKD trial network in London in 2022, with partners including BT, HSBC, and AWS. The system achieves ranges of over 100 km with key generation rates of hundreds of kilobits per second.

"What we endeavour to do is to realise a global quantum safe network (QSN)," Paraïso explained, “because one of the main threats to cryptography as we know it is the onset of quantum computers. We don’t know when this would happen, but we want to prepare for this, which means addressing the deployment of QKD in all segments of our conventional communication networks.”

But Toshiba’s demonstrations so far are based on discrete optical components, meaning that efforts to scale them up will face challenges in terms of cost, power consumption, and reliability. This is why Paraïso’s photonic integration team is investigating how PICs could support the deployment of QKD systems. They have already developed quantum random number generators (QRNGs) and transmitter chips based on indium phosphide, as well as receiver chips based on silicon nitride to minimise loss at the point of detection. This is of particular importance, Paraïso noted, for picking up extremely faint signals at the single-photon level, as required by QKD.

Back in 2021, Toshiba demonstrated full real-time operation of QKD using these PICs, implementing key exchange and post processing, and interfaced with commercial-grade 100G data encryptors. And the team has continued to improve the system since then, for instance by bringing light detection onto the QRNG chip and halving its footprint. The researchers have also changed the QRNG chip’s packaging to standard QFN, enabling them to treat it as a standard EIC and to fabricate highly stable multiple-QRNG boards which could be deployed in a commercial system.

Going beyond a binary sender-receiver system, another target for Toshiba is to create multi-node QSNs connecting large numbers of devices, but this requires multiple functions to be combined on a chip. To this end, Toshiba has developed a transceiver that leverages hybrid integration of InP modulators with ultra-low-loss silicon nitride interferometers, showing that a node could talk to both a transmitter and a receiver side at the same time.

Looking further towards the future, Paraïso also noted that, Toshiba has shown a path towards addressing long-range QKD with PICs, and is even exploring their use in satellite communications, where their compact size, low weight, and low power requirements would be invaluable.

“We hope that with this set of technologies, we will be able to support deployment in all the different segments of our communication networks, each having different requirements that we can meet with PICs,” Paraïso concluded.

PICs for qubit platforms

While QKD systems are already here, the wider quantum industry is pursuing many different technological goals, some with longer timelines than others. This came through in a talk by Eric Mounier from YOLE, who provided a broad overview of the quantum landscape, as well as the importance of integrated photonics in bringing many of the envisioned applications to fruition.

Quantum 2.0 technologies fall roughly into three categories: cryptography, sensing, and computing. The first two are nearer-term applications, but what gets the most attention – and draws the most funding – is a longer-term endeavour: large-scale, universal, fault-tolerant quantum computing. In fact, according to Mounier, between 2020-2025, quantum computing attracted almost $8 billion in private funding, representing around 65 percent of private investments in quantum technology during that time.

Yet within the category of quantum computing alone, Mounier pointed out that there are also different types of quantum computers, again with different timelines. For instance, quantum annealers, which can solve complex optimisation problems, already exist and are used commercially for niche problems. So too do quantum simulators – systems of qubits that are arranged and controlled to mimic materials and chemical reactions in which quantum properties are important, and which are too complex to be simulated by classical computers.

But the holy grail, of course, is a universal, fault-tolerant quantum computer, which Mounier estimated could be 20-30 years away. Although, he caveated, so-called noisy intermediate-scale quantum systems (NISQs), of between 10-100 qubits, could appear in the next 5-10 years.

“It’s interesting to see that the roadmap is really accelerating,” said Mounier. “At the moment, some companies achieve a few tens of logical qubits. And the roadmap is to have by 2030 at least a few hundred logical qubits to achieve some real use case for a quantum computer.”

Among the companies in Mounier’s presentation were players developing several different qubit platforms, but Mounier said there were plenty of reasons to be optimistic about those that use photons as qubits. “Compared to other qubit approaches like trapped ions or cold atoms,” he explained, “they are less sensitive to decoherence, less sensitive to temperature, and of course they can benefit from all the developments that have been made in PICs, so it can be a scalable technology which is a huge challenge for developing quantum computers.”

Indeed, several of the biggest names in the sector use photons either as qubits or as an otherwise central component in their designs. Perhaps one of the most positive signs is that, according to Mounier’s analysis, photonic approaches garnered more private funding – over $1.35 billion – over the past five years than any of the other qubit technologies. It is nonetheless still a tight race, with superconducting qubits and trapped ions not far behind, earning more than $1.34 billion and $1.15 billion respectively in the same period. Other contenders are also

➤ Taofiq Paraïso from Toshiba's quantum information group discussed how his team is investigating the use of PICs to develop global quantum safe networks.

emerging in the form of silicon spin qubits and quantum dots, for example.

But a further cause for optimism is that other approaches besides photonic-centred ones are also likely to need integrated photonics. Describing the photonic components that different platforms need, Mounier pointed out that both trapped ions and neutral atoms will need components including lasers, photodetectors, and modulators to work.

While current trapped-ion and neutral-atom approaches use discrete optical components, they are likely to start incorporating PICs instead, in order to advance and scale the systems. Indeed, in the weeks following the conference, both IonQ – a trapped-ion quantum computing company – and Pasqal – a neutral-atom quantum computing company – both announced they were acquiring integrated photonics companies (Lightsynq and AEPONYX, respectively).

Furthermore, Mounier noted, any quantum computing system will be limited in the number of qubits, so systems will need to be interconnected to expand to a large-scale network. This will mean integration with existing optical infrastructure, representing another opportunity for PICs to support this scaling.

But, while we focus on the future, it's also useful to see how much progress has already been made. "It's interesting to see actually that these markets are real," said Mounier. "By 2024 I estimate that the total market revenue from quantum technology including all types of quantum approaches, computer hardware, services, sensors, communications QKD, is close to $1 billion. Going forward, in 2035 my estimation is that quantum technology hardware and services will reach more than $17 billion."

➤ Thien-An Nguyen from ORCA Computing spoke about how the company is already delivering value with photonic quantum computing systems today, while also working to scale the technology to a full fault-tolerant quantum computer in future.

Quantum value today

After Mounier's talk, we heard from Thien-An Nguyen, chief technical officer at ORCA Computing, a quantum computing spin-out from Oxford that was established in 2019. Nguyen joined ORCA when it acquired the integrated photonics division of the Texas-based company GXC in January 2024, speaking to the importance of PIC technology in the company's roadmap.

Reiterating the benefits of photonic qubits, which underpin ORCA's systems, Nguyen emphasised that the company aims to stand out by delivering value today, while continuing to scale and improve its technology for the future. Referencing the company's "core philosophy of delivering quantum computing solutions to customers early and often," he noted that it has so far delivered more than 10 of its PT series quantum photonics systems to customers worldwide. This includes a system delivered to the UK's National Quantum Computing Centre (NQCC) in March this year.

The way that ORCA is achieving this current market traction, Nguyen explained, is by creating hybrid quantum-classical systems specifically tailored for a type of machine learning framework called generative adversarial networks. But with another eye on the future, he also outlined how the company plans to scale from the PT series to a universal fault-tolerant computer, both by increasing the number of photonic qubits in the system and expanding the number of different ways they can be manipulated.

On the first point, Nguyen pointed out that a full fault-tolerant quantum computer will need millions of different components integrated and working cohesively together, driving the need for an integrated photonics platform.

This is why ORCA acquired the integrated photonics division of GXC. "Everything that we do is based off the ultra-low-loss silicon nitride platform that is part of the ORCA infrastructure today," said Nguyen. "That allows us to receive light from an optical fibre onto the chip with very low losses, route the photons around to interact with the various materials with very low losses and then couple again to the output fibre once again with very low losses. The key thing is that we need to keep a very tight hold of every single photon that we generate, from the beginning all the way to the end."

When it comes to the second goal – increasing the range of operations that the system can perform on the photons – Nguyen explained that no single material can offer all the functionalities required for a universal fault-tolerant computer. Using multiple different materials is therefore necessary, but each material also has its own specific integration challenges.

For this reason, Nguyen said, "ORCA's approach is not to create a single PIC to rule them all, but rather to have a distributed network of PICs that are specifically designed for different functionalities that then couple to optical fibre for networking." To support this networking and thus enable a large-scale photonic quantum computing system – which may require millions of fibre-chip connections – Nguyen added that ORCA is on track to develop a fibre-chip coupler with a record low loss of 0.05 dB per facet later this year. Going forward, he highlighted three key priorities for progress in photonic quantum computing: lower-loss components, heterogeneous integration, and networking between modules.

Nguyen's references to novel materials, such as thin-film lithium niobate (TFLN) and barium titanate, echoed a recurring theme of the conference as a whole. TFLN, for instance, had a stronger presence at this year's event than at any PIC International before, showing just how swiftly it has made technological strides and gained traction as a promising material in the industry. And who knows which other new materials that we may not yet have heard of will emerge as potential game-changers in the years ahead? There may be plenty more surprises in store on the path towards universal quantum computing. But one thing is for sure: when it comes to quantum, the PIC industry has a lot to be excited about.

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From lab concept to production reality

As photonic integrated circuits (PICs) evolve from lab-scale concepts to high-volume products, manufacturers face growing challenges in achieving precision, repeatability, and throughput. This article explores how Krell Technologies' NOVA™ Workcell System addresses these demands—bridging the gap between R&D flexibility and production-grade performance for advanced PIC polishing.

BY KRELL TECHNOLOGIES

AS PHOTONIC integrated circuits (PICs) move from prototype to production, the challenges of die-cut variation, fixture alignment, and polishing precision become critical. Krell Technologies (KrellTech)' modular NOVA™ Workcell System integrates micron-level positioning, in-line inspection, and process control into a scalable platform designed to meet these challenges – bringing R&D flexibility and production-grade repeatability to one advanced system.

Solving PIC Polishing Challenges with a Scalable Workcell Approach

As the PIC landscape evolves, the industry is continually pressed to improve the manufacturability and performance of these highly sensitive components. While often viewed as a secondary process, polishing plays a pivotal role in determining the final optical and geometric quality of a PIC. From die-cut inconsistencies to fixture alignment and scalable production needs, manufacturers face numerous challenges when moving from research and development to volume production.

KrelTech, with its decades of experience in photonic component processing, has tackled these challenges head-on with the development of its NOVA™ Workcell System – a modular platform that integrates precision polishing with in-line inspection (see Figure 1). This article walks through the key hurdles in PIC and waveguide processing and how NOVA's design philosophy addresses each of them in a flexible and scalable way.

➤ Figure 1. Krell Technologies' NOVA™ System provides processing flexibility for R&D applications while providing a platform for migration to high volume production. It is highly configurable supporting the addition of various in-line vision systems and polishing fixtures for most photonic components.

The importance of repeatable component loading

Any polishing process begins with how the chip is loaded and secured. Repeatability in loading directly impacts the uniformity of polishing, especially when dealing with micro-scale tolerances. The challenge lies not only in holding the chip securely but also in referencing it to a common datum point. This becomes particularly difficult when the chips themselves exhibit inconsistencies from upstream fabrication—non-parallel edges, uneven widths, or excess epoxy from layered assemblies.

KrellTech's approach is to design adjustable fixtures that accommodate varying chip dimensions while avoiding contact with critical optical areas. Clamp materials are carefully selected to be non-abrasive, and force is applied in opposing directions to prevent rotation or lifting during polishing.

For ultra-small chips, an off-line carrier-based loading method combined with video-assisted referencing ensures micron placement accuracy. These carriers are then seamlessly transferred to the polishing fixture mounted on the machine, eliminating technician-to-technician variability.

Fixture design and calibration: foundation of precision

A fixture is not just a clamp – it's a precision instrument in itself. Accurate fixture design ensures that the polishing action is aligned with the intended geometry of the chip. For photonic devices that demand variable endface angles or multiple facets on a single edge, fixtures must allow rotation and angular control without removing the sample. This requirement calls for both flexibility and stability in fixture orientation.

To further improve alignment accuracy, KrellTech employs active calibration techniques. By using a gold-standard reference sample and monitoring its alignment over an interferometric plane, the fixture can be precisely tuned to align with the polishing surface. This method bypasses the limitations of passive, machined alignment and sets a new benchmark for repeatability.

The inclusion of an independent suspension system is another cornerstone of KrellTech's fixture design. It ensures that contact pressure between the chip and polishing film is consistent – even as material is removed. This prevents chatter and vibrations while allowing the fixture to "ride" the z-axis on a linear slide, maintaining steady contact via a precision-tuned spring.

Polishing and process control at the micron level

Beyond mechanics, polishing depends on managing pressure, speed, and cycle time. A polisher must have the ability to precisely control each of these variables. PICs are sensitive to stress and thermal buildup, making traditional polishing systems inadequate.

The NOVA platform introduces programmable descent control with micron-level positioning. Rather than initiating full pressure on contact, the chip is advanced incrementally to the polishing film, reducing the risk of edge chipping or over-polishing. This also provides a means to control material removal to a high degree (see Figure 2).

Each polishing cycle can be adjusted in real time during R&D and later saved as a repeatable program for volume manufacturing. This level of control extends to abrasive film selection. Given the diversity of PIC materials – from silica and silicon nitride to lithium niobate and indium phosphide – the NOVA system supports multi-step processes using a wide range of abrasive films, including silicon carbide, aluminum oxide, diamond, and silicon dioxide.

To provide real-time feedback, an integrated video inspection module allows the operator to monitor polishing in progress and inspect the surface without removing the chip. Endface geometries and material removal can be confirmed immediately, reducing scrap and minimizing handling risks. This is especially valuable during development phases, where quick iteration is necessary to refine processes.

Scaling from R&D to Production

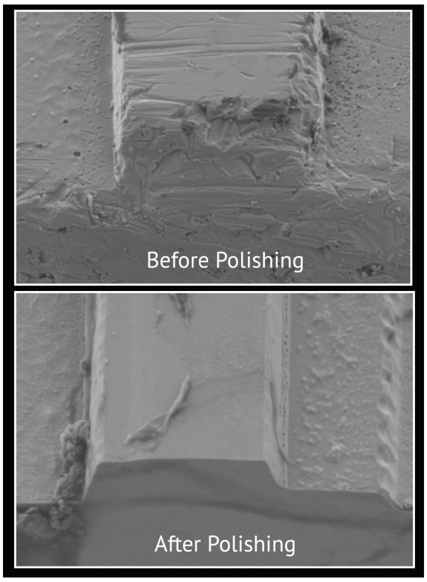
A key strength of the NOVA system is its scalability. Many polishing platforms are designed either for R&D or production, but few transition seamlessly between the two. NOVA is modular from the ground up, allowing users to start with a single position workholder for process development and later upgrade to multi-position fixtures. Each position includes the aforementioned suspension mechanism, compensating for individual chip loading variations and ensuring uniform pressure distribution.

Moreover, NOVA's intuitive Android-based software platform simplifies training and process transfer. Step-by-step prompts allow even inexperienced technicians to reproduce complex polishing sequences. This ensures consistent results across operators and shifts, enabling users to transition from prototype to product with minimal disruption.

Importantly, NOVA isn't limited to PIC chips alone. As photonic systems become more complex, they incorporate a variety of components – from fiber arrays to shaped bare fibers and terminated chips. KrellTech has designed NOVA's fixture system to be interchangeable, allowing users to configure the platform for virtually any photonic polishing application.

NOVA: A workcell for the future of photonics

With its integrated inspection capabilities, modular fixture design, and micron-level process control, NOVA represents more than just a polishing system. It's a complete workcell solution designed to meet today's challenges while providing a pathway for tomorrow's innovations.



➤ Figure 2. NOVA's Android interface controls all critical polishing parameters with micron-level movement. PIC lightguide structures are polished with superior surface finishes and clean-cut edges while maintaining material removal specifications.

As the photonics industry pushes the limits of chip functionality, precision, and integration, equipment that bridges the gap between concept and commercialization becomes increasingly vital. NOVA is that bridge – engineered for flexibility, built for repeatability, and optimized for every step from the lab bench to the production floor.

Each polishing cycle can be adjusted in real time during R&D and later saved as a repeatable program for volume manufacturing. This level of control extends to abrasive film selection

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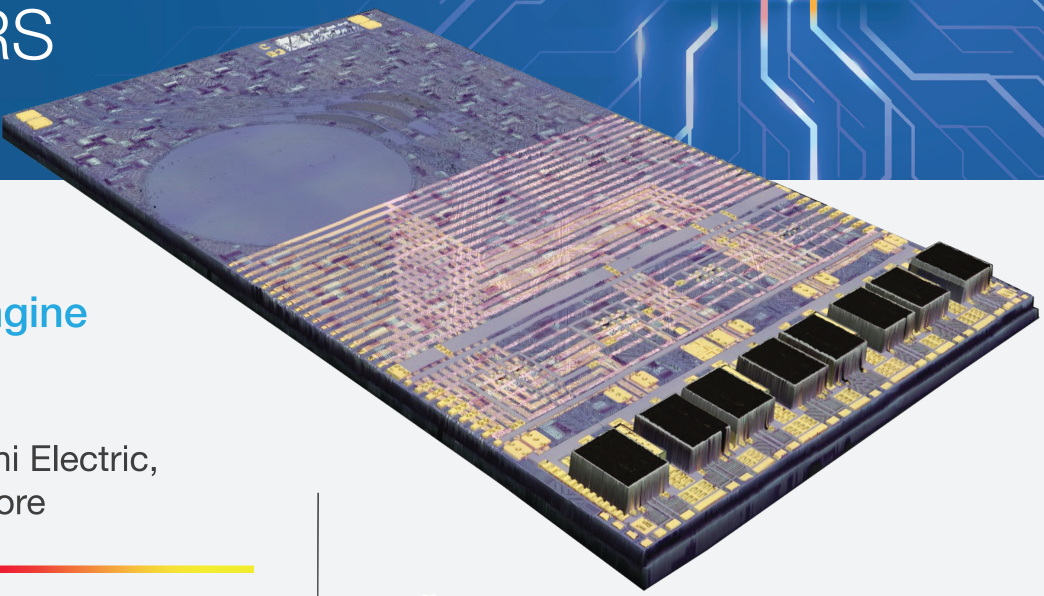

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