PHOTONIC INTEGRATED CIRCUITS

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PIC ANGELTECH INTERNATIONAL CONFERENCE

ISSUE II 2023

AN ANGEL BUSINESS COMMUNICATIONS PUBLICATION

PICMAGAZINE.NET

VIEWPOINT

By Jackie Cannon, Acting Editor

PIC International reaches new highs

AS THIS EDITION of PIC Magazine comes together, PIC International has been successfully delivered to an enthusiastic audience from across the globe.(p.34) Now in its 8th year, PIC International is the conference to attend if your interest is Photonic Integrated Circuits (PICs) not only in optical networking and internet, but other market verticals such as automotive, sensing, medical, displays, instruments, agriculture etc.

This year, there were over a record 800 delegates attending two days of highly condensed sessions on PICs that focused not only on innovative technology, but how PICs could alleviate major headaches, issues and opportunities that optical networks, datacentres, telecommunications systems, automotive applications see today.

Many talks focused on how PICs could be implemented into novel and innovative applications to move the industry forward, and keep the industry moving forward such as Automotive LIDAR, sensing, displays, healthcare, etc. Dates for 2024 have already been announced.(16-17 April) Join us in Brussels in 2024 if you believe you have a contribution to make to the PIC industry.

This issue will also look at how integrated photonics can transform the agrifood industry. PhotonDelta and OnePlanet Research Centre have launched the 'Integrated Photonics for Agrifood Roadmap,' describing the future of sustainable food production and distribution using photonic microchip technology and the role of integrated photonics.(p.14)
As PICs are more widely adopted in component design and manufacturing, addressing the need for scalability, speed and reliability of testing are emerging as keys to optimizing the value of PICs in everything from telecommunications to LiDARS and biosensing technologies. EXFO discusses the challenges labs and foundries typically face when looking for accurate agile component testing, and how automation can help elevate testing to the next level.(p.18)

Included in this issue is a feature from Yole Intelligence (p.28) who discuss the very bright promise of silicon photonics in the data centre. The driving forces of social media, digital entertainment, and cloud computing, have voracious appetites for more bandwidth and faster interconnect speeds. This, in turn, affects the data centre network architecture (disaggregation, AI and ML, power consumption). All this will require new high-speed, low latency technologies for data transfer (heterogeneous packaging, interposers, PICs,).

The future for PICs is very promising.

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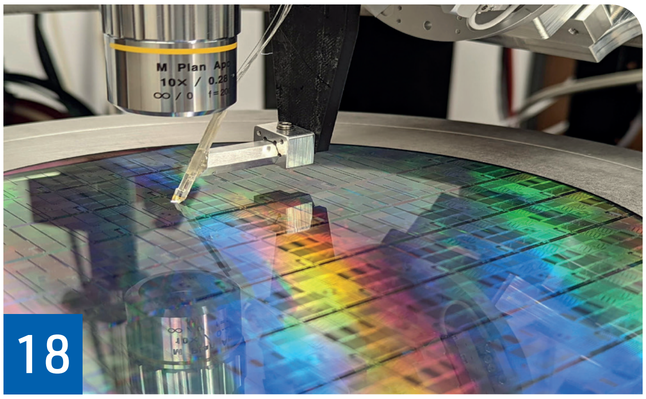

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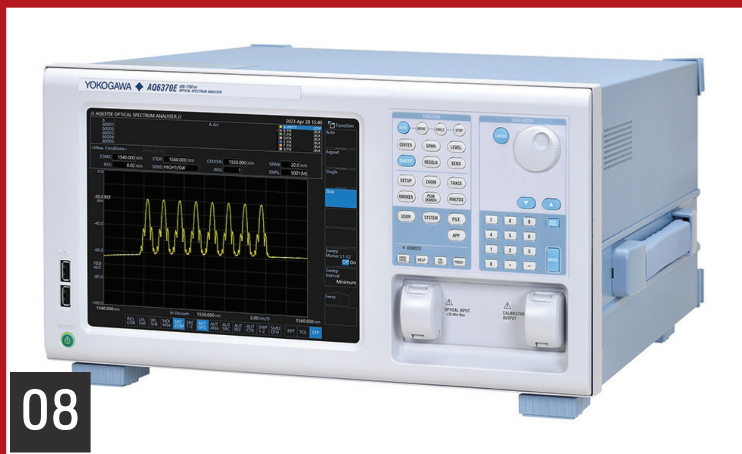

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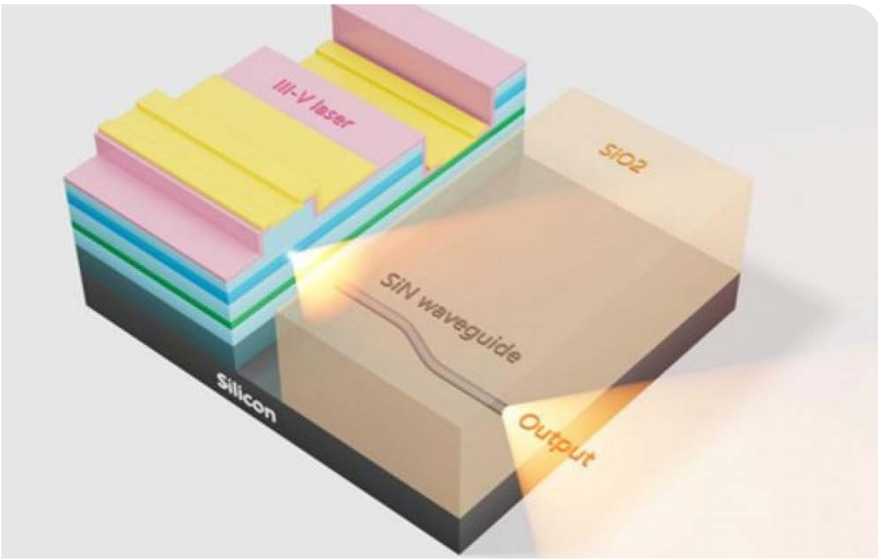
European team integrates GaSb lasers into PIC chips

Approach relies on Si-PIC design and fabrication, III-V material deposition, and laser fabrication

IN A NEW PAPER published in Light Science & Applications, a team of scientists from France, Italy and Ireland, led by Eric Tournié from the University of Montpellier (France), claims to have unlocked the efficient integration of semiconductor lasers onto silicon photonics chips and light coupling into passive photonic devices.



Their approach relied on Si-PIC design and fabrication, III-V material deposition, and laser fabrication. For this proof-of-concept, the PIC was made of transparent, S-shaped, SiN waveguides embedded in a SiO2 matrix. The SiO2/SiN/SiO2 stack was etched away in recessed areas to open silicon windows for the deposition of the III-V material.

GaSb was used as the III-V material because it can emit in the whole mid-infrared wavelength range, where many gases have their fingerprint absorption lines. Molecular-beam epitaxy was used to grow the semiconductor layer stack. The scientists had previously shown that this technique allows removing a special defect that usually occurs at the Si/III-V interface and kills the devices. Further, MBE allows to precisely align the laser part that emit light with the SiN waveguides.

Finally, a microelectronics process was used to create diode lasers from the epitaxial layer stack. At this stage high quality mirrors must be created through plasma etching in order to achieve laser emission. In spite of the process complexity, the performance of these integrated diode lasers were similar to those of diode lasers grown on their native GaSb substrate. Further, the laser light was coupled into the waveguides, with a coupling efficiency in line with theoretical calculations.

The scientists summarised the work as follows:

"The different challenges (PIC fabrication and patterning, regrowth on a pattern PIC, etched-facet laser processing in recessed areas, etc.) due to the particular architecture of the final devices were all overcome to demonstrate laser emission and light coupling into passive waveguides, with a coupling efficiency in line with theoretical calculations".

> Although demonstrated with mid-infrared diode lasers targeting gas sensing applications, this approach can be applied to any semiconductor materials system. In addition, it can be scaled up to any Si-wafer size up to at least 300 mm diameter, epitaxial reactors being available

"Although demonstrated with mid-infrared diode lasers targeting gas sensing applications, this approach can be applied to any semiconductor materials system. In addition, it can be scaled up to any Si-wafer size up to at least 300 mm diameter, epitaxial reactors being available. The reported method and technique will open new avenues for future silicon photonics integrated circuits. They solve a longstanding problem, and lay the foundation for future low-cost, large-scale, fully-integrated photonic chips."

Reference

'Unlocking the monolithic integration scenario: optical coupling between GaSb diode lasers epitaxially grown on patterned Si substrates and passive SiN waveguides' by Andres Remis et al; Light: Science & Applications volume 12, Article number: 150 (2023)

BluGlass shows expanded GaN laser portfolio

Enhanced products on show at Laser World of Photonics include new 397nm UV alpha product

BLUGLASS showcased enhanced GaN laser products at Laser World of Photonics in Munich, Germany. It says these updated GaN lasers feature performance improvements in light emission, power conversion efficiencies, and voltage.

The company's blue 450nm single-mode and multi-mode devices, for instance, feature significant increases in power conversion efficiencies from those launched at Photonics West, up more than 55 percent and 42 percent respectively. These improvements enable their use in more demanding customer applications, such as quantum computing, robotics and biotechnology.

Customers can inspect BluGlass' enhanced performance data at Laser World across the 405nm, 420nm and 450nm wavelengths in single-mode and multi-mode devices. BluGlass is also using the conference to launch a new 397nm ultra-violet single-mode alpha product to market. Ultra-violet lasers are increasingly being sought after for quantum sensing applications, advanced disinfection technologies, water and surface purification applications, and medical devices.

BluGlass' product suite now includes six commercial and three prototype products, and are available in a range of form factors including TO Cans of different sizes, and Chip-on-Submounts.

DFB update

BluGlass, together with its collaboration partner the University of Santa Barbara California (UCSB), has made significant improvements to its GaN Distributed Feedback Laser (DFB) demonstrations using its proprietary RPCVD technology for longer-wavelength devices.
The company improved DFB side-mode suppression ratio by more than 50 percent since Photonics West, delivering advanced single frequency performance at 450nm and demonstrating longer-wavelength DFB lasers up to 478nm.

DFB lasers are a highly promising single frequency laser technology commonly utilised in non-visible wavelengths to enable devices that require narrow spectral width and high-spectral purity, such as quantum applications. GaN-based DFB lasers are currently not commercially available in visible wavelengths. BluGlass is releasing an updated GaN DFB white paper at Laser World.

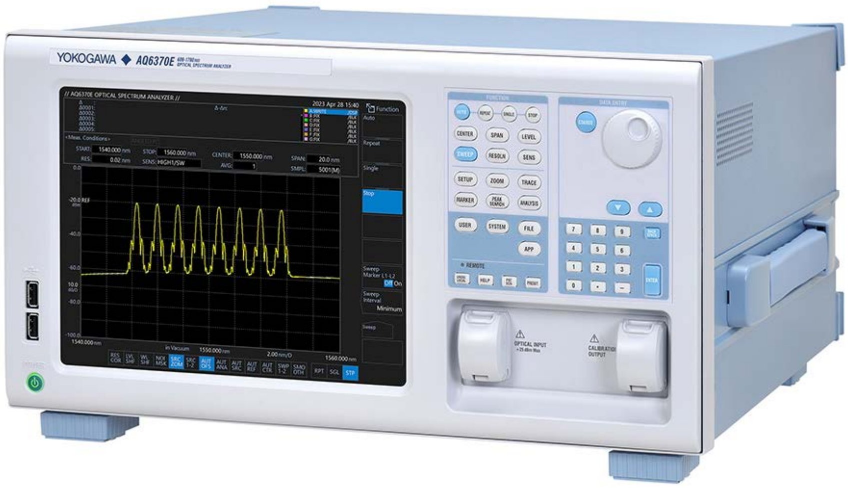
Vertical integration

BluGlass is nearing vertical integration completion with production moved from four out of five contract manufacturers (CMs) into its Silicon Valley fab. The company is now in advanced stages of completing the integration of the final back-side contract manufacturer. Since acquiring its laser diode fabrication facility in Silicon Valley and commencing operations in July last year, BluGlass has accelerated development and production, mitigated reliability challenges to launch a suite of GaN lasers, advanced long-term roadmaps, and commenced shipping products to customers.

BluGlass CEO Jim Haden said, "Our enhanced GaN laser products are shifting our market position from an emerging alternative supplier to an agile player that is focused on providing high quality and competitive GaN lasers. As a dedicated GaN laser supplier, we are focused on launching innovative products that address gaps in the market whilst also improving the baseline performance of our existing lasers as we strive to meet or exceed competitor benchmarks. This strategy broadens our target customer base while building our reputation as a partner- of-choice in the industry."

Yokogawa releases high performance optical spectrum analyzer

Yokogawa Test & Measurement has announced the release of the AQ6370E optical spectrum analyzer. An upgraded version of the popular AQ6370D, the new model comes equipped with features that enhance performance and improve usability



EQUALLY SUITABLE for industry, universities and research institutions, the AQ6370E can be used to characterize a wide range of components, including lasers for optical communications, optical transceivers, and optical amplifiers.

Based on the technologies and expertise developed through over 40 years in this field, the Yokogawa AQ6370E optical spectrum analyzer is designed to meet the growing need for highly precise and easy to use test equipment in the R&D and production of optical communications devices and equipment. This is driven in part by the growth in the use of cloud services, 5G communications, and other information and communication services that require large-capacity and high-speed optical communication networks.

This trend is driving the development of next-generation optical devices and components that support large-capacity optical communication networks. Evaluating the characteristics and quality of these devices and components requires high-precision optical test instruments that are able to analyze the light wavelength components and measure the wavelength characteristics. Since its release in 2014, Yokogawa's AQ6370D optical spectrum analyzer has been widely used both in R&D and production testing. The newly released AQ6370E offers several new functions and features that streamline development and production processes.

One of these new features is HCDR (high close-in dynamic range) mode, with which a user can measure a single longitudinal mode laser with a high close-in dynamic range. Close-in dynamic range is a key performance criterion when developing lasers and optical devices. There is also a SMSR (side mode suppression ratio) mode, which can reduce SMSR measurement time, and an APP mode.

APP mode provides a device under test (DUT) specific user interface that navigates the user from configuration settings to test result output, so that even customers who are unfamiliar with optical spectrum analyzers can use it easily.

Sivers Photonics receives $1.3 million order

SIVERS SEMICONDUCTORS AB has announced that its subsidiary, Sivers Photonics, has received a new order worth $1.3million (approx. MSEK 14) for the qualification and supply of advanced photonic devices for optical sensing applications from a US-based customer.

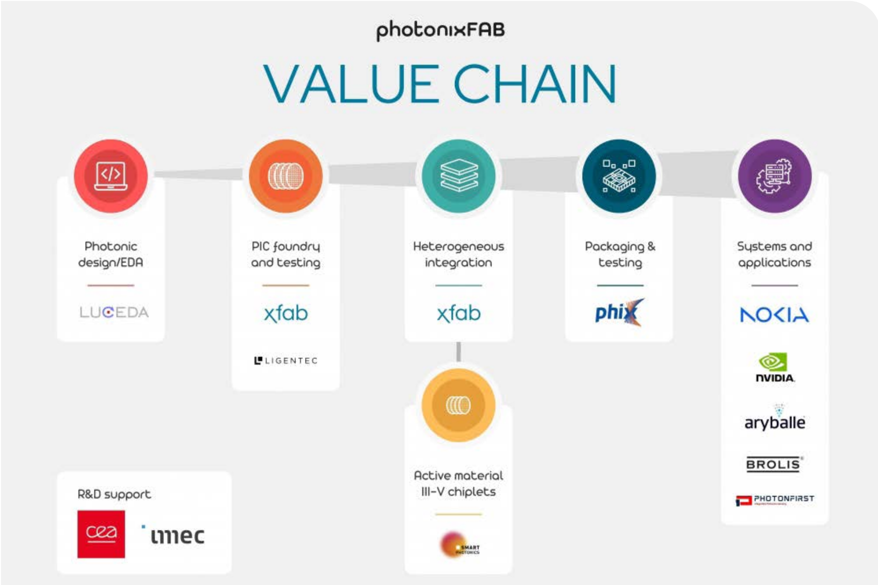
This order is the next step in an ongoing partnership where Sivers received the first order in December 2021. The order includes the development, qualification and supply of custom photonic devices manufactured on Sivers' InP100 technology platform and forms an essential part of the customer's advanced sensor product range. "We're excited to continue our relationship with this customer, supplying custom devices designed and manufactured on our InP100 platform, on which we support many customers across several applications," said Dr Andrew McKee, Interim Managing Director and CTO at Sivers Photonics. "We are thrilled that our technology is playing a critical role in allowing this customer to move closer to volume production."

"This order strengthens our relationship with this important US customer, and this market is definitely one of the major megatrends that Sivers Photonics offers a strong portfolio towards." said Anders Storm, Group CEO of Sivers Semiconductors.

X-Fab leads EU-funded photonics consortium

photonixFAB project aims to industrialise the European silicon photonics value chain

X-FAB is spearheading an initiative to enable the European semiconductor and photonics industries to gain greater sovereignty. The photonixFAB project aims to empower photonics innovation by providing low barrier access to both low-loss silicon nitride (SiN) and silicon-on-insulator (SOI) based photonics platforms with InP and lithium niobate (LNO) heterogenous integration capabilities.



THE photonixFAB consortium is made up of public and private enterprises, plus research institutes – all focusing on the development and production of next-generation silicon photonics.

They include LIGENTEC, SMART Photonics, PHIX Photonics Assembly and Luceda Photonics plus application developers Nokia, NVIDIA, Aryballe, Brolis Sensor Technology and PhotonFirst, as well as the major research organisations CEA-Leti and IMEC.

The objective is to establish a European photonics device value chain and initial industrial manufacturing capabilities. Thus, providing a path to scalable high-volume manufacturing for innovative product developers.

A comprehensive set of photonics foundry and assembly capabilities will be covered by photonixFAB. These will include:

- Industry-scale silicon photonics manufacturing services with low entry barriers and fast turnaround times for both low-loss SiN and SOI based PICs.
- Enablement of microtransfer printing and direct bonding technologies for InP, LNO and germanium based active and passive component heterogeneous integration on SiN and SOI based PIC platforms.
- Development of scalable packaging and testing solutions in alignment with the (heterogeneous) PIC platform developments.
- Process design kit based design automation enablement for the photonic platforms.

As a part of the project, six demonstrators are being built to validate the implemented photonics value chains. These include applications such as datacom and optical switches, coherent optical transceiver, IR spectrometer for sensing, digital olfaction sensor for consumer healthcare and a health monitoring demonstrator.

Prospective opportunities for the cutting-edge photonic devices fabricated via the photonixFAB project have already been identified. Among them are data communication, telecoms, biomedical sensors/detectors, quantum computing and vehicle LiDAR.

"Seeing huge potential emerging there, traditional semiconductor vendors, OEMs and start-ups are all now exploring photonic-enabled applications," states Rudi De Winter, CEO of X-Fab. "Consequently, this is the right time for companies to work together on building an extensive Europe-centric silicon photonics ecosystem that will help drive the continent's competitiveness in this exciting new market."

The project is being supported by the Key Digital Technologies Joint Undertaking (KDT JU), with funding from EU and the national authorities. The combination of this funding and the investments being directly made by each of the consortium members comes to a total of €47.6 million.

A major part of the work of this 3.5 year project will be conducted at X-Fab's foundry operation in Corbeil-Essonnes, France, with additional activities also undertaken at the numerous other partners' sites across Europe.

TOPTICA completes the acquisition of Azurlight Systems

TOPTICA Photonics SAS employees in front of their premises located in Pessac/Bordeaux together with TOPTICA Photonics AG's executive board visiting for the inauguration of the new subsidiary

TOPTICA Photonics AG has successfully closed the acquisition of Azurlight Systems SAS on 5th of May 2023 after final approval from the French government.

The effective date is 1st of Jan 2023. Azurlight will continue its successful fiber laser and amplifier business under the new name TOPTICA Photonics SAS. Located in Pessac/Bordeaux (France), TOPTICA Photonics SAS also will become the French hub of the TOPTICA group, demonstrating TOPTICA´s commitment to the local photonics ecosystem, including a Joint-Lab arrangement with the LP2N Institute of Optics Aquitaine.

Enlarged product portfolio

The product offering of TOPTICA – now including also high-power cw fiber lasers & amplifiers – will serve customers in the fast-growing markets of quantum technologies, biophotonics, and industrial metrology and help to establish an even stronger European position in these markets.

The individual products are already invaluable tools used in industry and fundamental scientific research. The foreseen combination of world-class diode lasers, lowest-noise fiber amplifiers, and superior frequency conversion technology opens individual solutions ranging from low to high power and from ultraviolet to infrared wavelengths. Many applications will benefit from complete solutions that meet industry standards.

Extended sales, service, and expert network

Customers benefit from access to an experienced global team of TOPTICA experts covering laser technology, application knowhow, sales, and full technical support. Adding a French subsidiary to the global team is an important step towards TOPTICA's goal of providing world-leading professional-grade lasers with cutting-edge technology to scientific and industry customers. Dr. Nicholas Traynor (President TOPTICA Photonics SAS, Pessac/France): "We are delighted that we have finally joined TOPTICA. Our technologies are mutually beneficial, and their combination opens exciting opportunities for the next stage of development of the TOPTICA group. We identify strongly with the TOPTICA culture, enjoy adding a French twist to its internationality, and look forward to the years to come."

Dr. Juergen Stuhler (General Manager TOPTICA Photonics SAS & Vice President Quantum Technologies TOPTICA Photonics AG, Munich-Graefelfing/Germany): "High power low-noise cw fiber lasers & amplifiers are a perfect addition to our variety of technologies. Already the direct combination of existing products is a big plus for our customers, especially in quantum technology and industrial metrology applications. For example, we just realized more than 30 W cw optical output power at 520 nm by combining a 45 W ALS-fiber laser at 1040 nm with a DLC SHG pro resonant frequency conversion stage. The great potential that we see in combined product development is fascinating.

" Dr. Thomas Renner and Dr. Wilhelm Kaenders (Executive Board of TOPTICA Photonics AG, Munich-Graefelfing/Germany) add: "We are very pleased to establish a French subsidiary within the TOPTICA group. We envisage further strengthening of fiber laser development in the high-tech environment of the Route des Lasers in Nouvelle Aquitaine and look forward to a deep collaboration with local institutes and with the French ecosystem for lasers, quantum technologies, and biophotonics. TOPTICA Photonics SAS in Pessac/Bordeaux will also become the local point of contact for sales & service in France."

POET samples chiplet transmitter platform

Canadian photonics company POET Technologies has announced alpha sample readiness of 'POET Infinity', a chiplet-based transmitter platform for 400G, 800G and 1.6T pluggable transceivers and co-packaged optics solutions

Two customers have agreed to partner with POET to test the alpha version of the Infinity chiplet. The POET Infinity chiplet complements the POET 800G 2xFR4 receiver optical engine that the company announced in February 2023, and completes the 800G chipset for 2xFR4 QSFP-DD or OSFP applications with two Infinity chiplets and one receiver optical engine. Both customers intend to develop 800G 2xFR4 QSFP-DD and OSFP transceiver solutions using the POET Optical Engine chipsets.

The Infinity chiplet is said to be the industry's first implementation of directly modulated lasers (DMLs) for 100G/lane applications. DMLs are power efficient, cost effective and become a highly scalable solution when paired with the POET Optical Interposer platform.

The chiplet incorporates 100G PAM4 DMLs, DML Drivers and an integrated optical multiplexer for a complete 400GBASE-FR4 transmitter solution on a chip. The small size of the chiplet and a daisy-chain architecture enables side-by-side placement of multiple instances to achieve 800G and 1.6T speeds.

"The availability of a transmitter solution for 400G, 800G and 1.6T speeds that is power efficient, cost effective and highly scalable for the data centre market is a major achievement," said Suresh Venkatesan, chairman & CEO of POET. "Our customers are excited to receive the samples and test them because it simplifies their transceiver design significantly and shortens the design cycle with POET optical engines that incorporate all of the required optical elements as well as the key electronic components, including laser drivers and trans-impedance amplifiers." The development of a production version of the POET Infinity chiplet is on track and POET expects to deliver beta samples by Q4 of 2023 and start production by the first half of 2024. The ethernet transceiver market for 400G and above data rates is projected by Lightcounting to exceed $6 billion by 2028.

Etteplan accelerates photonics technology breakthrough

Etteplan has developed a smart solution to accelerate the global breakthrough in photonics

ETTEPLAN has developed a smart solution to accelerate the global breakthrough in photonics. Using a modular machine platform, lightning-fast assembly of optical elements with extreme accuracy is possible. With the latest innovation, particularly prototypes of photonics products can now be produced much faster.

Integrated photonics is an emerging technology where instead of electrons, photons (light waves) are used in chips or data transport, along with other applications. This technology is more energy-efficient and faster, which is why significant investments are being done worldwide. The number of applications is growing rapidly; for example, photonics is already being used in data centers and in LiDAR, but the big breakthrough is yet to come. One of the challenges companies worldwide are struggling with is being able to quickly produce different prototypes. Normally, it would take days of adjustments to the settings of a machine, capable of making these products, to switch in assembly from one prototype to another.

'Etteplan Indigo' is the modular machine platform which was developed in part to make this R&D process much easier. The machine can assemble a wide range of micro-optical elements because both the hardware and software are modular. One example is the alignment and connection of glass fibers to a chip. The innovative software is easy to use and allows the operator or company to quickly create and

modify the programming themselves. The changeover time required to make another product is thus drastically reduced. Assembly costs are thereby lowered and with that also ultimately the cost price of photonic application produced with the machine platform.

Rockley Photonics completes financial restructure

ROCKLEY PHOTONICS has announced that it has completed a comprehensive financial restructuring and emerged from Chapter 11 after filing for bankruptcy protection in Q1.

All of Rockley's material customer relationships remain in place. The company remains on schedule with all programs including its development of remote patient monitoring technology.

Rockley continues to see promising results relating to a number of biomarkers, including glucose and anticipates releasing those results in the second half of this year. The company emerged with a strengthened capital structure having received approximately $35 million of additional funding from its stakeholders.

Dr. Andrew Rickman, chief executive officer, said: "Rockley's ability to emerge from Chapter 11 in just 46 days was a significant achievement and marks the beginning of a new era for the company. Our stakeholder's ongoing belief in Rockley has provided us with a greatly strengthened balance sheet and the funds to continue to develop disruptive technology for the med tech market.

"We greatly appreciate the continued support not only of our stakeholders but also of our suppliers, partners and employees. I look forward to the opportunity to continue to develop Rockley's products and bring them to market."

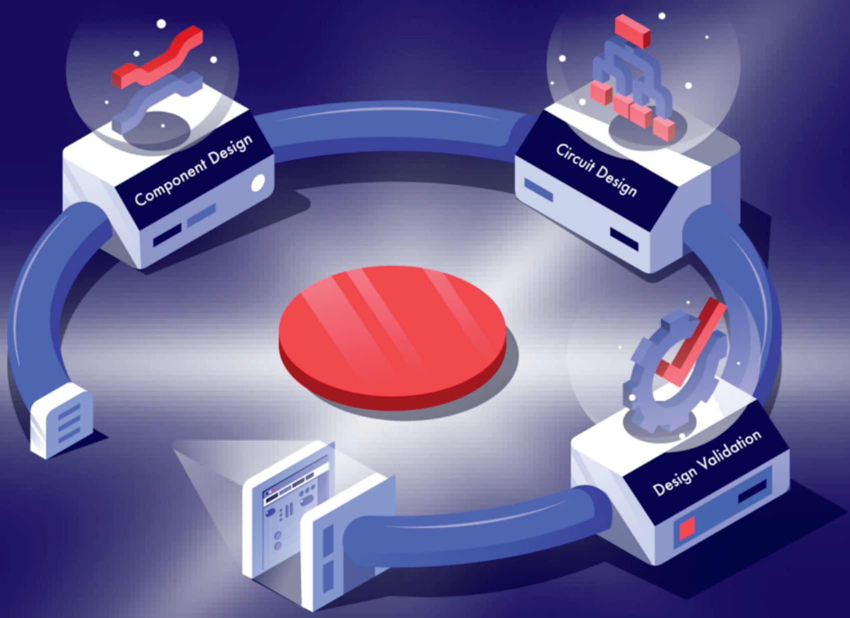
Dr. Richard Kuntz, former senior vice president and chief medical and scientific officer at Medtronic, said: "Rockley has developed breakthrough technology for non-invasive biomarker monitoring based on their unique photonics chip platform.

Rockley's progress towards wearable devices could have a profound impact on early diagnosis and disease management."

Dr. Tess Skyrme, Technology Analyst at research firm IDTechEx, said: "Medical conditions such as diabetes and hypertension are affecting a growing proportion of the global adult population. The market for wrist-worn remote monitoring technology, which helps people manage these conditions, is a sub-set of the growing wearable technology market - forecast to surpass $161 billion by 2033. Within this field, cuff-less blood pressure monitoring emerges as a particularly promising growth engine."

LUCEDA PHOTONICS

Luceda Photonics Design Platform



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How integrated photonics can transform the agrifood industry

PhotonDelta and OnePlanet Research Center – launched the 'Integrated Photonics for Agrifood Roadmap,' describing the future of sustainable food production, distribution using photonic microchip technology and the role of integrated photonics.

By Carol de Vries from PhotonDelta

FEEDING the world's ever-growing population requires a fundamental transformation of farming and food production techniques. The UN estimates that by 2050 our planet will be home to 10 billion people. To keep up with demand, the agrifood industry not only needs to develop smart solutions for preventing global food shortages, it must also mitigate the environmental impact. Alongside those challenges, agriculture must remain a sustainable and commercially-viable enterprise for farmers.

➤ MantiSpectra's SpectraPod, a portable spectral sensor solution for the agrifood industry - Source MantiSpectra

Global challenges in agrifood

The global agriculture, food retail, food processing, and food service sectors have a combined total of $30 trillion per year. Under the banner of 'agrifood' they constitute an enormous global market facing two interconnected challenges: the elimination of food losses and wastage, and the reduction of greenhouse gas (GHG) emissions.

A study by the Food and Agricultural Organization of the United Nations (FAO) found that around one-third of the world's food is lost or wasted – about 1.3 billion tons of 'edible' parts. At the same time, these food losses and waste are responsible for creating 3.3 billion tonnes of carbon dioxide. To put that into context, if food loss and waste were a country, they'd be the third-biggest generator of GHG emissions in the world.

On top of that, the Food Climate Research Network (FCRN) estimates that livestock are responsible for generating around 14.5% of global GHG emissions every year. Most prominent are ammonia and methane, closely followed by nitrogen dioxide and nitrous oxide. There are also related issues to consider, including water scarcity due to agriculture, and the depletion of soil nutrients and fertility through over-farming.

At the same time, the mounting costs associated with running a farm place a heavy financial burden on farmers. The increasing cost of fertilizer, rising energy prices, and the amount of herbicides and pesticides needed, push up production costs and pull down profitability for farmers under pressure. This global picture reveals a clear and obvious need to improve crop yields and output whilst avoiding food losses and waste.

What's needed are sustainable farming practices that do not deplete the Earth's resources or reduce biodiversity, and allow farmers to run a viable, profitable business.

Precise sensing technology

To meet the objectives of increasing crop yields, reducing food loss and waste, and minimizing the negative environmental impact of food production, new methods are needed. Enter precision agriculture as part of the answer. Precision agriculture uses sensing technologies to enable more precise and optimized growth conditions. Combined with robots and diagnostic software, it enables farmers to focus on smaller sections or even specific plants, instead of applying crop management to an entire field.

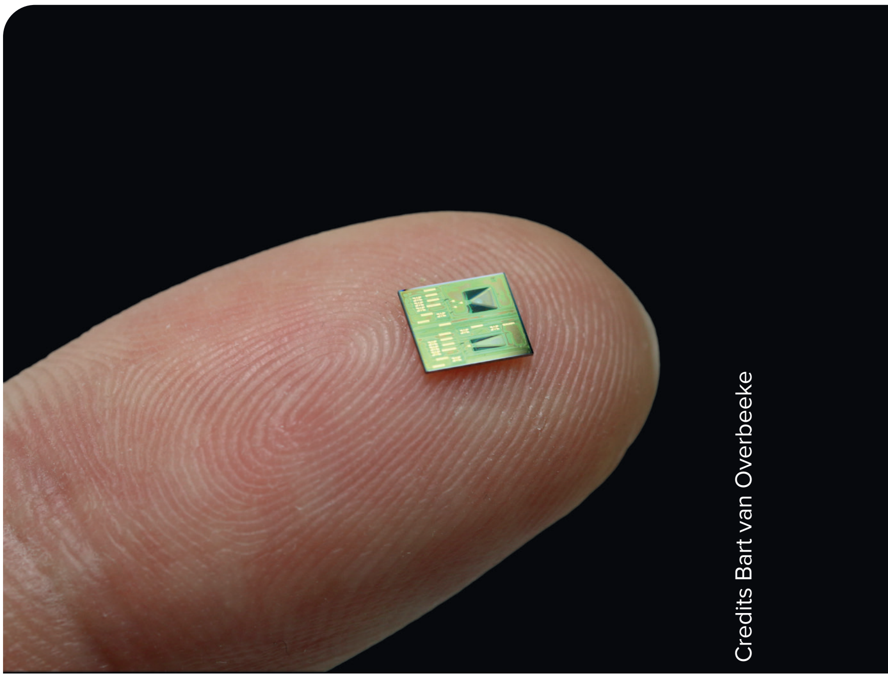
Monitoring and processing individual plants means that farmers can optimize plant growth and improve the quality and quantity of crop yields. As well as that, it enables farmers to have exact control over resources like fertilizer and plant hydration. That way, plants get precisely what they need for optimal growth, and precious resources – nutrients and water – are carefully conserved.

Precision agriculture has three core components: monitoring systems, data modeling and algorithms, and technology that can perform the required actions, such as drones. This points towards a future where large and powerful machinery – such as tractors – are increasingly enhanced with small, light, and cost-effective smart devices.

Better for the environment and ultimately more affordable, smaller and smarter connected devices have the potential to revolutionize farming practices and help to produce food more efficiently and economically. The agricultural sector is already gearing up for a future where robots and smart sensing systems support crop production.

Today's sensors are capable of taking a wide range of measurements including humidity, air pressure, chemical composition, and temperature. Smart sensing is a burgeoning market, with a growing number of applications within agrifood. It's already found applications in areas such as livestock management, soil management, and fruit farming.

However, commercially-viable smart technology needs to be easy to understand and operate without the need for extensive technical training. It must also be robust enough for farmers to use in the field. To address these practical and technical challenges, precision agriculture needs sensing technology that is small, cost-effective, and scalable — so that it can be produced in high volumes and at low cost.



Integrated photonics – in the form of highly-precise sensing functionality delivered on a single low-power and miniaturized chip – can provide the sensing solutions needed by agrifood.

Applications for integrated photonics in agrifood

Taking analysis and testing out of the laboratory and putting it in the hands of farmers and food companies opens up a multitude of potential applications for a limited number of PIC platforms.

Near infrared

Near infrared (NIR) testing is already on the market. In dairy farming, NIR testing is used to extract precise data about the composition of a cow's milk at the point of milking. This includes things like fat, protein, lactose, and temperature. For farmers, this means livestock can be sectioned off into different groups to make processing easier further down the milk production line.

NIR technology is also used to measure moisture and the composition of produce grown in greenhouses, such as tomatoes. Right now, very small multiband NIR sensors on a chip – measuring a few mm2 – have been developed. They allow both qualitative and quantitative analysis of the composition of nutrients in produce from tomatoes to coffee, and even the alcohol content in wine.

Raman spectroscopy

Raman spectroscopy is a complex and expensive sensing technology capable of delivering highly-sensitive and very specific chemical analysis, including biochemical markers, bacteria typing, pharmaceutical analysis, and food nutrient analysis. Potential applications vary, from in-line controls in food processing to online or offline analysis of plants.

This makes it ideal for use in special instruments to determine growth conditions, measuring the chemical composition of plants. It also has viable applications in livestock management to monitor and control emissions such as ammonia, methane, nitrogen dioxide, and nitrous oxide – helping to both improve gas detection systems and monitor animal health.

Photoacoustic spectroscopy

Photoacoustic spectroscopy is a laboratory technique. Laser pulses are fired at the sample at a chosen wavelength, creating local heating. The thermal expansion creates a pressure wave which can be measured as sound. Its useful spectral range varies from 200 nanometers to 10 microns.

In the future, this could be miniaturized on a microchip. Its sensitivity makes it well-suited to the detection of low concentrations of gasses. For example, photoacoustic spectroscopy can detect the ethylene emitted by bananas and other fruits when the fruit is ready to ripen.

This technology is already used in medical devices for cancer diagnosis and Covid testing. But what works in healthcare can also work for agriculture, wherever there is a need to measure biological compounds, such as pollution or mold. Results are fast – typically, within 10 to 20 minutes

Recent tests show that through relatively straightforward measures, farmers using real-time diagnostics can reduce emissions by up to 50%. This can make the difference between costly investments and reducing livestock to fulfill regulatory requirements.

LIDAR

Lidar adds enhanced functionality to sensor data. 3D mapping of landscapes and structures is one thing. Mapping orchards, soil conditions, and water flow is another. This would enable farmers to precisely pinpoint where a problem lies and make adjustments or take intervening action where needed. In combination with robots, it can also help to pick exactly the right produce.

Lidar is also useful for mapping the precise location of farm machinery and livestock. Firstly, to keep track of assets, and secondly for collision detection for automated and expensive equipment such as drones and robots.

Biochips

Biochips incorporate a bioactive layer that's sensitive to a single virus or bacteria. Extremely sensitive detection is possible using ring resonators or Mach-Zehnder interferometer chips. The active layer sits on top of a waveguide. Detection causes a wavelength shift in a resonator or interferometer.

This technology is already used in medical devices for cancer diagnosis and Covid testing. But what works in healthcare can also work for agriculture, wherever there is a need to measure biological compounds, such as pollution or mold. Results are fast – typically, within 10 to 20 minutes.

Terahertz spectroscopy

For a long time, it was complicated and expensive to create tunable sources and sensitive detectors for terahertz (THz) spectroscopy. That's because it sits below the frequency of light and above the frequency of standard electronics. However, integrated photonics allows the mixing of two laser wavelengths with the differential signal output in the THz region. Whilst currently in the laboratory phase, it opens the door to small, affordable sensing systems for both moisture and specific chemical compounds.

Laser speckle imaging

Laser speckle imaging as a sensing technique uses the interference of a wide field coherent light source on a rough surface. When particles move during the illumination period, the intensity fluctuations can be detected with a photodetector or imaging device. This can be used to measure sap flow in a leaf and therefore helps to optimize plant growth

The future of food production

Existing methods of farming and food production will not be enough to sustain the global population of the future. Agrifood has no choice. It must transform to minimize losses and optimize food production processes and yields. At the same time, agrifood needs to adopt cleaner and greener solutions – reducing GHG emissions and supporting biodiversity – in order to conserve, sustain, and more evenly distribute the Earth's natural resources.

Precision agriculture is a huge opportunity to optimize yields, reduce waste, and ensure that consumers get great-tasting food products. However, it requires smart technology which can take monitoring and testing out of the laboratories onto the farms, and into the fields. That's where integrated photonics comes in.

Cost-effective and easy to scale, PICs will allow the farmers of the future to closely monitor plants and livestock in order to optimize growing conditions and yield. It will also give food supply chains clear oversight of the food journey, ensuring peak conditions from field to fork, and ultimately eliminating food wastage. As a result, consumers can look forward to food that is harvested at precisely the right moment, and transported in the optimum conditions to ensure freshness of flavor.

Investment in integrated photonics

The Netherlands Government has heavily invested in integrated photonics via the National Growth Fund (NGF). The industry has been allocated €470 million – together with €1.1 billion in public and private investments – over the next 6 years.

PhotonDelta is a public-private initiative and a world-leading hub for integrated photonics based in the Netherlands and the rest of Europe. We're a vibrant ecosystem of tech developers, investors, and users of photonic chips and products.

Our members research, design, develop, and manufacture solutions for a better future in agrifood and other industries. Here are some of the companies already developing agrifood applications within the PhotonDelta ecosystem:

- **MantiSpectra** is one of the most mature in this sector, offering a miniaturized spectral sensor solution for NIR analysis of soil, fruit, milk, and other food products.
- **Spectrik** is gaining attention for developing an integrated photonics gas sensor to measure ammonia emissions in agriculture.
- **Ommatidia Lidar** manufactures a 3D Light Field Sensor that combines flood illumination with single-photon sensitivity, resulting in unprecedented range and high resolution. It's active in a range of markets including engineering, metrology, and space.
- **Scantinel Photonics** has a long-range and reliable Lidar sensor which uses coherent FMCW ranging and solid-state scanning technology for applications in fully autonomous driving vehicles.
- **Neuruno** produces field-based organic substance sensing solutions measuring in the infrared spectrum. Applications include food safety, waste reduction, and quality control.
- **Deloq** has a cost-effective, spectroscopic sensor that enables continuous monitoring of methane emissions. It measures ammonia emissions from livestock farms with an integrated photonics gas sensor.

The full 'Integrated Photonics for Agrifood Roadmap' is available to download from our website.

Visit https://www.photondelta.com/downloads/ for more information.

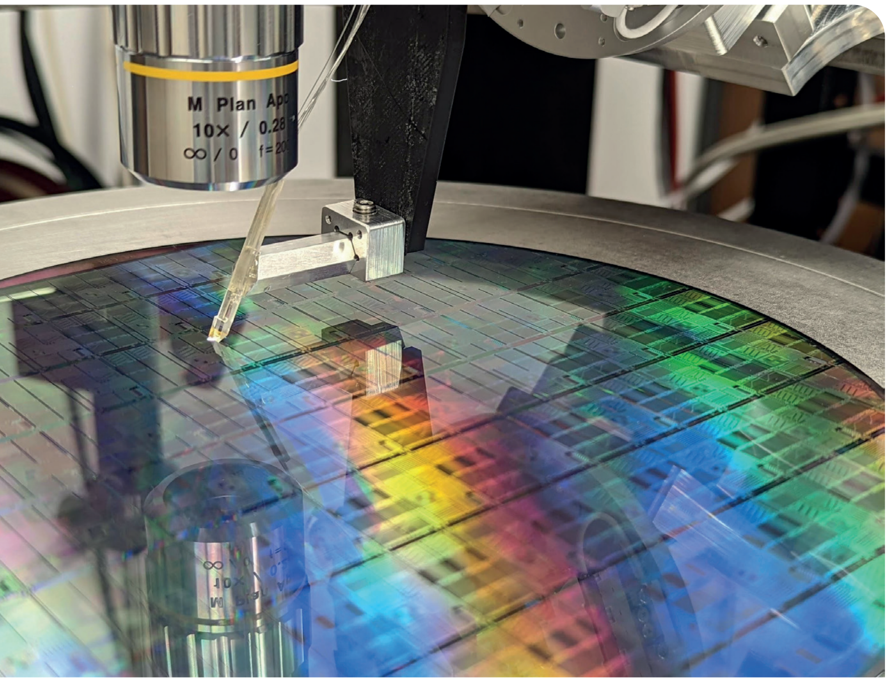
Automation: an essential tool for testing PICs

As Photonic Integrated Circuits (PICs) are more widely adopted in component design and manufacturing, addressing the need for scalability, speed and reliability of testing are emerging as keys to optimizing the value of PICs in everything from telecommunications to LiDARS and biosensing technologies.

By Francois Couny, Ph.D., Senior Product Line Manager, EXFO

THE PHOTONIC INTEGRATED CIRCUITS (PIC) testing ecosystem is comprised of both hardware and software solutions that have been evolving rapidly to meet the expanding needs of PIC scientists and technicians in labs and production facilities. But because foundries and labs need tests that can be reliably replicated and, in many cases, expanded to support mass production, automated processes are becoming more important than ever to support PIC testing.

In this article we'll look at the challenges labs and foundries typically face when looking for accurate, agile component testing, and how automation can help elevate testing to the next level.



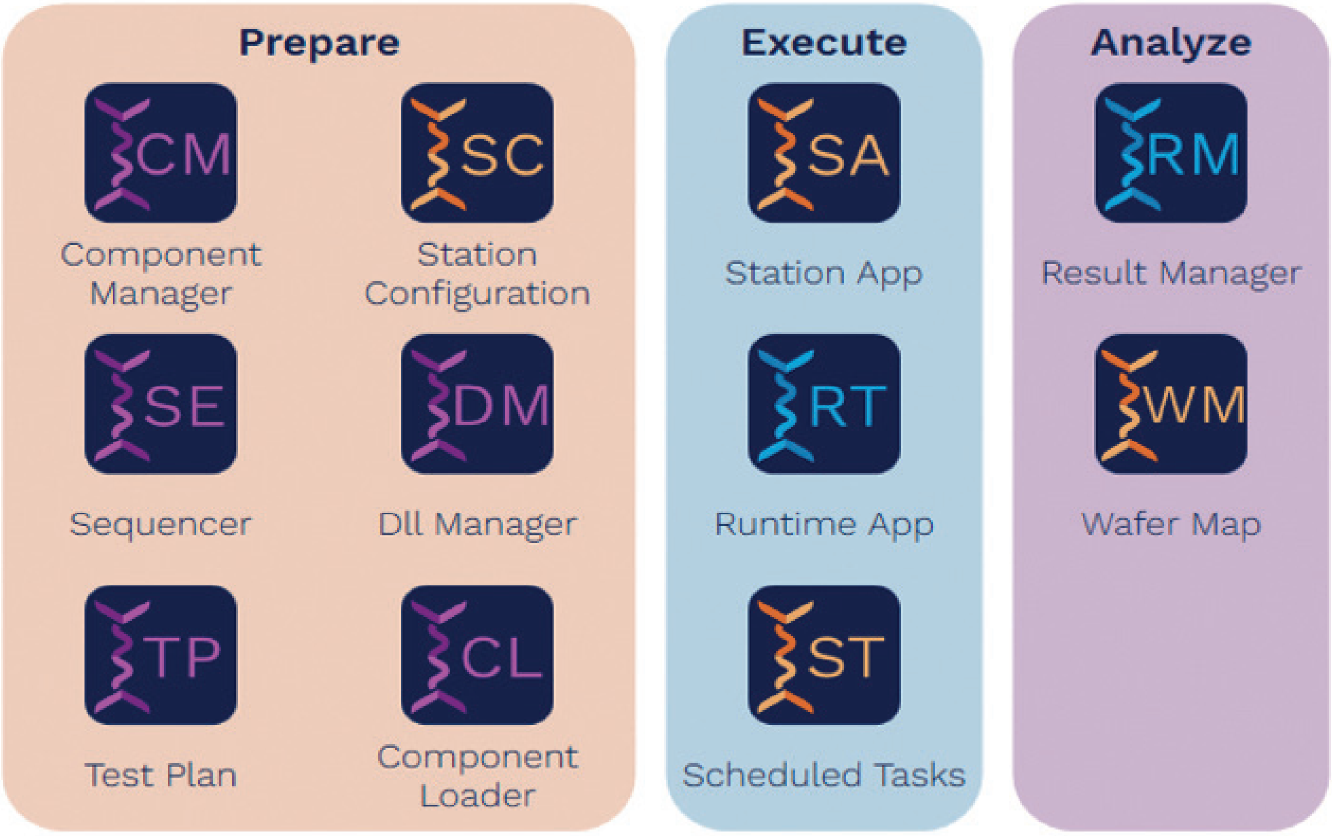
Hardware challenges

In the photonic component testing field, the industry has collectively applied creative thinking to use hardware to deliver new, more optimized test approaches. An excellent example of this is edge coupling at the wafer scale.

Generally, chips are designed such that a given circuit makes use of edge and surface couplers. While surface coupling enables light coupling into a device from the top surface – which is ideal when testing a wafer -- the final diced chip is often designed to use edge couplers. In these cases, the purpose of the surface coupler is merely to provide an interface for screening and early testing, enabling the die to be qualified as early as possible in the process. That is then followed by the edge coupler which is later used as a production interface.

However, that has inherent problems because partial screening using a surface coupler can leave unchecked some problems arising from the untested section (the edge coupler section). An inadequate testing solution consists of designing optical "taps" on the component being tested, to serve both surface and edge-couplers. Such a design can have detrimental effects on chip performance, resulting in less efficient and more costly production chains.

➤ Testing edge coupling directly on the wafer can save costs and increase efficiency.



This kind of hardware problem needs to be solved from the test station viewpoint by providing a set of hardware probe systems that deliver the agility and reliability required while ensuring speed and accuracy in all test conditions. Stations of that type available from EXFO can be reconfigured quickly to accommodate a variety of optical probes and PICs of different sizes and scope, while making use of different coupling methods. Ultimately, this comprehensive, automated solution ensures that testing can be optimized and replicated throughout the PIC production chain.

But the challenges don't stop with coupling light in and out of the PIC device. Optical testing of components is often demanding due to the possible high port count of some components like arrayed waveguide grating (AWG) or the sheer number of components to test on a single die. EXFO has been leading the charge on PIC testing for some time and has advanced the industry with a component test platform designed to tackle multiport detection on complex devices.

Directly controlling one or several continuously tunable lasers, the instrument measures --quickly and with high fidelity -- insertion loss, return loss and polarization-dependent loss across the laser's spectral range. With its modular approach and SCPI commands for automation, EXFO's CTP10 overcomes test challenges on the hardware side by increasing PIC testing throughput while reducing test time.

Software challenges

It's important to note that in a PIC ecosystem where complex tests must be programmed, hardware and software must operate in symbiosis to ensure effective PIC characterization. Clearly, automation is not only critical for chip & test preparation and execution, and for data analysis and reporting, but it is also a cornerstone for hardware setup and calibration.

A key challenge regarding configuring PIC testing is tracking and documenting successful test configurations so they can be correlated, replicated, and adopted within a lab or production facility. Furthermore, testing elicits lots of data that must be properly tracked and analyzed so testing can be optimized to meet new requirements.

Every PIC facility has experienced setting up test configurations using home-grown test processes and methods, and been challenged when trying to draw on broader industry insights.

Frequently, full visibility of what is being done and archived is simply not obtainable using in-house software, weakening any actionable data obtained from testing.

Because of the extensive manual effort required and the high volume of chips, some R&D prototyping only involves fully and extensively testing a small percentage of available chips. Tracking data and being able to analyze outcomes, as to whether a

> One single software platform enabling preparation, execution, and analysis is key to scaling up production in a PIC ecosystem.

trend was emerging or whether one-off situations were occurring, was nearly impossible. In-house automation solutions generally lead to data that is not statistically significant, another negative impact on the usability of the data.

One additional challenge to address is test reach. Fast and easy to implement, simple testing involving insertion loss using only a photo detector is too limited to grasp the full picture of why and how a particular chip fails and what actions to take to remedy it. Clearly, manual and in-house automated testing can only take things so far in the PIC development process because of the inability to scale up, replicate, and completely control tests -- and because operation is based on a mere subset of what's possible to test and analyze.

Automation to support a burgeoning industry

As noted earlier, software automation in PIC testing is critical for the industry to respond to the rapid expansion in use of PICs in multiple markets and in high-volume manufacturing.

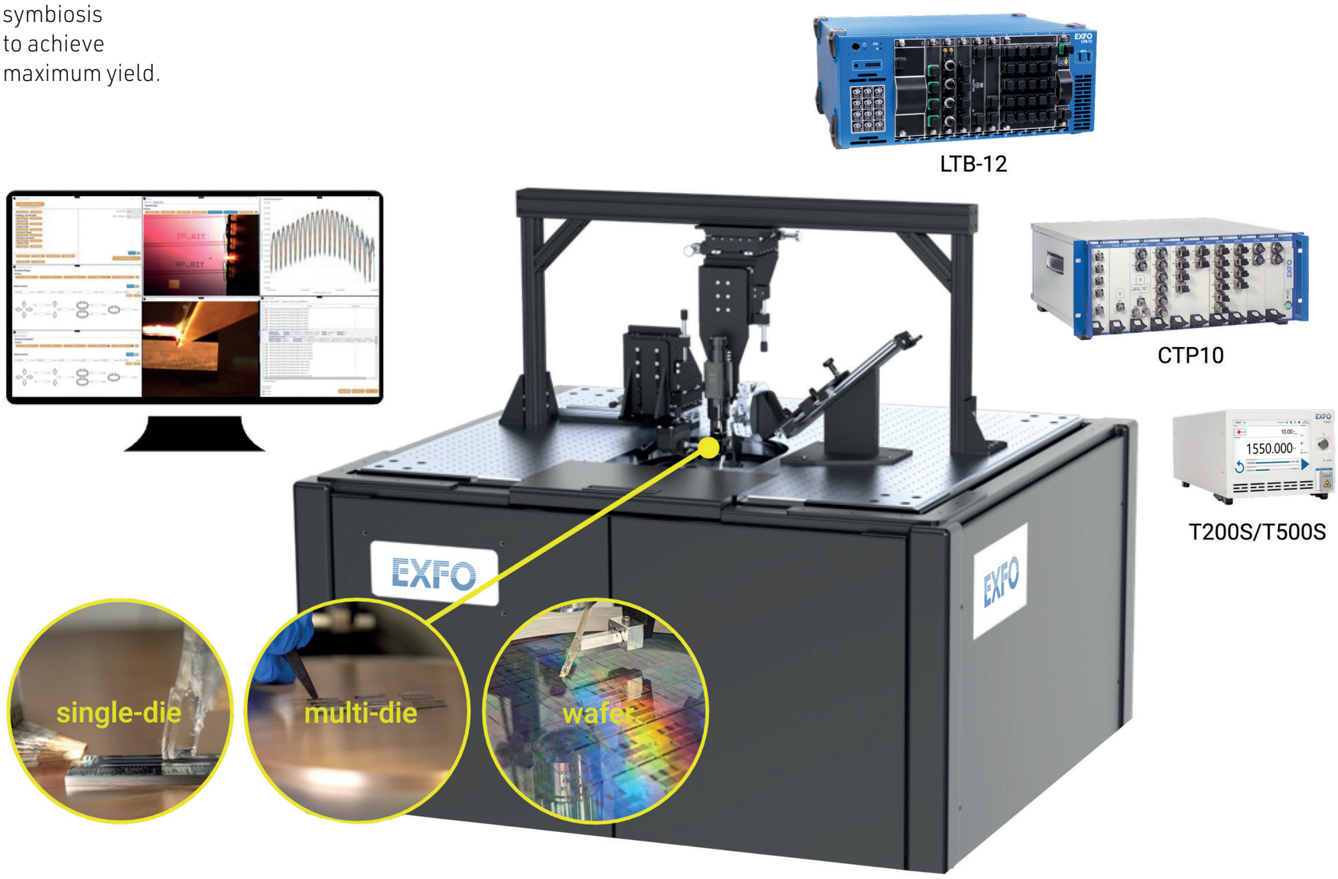
When introducing automation, it forces decision-making on what's important to test and what information is critical to track. An up-front assessment can help ascertain if current testing is useful or whether new test methods are needed.

The ability to use software algorithms to extract more information from available data is highly valuable.

Automating the existing test bench means that optical aligners can be motorized to streamline test processes. While test capacity can be as much as doubled, testing configurations can either cover more ground, giving an exhaustive view of the chips under test, or reduced to a few performance checks for more cost-effective and nimble production.

Another advantage of a fully-automated system is the complete autonomous testing that can yield in-depth test analysis. As such, labs and foundries are no longer limited to creating "gaussian curve" statistics but are empowered to understand the root cause of anomalies and what to do to resolve them. Test summary dashboards, populated automatically, provide the right information to the right people at the right time for best decision-making.

Instead of a tedious manual process, automated testing, analysis, and reporting are streamlined, resulting in better specifications, fewer iterations to optimization and a better overall finished product and production. As a result, PIC chips are cheaper to develop, cheaper to produce and have a faster time-to-market, ready for mass production.



➤ PIC testing requires a set of state-of-the-art equipment operating in symbiosis to achieve maximum yield.

Industry advances in automation: EXFO acquires EHVA to accelerate PIC testing

EXFO has worked over the years to develop test and measurement hardware and software solutions that are automated, scalable, fast, accurate and cost-optimized. These solutions range from simple optical testing to spectral optical characterization or traffic analysis, and they have proven interoperability with third-party instrumentation such as wafer disc handling systems.

To further accelerate EXFO's innovation engine in PIC testing, in 2022 EXFO acquired EHVA, an innovative maker of test and measurement systems for PICs and system automation. Developed by PIC engineers for PIC engineers, EHVA's expertise in manufacturing intelligence and wafer-to-single device test capabilities through their scalable PIC testing solutions enabled faster component manufacturing and better reliability of production processes. This resulted in a series of advanced test stations that are reconfigurable from single-die test to 300mm wafer, offering flexible testing of surface and/or edge coupling PICs with DC and RF test capabilities.

Now part of the EXFO portfolio, EHVA's process software suite, integrating advanced test systems such as the CTP10, can be implemented in customer lab and manufacturing settings for exceptional testing reliability and efficiency; a fully automated solution that can help avoid production bottlenecks. Together with world-class photonics industry leaders, EXFO works toward testing standardization and looks forward to developing many new innovations to address the growing PIC market.

Future opportunities based on automation
As with all evolutionary technologies, some innovations are more impactful than others. The ability to scale testing to support PIC technology is the next gamechanger. Automated testing is already critical for telecommunications with the advent of PIC-based transceivers, but it also holds major promise for LiDARS, quantum computing/sensing/encryption, biosensing, high-performance AI, and more. Some of those applications are even more sensitive and require much higher specifications or much lower tolerances than components seen in telecom applications.

The importance of PIC technology cannot be underestimated, given it is expected to be the backbone for most future key innovations. Testing complex AI chips, quantum chips and more will be required in future, and today's PIC testing is laying the foundation for those evolutionary – and revolutionary – technologies. And none of that can happen without the underpinning of automated processes now available for PIC testing with scalability, reliability, and speed.

Component viability risks bursting the quantum bubble

To speed the arrival of quantum technologies, the incredibly demanding compound semiconductor devices that lie at the heart of them need to be produced on high-volume platforms

By Denise Powell and Wyn Meredith from The Compound Semiconductor Centre, Samuel Shutts from Cardiff University, Mohamed Missous from the Integrated Compound Semiconductors, Mohsin Haji from the National Physical Laboratory and Chris Meadows from CSconnected

THERE IS no doubt that quantum technologies have the potential to revolutionise every sector we can think of. Their impact will include: highly accurate navigation, enabled by quantum gyroscopes; GNSS-free communications, underpinned by atomic clocks; ultra-secure communications, via quantum key distribution; improved manufacturing control and timely maintenance on infrastructure; the detection of anomalies in organs such as the brain and heart, through quantum magnetometers, alongside rapid drug and materials discovery; and financial modelling, enabled by quantum computers.

The possibilities for quantum technologies are so vast that this revolution is anticipated to be on a par with that of AI, in terms of scale. In fact, these two headline-grabbing technologies are complementary, with the true magic underway when quantum systems are enabled by AI. This is not just fantasy:

AI is already applied to data from quantum systems at the UK's National Physical Laboratory to ensure rapid analysis.

Unfortunately, for any nascent technology, promise is no guarantee of success. History attests that when a technology with great potential delivers encouraging results, substantial investment follows – but this optimism may well be short lived, with the bubbles breaking to induce a widespread cull that leaves those hanging under the spotlight having trying to salvage a future for their revolutionary technology. Today some firms are still recovering from the lidar aftermath, and reports suggest AI is next for re-evaluation.

And what of quantum? Why aren't we seeing widespread deployment of this technology, on the back of investment totalling hundreds of millions of dollars? You might be thinking that the humble laser draws on quantum effects, so quantum is already well-embedded in our lives. That's somewhat true, but misses the point that here we are considering what most refer to as 'Quantum 2.0' – that is, technologies that utilise superposition or entanglement, or as Einstein famously said, "spooky action at a distance".

To delve deeper into the future of quantum, it's helpful to consider an example. One highly successful Quantum 2.0 product is the world's first commercially available chip-scale atomic clock, Microchip's Microsemi SA.45s CSAC. According to the National Institute of Standards (NIST), this triumph is the culmination of more than 10 years of extensive R&D, costing several tens of millions of dollars, with support from both the Defence Advanced Research Project Agency (DARPA) and NIST. John Kitching, a key researcher at NIST involved in this development, rightly suggests that given that the market for chip-scale atomic clocks is worth around $200 million per annum, it's difficult for industry to invest the amount needed for fundamental R&D in this area.

VCSELs: a hero in the making

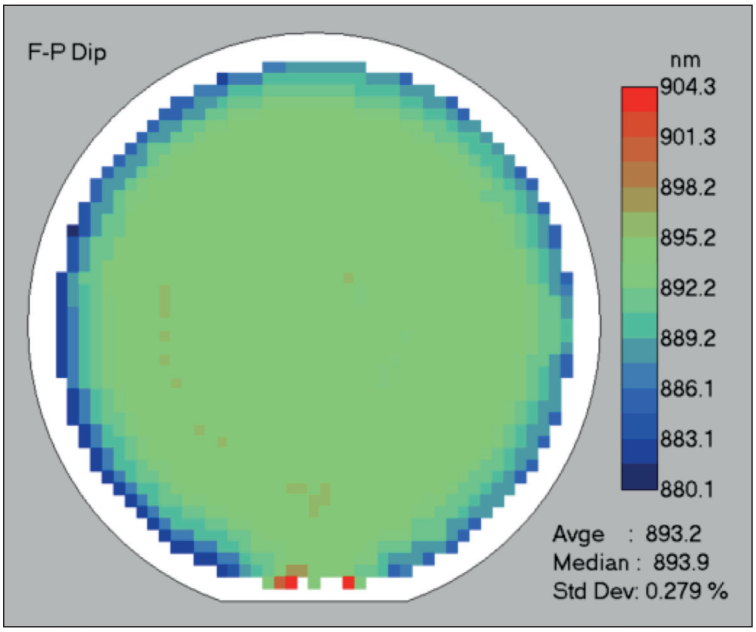
A key component in miniature atomic clocks, as well as other quantum systems based on alkali metal vapour, is the VCSEL. Renowned for its low power operation, circular beam profile and intrinsic reliability characteristics, this class of laser is ideal for interrogating the alkali metal atomic species, typically rubidium or caesium, that are contained in a small cell within the atomic clock. As the clock's principle of operation is coherent population trapping, the VCSEL must emit at highly precise wavelengths corresponding to atomic energy transitions. For example, the emission must coincide with D1 transitions at elevated temperatures, which occur at 795 nm and 894.6 nm for rubidium and caesium, respectively.

In addition to these highly stringent wavelength requirements, there are many other specifications that must be met, including single-mode operation with a narrow linewidth and high mode stability. Fulfilling them all is not easy, as in some cases adhering to one narrow tolerance makes it harder to meet the demands of another. Given this state of affairs, it's no surprise that it's not a stroll in the park to realise the high levels of epitaxial material design, growth and fabrication demanded for VCSELs deployed in quantum technologies.

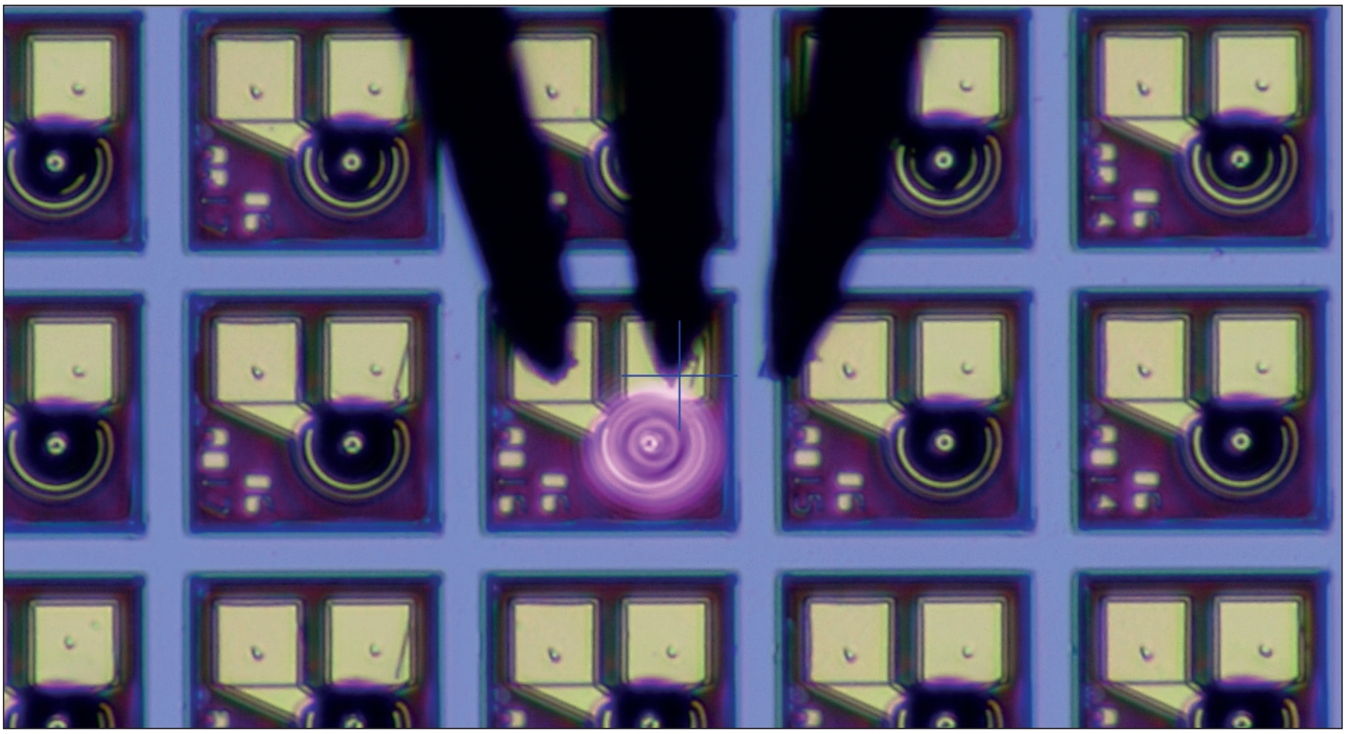
To illustrate this point, when VCSELs serve in quantum technologies, the ideal uniformity for the Fabry-Pérot dip across a wafer is below 1 nm, with the precise figure depending on the current tuning capability. In stark contrast, telecommunications applications can tolerate a non-uniformity of this parameter of several nanometres across a wafer.

There is significant effort in the UK to develop VCSEL technology that is customised to the stringent needs of quantum applications. The Compound Semiconductor Centre (CSC), a joint venture between IQE Plc and Cardiff University, has worked extensively on improving the centre-uniformity profile for 100 mm epiwafers produced with Aixtron series G3/4 MOCVD tools. This is the preferred substrate size for the VCSEL design, fabrication and test partner Integrated Compound Semiconductors, of Manchester, UK.

Fabrication is equally challenging, demanding tight control of the oxidation processes to ensure single-mode operation at the required optical output power. Naturally, these process challenges impact yield. Whilst standard VCSEL platforms boast yields typically in excess of 90 percent, those developed specifically for quantum applications are far lower, due to the cumulative effects of stringent specifications.



➤ The Fabry-Pérot profile across a 894.6 nm VCSEL structure grown on a 100 mm GaAs substrate using Aixtron G3 series MOCVD system.

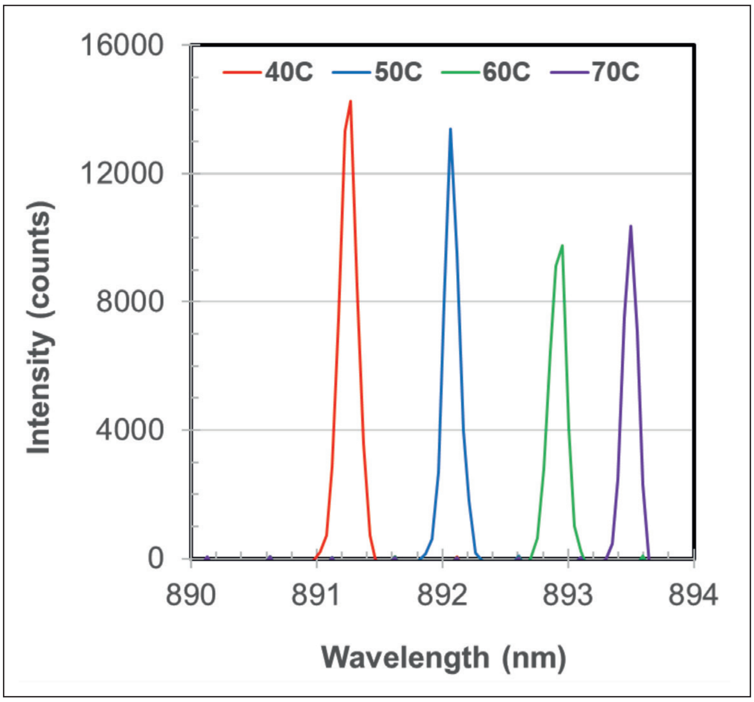


Fabricated VCSEL devices at ICS, Manchester

The hefty price tag on Quantum 2.0

Product pricing depends heavily on manufacturing yields. For VCSELs for consumer applications, many thousands of lasers can come from a 150 mm wafer, with yields typically allowing for a fully processed device to cost up to $5. That's not a feasible price-point for highly customised VCSELs for quantum applications.

VCSELs can also serve in other alkali metal vapour-based quantum systems, such as quantum magnetometers and gyroscopes, where they are again used for coherent population trapping. In all these products, other custom components are also required, such as: wafer cells to contain the alkali metal species; niche optics; crystal oscillators, in the case of atomic clocks; and shielding and/or coils, when fabricating gyroscopes and magnetometers. Progress is being made on all these fronts. For example, MEMS wafer cell technologies are emerging. However, in addition to efforts at improving yield, a lot of fundamental research and development still needs to be undertaken to understand the effect of process and cell parameters on application performance.



Optical spectra of a single mode VCSEL fabricated at ICS, Manchester

One crucial question plaguing the quantum sector is this: What level of product mark-up is tolerable for end-users, so they don't stick to other, perhaps more proven technologies? And related to this is the question of what is the price-point at which the advantage of Quantum 2.0 is too expensive to justify? It's an unspoken reality that quantum systems will not be widely deployed until critical components are manufactured at accessible costs, unless value at the system level far outweighs the cost. You'll not be surprised to hear that defence and security are often the early adopters for emerging technologies, enabling low-volume production that provides a pipe cleaner step for a subsequent volume ramp.

Upscaling an existing asset base

The issue of manufacturability for quantum is not limited to VCSELs. There are applications requiring single-photon light sources or detectors. Producing these devices is even more challenging

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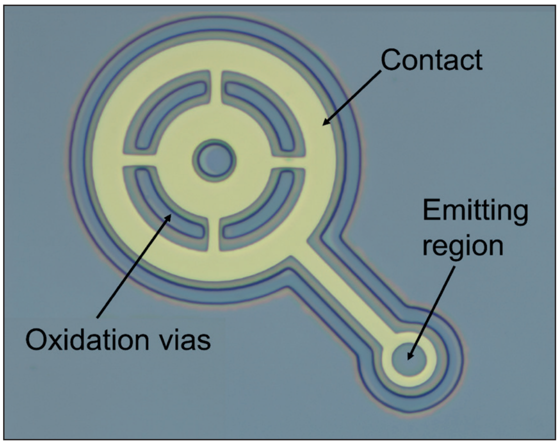
The lack of maturity in the production of some types of devices, along with their high manufacturing costs, creates a substantial barrier for many quantum industries, including quantum key distribution, quantum sensing and quantum computing. The solution is to manufacture quantum devices alongside other semiconductor processes, and leverage existing assets and infrastructure

than VCSELs, because they are at a lower technology readiness level, having not benefited from years of volume production for non-quantum applications. Viewed in that light, it's not that surprising that miniaturised atomic clocks are one of the first quantum systems to be commercialised. The lack of maturity in the production of some types of devices, along with their high manufacturing costs, creates a substantial barrier for many quantum industries, including quantum key distribution, quantum sensing and quantum computing. The solution is to manufacture quantum devices alongside other semiconductor processes, and leverage existing assets and infrastructure.

Helping to bridge that gap is a three year, £5.8 million project, part-funded by the UK Quantum Technologies Challenge under UK Research & Innovation (UKRI), that draws on existing assets and infrastructure across 12 partners in the UK.

This venture, the QFoundry project, is establishing a foundry for quantum photonic components and is focused on upscaling manufacturability of these devices and understanding drivers of yield, reproducibility and reliability.

Another contributor to the progress made by CSC is through the CSconnected compound semiconductor cluster in South Wales, that is supported under UKRI Strength in Places programme and is actively involved in establishing UK supply chains for a range of quantum technologies. CSC, which has access to volume MOCVD reactors through IQE, works closely with Cardiff University who have developed a novel Quick Fabrication (QF) VCSEL process to determine the impact of material design changes or growth parameters in less than half the time it would normally take to fabricate full devices.



➤ A Quick Fabrication VCSEL structure produced at Cardiff University.

Those that have read *Move Over MOCVD* (issue V, p. 20, 2022) may wonder why MBE is not the growth method of choice, given its capability to deliver superior uniformity. However, the reason is simple: MBE would cast an additional financial burden on the already high cost for custom design and fabrication of VCSELs for quantum technologies.

To ensure the success of quantum, its devices must be made alongside volume platforms and create additional market opportunities for the same wafer platform.

Underscoring the importance of running quantum fabrication alongside standard volume semiconductor processes is the approach taken by the leading developer of quantum computers, PsiQuantum, which has partnered with Global Foundries.

According to PsiQuantum, the only path to creating a commercially viable quantum computer is the one that leverages the trillions of dollars invested in the semiconductor industry, which now dates back more than half a century. Through collaboration with Global Foundries, PsiQuantum gains access to high-precision lithography and other high-end toolsets, as well as running design-of-experiments at volume to accelerate development. It's a sure bet that one day quantum will be a natural part of everyday life.

However, getting there involves tackling fabrication challenges, and taking sensible pathways to commercialisation and eventual volume deployment.

FURTHER READING

- C. Hentschel *et al.* "Gain measurements on VCSEL material using segmented contact technique." J. Phys. D. **56** 74003 (2023)
- J. Baker *et al.* "VCSEL quick fabrication of 894.6 nm wavelength epi-material for miniature atomic clock applications." IET Optoelectron. **17** 24 (2022)
- J. Baker *et al.* "VCSEL quick fabrication for assessment of large diameter epitaxial wafers." IEEE Photonics J. **14** 1530110 (2022)

Datacom will be the main driver for Silicon Photonics

Despite the dashed hopes of using Si photonics for consumer applications in the short term, this technology is still very promising, especially for data centers.

By Eric Mounier, Ph.D., is Chief Analyst at Yole Intelligence, part of Yole Group

OVER THE PAST 50 years, mobile technology innovations have been rolled out each decade. Mobile bandwidth requirements have evolved from voice calls and texting to ultra-high-definition (UHD) video and a variety of augmented reality / virtual reality (AR / VR) applications.

Despite the profound implications of the COVID-19 outbreak for the telecom infrastructure supply chain, consumers and business users worldwide continue to create new demand for networking and cloud services. Social networking, business meetings, UHD video streaming, e-commerce, and gaming applications will continue to drive growth.

The driving forces are mainly social media, digital entertainment, and cloud computing, which have voracious appetites for more bandwidth and faster interconnect speeds. This, in turn, affects the data center network architecture (disaggregation, AI and ML, strong focus on power consumption). All this will require new high-speed, low-latency technologies for data transfer (heterogeneous packaging, interposers, PICs,).

Optical interconnects have become an essential technology in data/telecommunication infrastructure. In the Co-Packaged Optics for Datacenter 2023 report, Yole Intelligence, part of Yole Group,

asserts that the development of semiconductor technologies such as lasers, modulators, and DSPs enabled an increase in bandwidth and accelerated the development of the overall infrastructure.
Over the past years, many technological evolutions occurred and will continue to develop at different network levels (see figure 1). For long haul and metro core, InP PICs might play a significant role in future optical modules. DSP will improve with higher levels of modulation. As we move from metro access (below 100 km) to intra- and inter-data center networks, silicon photonics will be increasingly used; optics will become standard for ultra-short reach connections, coherent technology will be used, and new switching architecture (co-packaged optics) may become commercially viable.

But we currently see some macroeconomic headwinds that will negatively impact budget-intensive projects, particularly for emerging technologies such as CPO. Recent news indicates that most of the main CPO proponents have suspended support for CPO programs. There are several reasons why CPO is losing attractivity, and the first is the well-established industrial ecosystem around pluggables.

Also, new optical technologies for pluggable form factors, including TFLN, BTO, carbon, and polymer modulators, can help achieve the required low power and be introduced to the market without changing any existing network system designs.

Historically, integrated photonics has been developed on an SOI platform. The goal was to benefit from wafer-scale manufacturing in the CMOS industry and use it for photonic chips. But SOI is expensive, and silicon is not the ideal material for all the different photonic functionalities. Since the very start, laser has been one of the greatest challenges for silicon photonics.

The considerable development effort made by Intel for InP chiplet integration on SOI has been key to Intel's actual business success in silicon photonics. More companies are now trying to duplicate this model to offer Si photonic wafers with integrated laser chips. Today, as data rates increase, high-speed modulation using Mach-Zehnder on Si is becoming a bottleneck.

There are numerous developments in new materials to overcome the current limitation (TF LNO thin films, InP, BTO, polymer, plasmons). This creates opportunities for companies focusing on materials for silicon photonics: Lumiphase and Polariton, Hyperlight and Liobate in China for thin film LNO, and Riber for BTO. As integrated optics moves towards increased functionalities, the definition of Si photonics would expand to incorporate other materials (figure 2).

But the situation for AI / ML systems is different. The potential for billions of optical interconnects (chip-chip, board-board) in the future drives big foundries to prepare for mass production. Since most of the photonics manufacturing IP is held by non-foundry firms, big foundries such as Tower Semiconductor (Intel), GlobalFoundries, and others are preparing silicon photonics process flows to accept any PIC

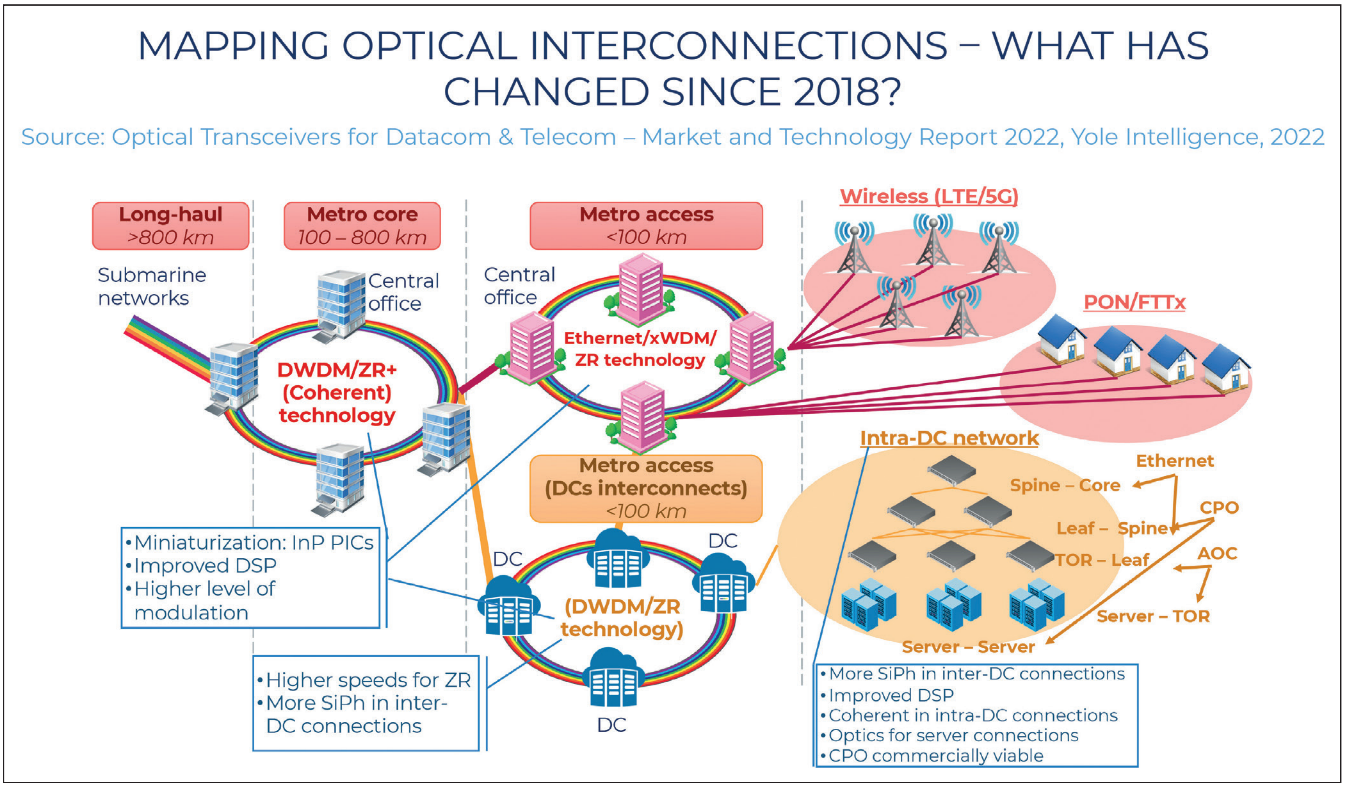


Figure 1.

2022 INTEGRATED PHOTONICS PLATFORMS

Source: Silicon Photonics report, Yole Intelligence, 2022

SiPh platforms and possible functions:
The table below shows which optical functions and corresponding materials can be integrated in SiPh. Several functions can be implemented on InP PICs. Electronic controls and coupling can be done on a separate die.

	SIGNAL MODULATION	EMISSION	AMPLIFIER	WAVEGUIDE	PASSIVE FUNCTION	FILTERING	DETECTION	CONVERSION	ELECTRONICS CONTROL	COUPLING
Si photonics	SiPh die	Separate InP EEL die needed O	Separate InP EEL die needed	SiPh die (SOI)	SiPh die (SOI)	SiPh die (SOI)	SiPh die (PN photodiode or PIN diode: Si or Ge)		SiPh die	O
InP	EML: EAM + DFB/DBR	Laser	PIN diode	WG	DWDM	O	InP PIN /APD	EML w/ SOA	O	O
SiN				Low loss WG						Coupler
Polymer	Modulator			WG	Mux/Demux					Spot converter
GaAs		VCSEL					PIN			
Silica				Splitters	AWG					
LiNbO3										
Glass				WG	Splitters, taps, mux/demux, polarizers					Coupler

*The one optical component that has not yet been built into a **silicon** IC is a compelling, high-performance **silicon-based laser**. There have been several attempts at making a laser out of silicon, but no technology has yet proved to be commercially viable. The only solution is to use InP EELs.*

O **Needs a separate die of different material**

➤ Figure 2.

architecture from design houses. All of them are joining forces in industry consortiums such as PCIe, CXL, and UCIe.

So datacom and servers will continue to be the main drivers for integrated optics. Silicon photonics will be central in data center evolution in the short-term for 100G (already well implemented in data centers) and then 400G and 800G pluggables. It will also be an enabling technology for disaggregating data centers and a possible future CPO approach.

The Covid-19 pandemic and the Ukraine-Russia crisis have strongly impacted the semiconductor supply chain. However, the impacts have been less in silicon photonics than in other semiconductor markets. Indeed, silicon photonics requires low volumes of wafers and strategic technology, so allocated capacity does not affect the global fabs' capacity, which is generally much larger.

The market value of silicon photonics to the industry was more than 20% of the optical transceivers market for datacom in 2021, and this proportion is still growing. It will be more than 30% in 2027. Silicon photonics is increasingly used for 500 m DR and is also increasingly used as coherent technology enters datacom applications.

There is also an increasing demand for 400ZR (figure 3). And besides datacom, other applications are promising in computing, interconnects in data centers, and sensing. Optical interconnects using silicon photonics will enable disaggregated data centers with more power available for high-performance computing (HPC) and data communications.

The industrial ecosystem (Ayar Labs, Intel, Ranovus, Lightmatter, AMD, GlobalFoundries, and others) around ML machine vendors Nvidia and HPE has made decent progress, with a plan to ship products in volume between 2024 - 2026. Photonic computing, which allows for analog AI computations much faster than today's digital AI, has been developed and will also hit the market soon.

Other applications include sensors (immunoassays, gyroscopes, and LiDARs), 5G, optical processing, and CPO. Medical has begun to hit the market, with Genalyte and many other startups using Si-integrated optics as a manufacturing platform. In the automotive domain, more and more manufacturers are integrating LiDAR into their products.

At the supply chain level, Intel is strengthening its market leadership with a 58% market share in units in 2021, followed by Cisco and other smaller companies (Marvell/Inphi, Sicoya, Acacia, and others) that, step by step, are gaining market. After decades of investments from Intel, the silicon photonics market is now the centerpiece of the evolution of the data center. Intel is now securing its access and manufacturing capabilities to leverage all its core competencies for the next decades.

From autonomous mobility to data centers and the future of cloud computing, Intel is now strengthening its position in the silicon photonics landscape, with great results recently. From a decentralized on-the-edge central processing leader, Intel is transforming itself into the centerpiece of the future of computing based on photonics and data centers. While some players are taking the opportunity offered by silicon photonics to enter the optical transceiver market,

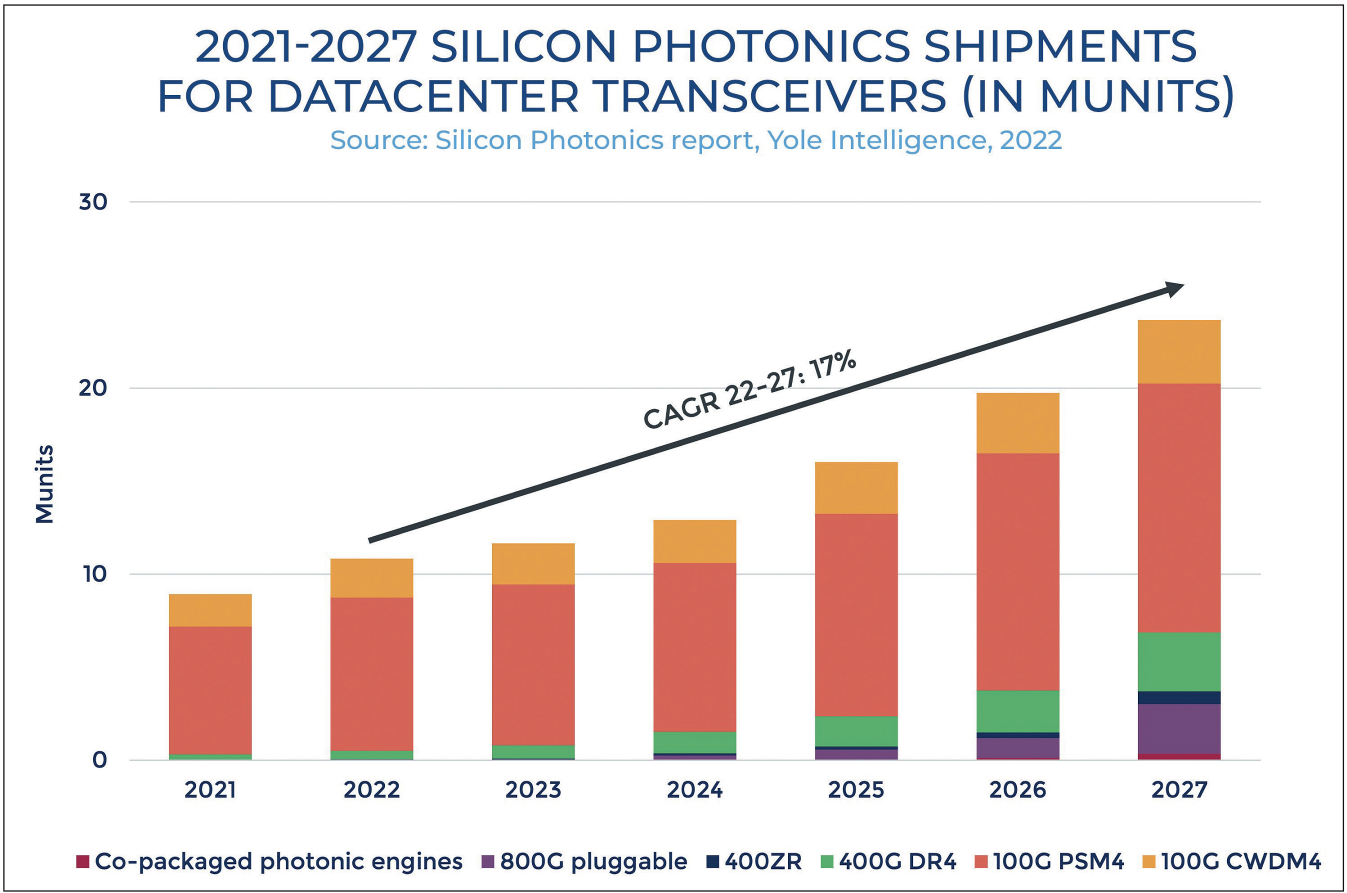


Figure 3.

others are seeking new applications, and the silicon photonics industrial landscape has remained very active. New potential applications of silicon photonics have resulted in the creation of various companies in the past three years. So, while some players are taking the opportunity offered by silicon photonics to enter the optical transceiver market, others are looking for new applications: medical, sensors, interconnects, computing. Co-packaged optics seem to require a considerable investment which is not yet acceptable to any player, delaying its introduction.

Maximum shipments of optical transceivers will probably arrive after 2026. This will push players that cannot get into the co-packaged optics application to move to new applications in 5 - 10 years. We should therefore see a shift in applications in the coming years. And China continues to be very active in the development of silicon photonics, with many players involved.

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About the Author

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Eric has spoken at numerous international conferences, presenting Yole Group's vision of emerging semiconductor technologies, markets, and applications.

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PIC International 2023: The growth of silicon photonics continues

Co-Conference Chairs Dr Michael Lebby and Dr. David Cheskis reflect on the 2023 event.

WE HAVE just completed the 8th annual PIC International Conference, and again, this conference not only surpassed everybody's expectations, but thrilled us with live presentations, audience, panels, exciting Q&A, the best of the best in personal networking, and finally completely full exhibit.

The technology updates and progress were again exciting and generated lots of audience questions for the speakers. Speaker presentations were shortened to 15mins to allow the full 2 days of conference programing to contain a broad and wide cross-section of the PIC industry. The whole value chain for the PIC industry was represented that ranged from wafers to epitaxial growth, devices, packaging, modules, testing, and systems, to social media. It is now very clear that PIC International is the conference to attend if your interest is Photonic Integrated Circuits (PICs) not only in optical networking and internet, but other market verticals such as automotive, sensing, medical, displays, instruments, agriculture etc. We again filled all of our seats, and believe it or not, we had standing room only throughout the 2 days of talks. There was much cross pollination between parallel sessions from CS International and Power Electronics International with attendees choosing to listen to talks from all 3 conference.

This year, there were over a record 800 delegates attending two days of highly condensed sessions on photonic integrated circuits (PICs) that focused

not only on innovative technology, but how PICs could alleviate major headaches, issues and opportunities that optical networks, datacentres, telecommunications systems, automotive applications see today. Many talks focused on how PICs could be implemented into novel and innovative applications to move the industry forward, and keep the industry moving forward such as Automotive LIDAR, sensing, displays, healthcare, etc. As in 2022, one of the biggest drivers for PICs are fiber optic communications for datacentre interconnects. A number of global giants and exciting SMEs (small and medium size enterprises)/ start-ups with PIC technology platforms conveyed their opportunities for PIC-based innovative solutions for their businesses. These addressed high speed, low power consumption, innovative packaging (via co-packaged solutions), reliability, and cost effectiveness.

There were also talks that explored PIC based technologies outside of fiber optics and optical networking, and those areas included healthcare, agriculture, bio, sensing, and LIDAR for automotive applications. One of the most promising segments discussed at the conference for the first time is the use of PICs in the agricultural market, and this was forecasted to grow very quickly over the next decade.

The conference discussed in detail incumbent PIC technologies such as InP and Silicon Photonics, as well as exciting new and emerging technology platforms such as electro-optic polymers, thin-film lithium niobate, barium titanate (BTO) and dielectric (SiN based) technologies. Hybrid PICs was used to denote the mixing of various technology platforms to improve the overall performance of PICs. Examples were the use of electro-optic polymers onto silicon photonics, and as well as dielectric materials for integrated Photonic solutions on silicon wafers from foundries.

The incredible growth of silicon photonics as a base platform continues with an increase in popularity and acceptance as a new incumbent technology with talks from market researchers and companies following the business trends. Indium phosphide as one of the incumbents for PICs was demonstrated to show higher density PICs that are expected to impact the 5G markets, datacenters, and telecommunications. Similarly as in 2022, there were exciting updates of PIC in sensing, medical, and LIDAR applications.

The conference also discussed both datacentre and telecommunications opportunities for PICs with forecasts for new architectures, standards, technologies and cost expectations. The latest results in the PIC field were also presented and showed a significant performance upgrade towards transceivers at 800Gbps and 1600Gbps. Some results presented included the use of electro-optic polymers that generated speeds of over 100GHz bandwidth.

There were a number of exciting sessions, where one session discussed improvements in PIC infrastructure for designing and manufacturing robust and reliable PICs using software tools for modelling, simulation, and production. This was supported by many PIC talks that addressed PDKs and other metrics needed to quickly grow PIC markets including the use of hybrid PICs that contemplated new materials such as electro-optic polymers, thin film lithium niobate, barium titanate, metals for plasmonics etc.

This year, new and innovative talks discussed how PICs based technologies can enable new products that are more miniature, low power, and high performance, which is becoming especially important for hand-held battery powered diagnosis and health monitoring products.

The conference speakers showed that the result of designing PICs for the popular verticals of telecommunications and data communications and how these solutions could easily be applied to medical, measurement, automotive, and other industrial applications for PICs. Live personal networking was truly first class with a well designed exhibit immediately next to the conference rooms that gave the attendees ample opportunities to meet

other folks in the PIC infrastructure. The excitement of a live conference was buzzing with meetings, discussions and business on the exhibit floor.

There was 1 live panel session this year that were chaired by Dr. Jose Pozo that addressed silicon photonics foundries for PICs. The panels were filled with technical experts that are internationally known for silicon photonics. The panelists discussed the merits and advantages of using silicon foundries for volume scale of PIC technologies. After a stimulating discussion between the panelists, 3 major themes emerged on the issue of silicon foundries to ensure that themes such as hybrid integration is accessible as the industry moves forward…

- The PIC industry still needs to scale in volume, and this will enable silicon and CMOS foundries to promote their best economics
- The PIC industry needs to continue its focus on working with foundries with PDKs.
- Foundries now see an opportunity with hybrid PIC technologies and are looking forward to incorporating these new technologies into their PDKs to support scale and volume with PICs in general.

All presentations over the past 2 days showed a number of improvements in PIC technology over the past year. PIC markets are growing strongly over the next decade, as well as the scalability of PIC technological platforms. The rise of the hybrid PIC and shared foundries showed that customers are now more open than ever to find the right PIC solution for their particular portfolio.

A focused, thrilling, and well attended, standing room only conference, with a high level of technical content, the 8th PIC International surpassed itself again in 2023. PIC International is the conference to attend for the latest and greatest in photonic integrated circuits and has become a truly global and credible event. We are all looking forward to 2024 as PIC International now has become the event to attend globally.

PIC International 16-17 March 2024
https://picinternational.net

All presentations over the past 2 days showed a number of improvements in PIC technology over the past year. PIC markets are growing strongly over the next decade, as well as the scalability of PIC technological platforms. The rise of the hybrid PIC and shared foundries showed that customers are now more open than ever to find the right PIC solution for their particular portfolio

InP-based lasers surpass 2.2 µm

Thanks to the antimonide surfactant effect, strained InP lasers are delivering milliwatt emission at almost 2.3 µm

ENGINEERS from NTT, Japan, are claiming to have enhanced the capability of InP-based lasers by smashing through the 2.2 µm barrier. The team's InP ridge-waveguide lasers, featuring strained InGaAsSb multi-quantum wells, are capable of emitting output powers of several milliwatts at wavelengths up to 2.278 µm.

This breakthrough increases the attractiveness of the InP laser as an alternative to the lattice-matched GaSb-based laser in a number of applications requiring sources in the 2.1 µm to 2.3 µm range. While GaSb-based lasers in this spectral domain can be used for gaseous sensors, biomedical sensors and car exhaust analysers, processing technologies for this material system are not as mature as those for InP, which has been the key material for telecommunications for many decades.

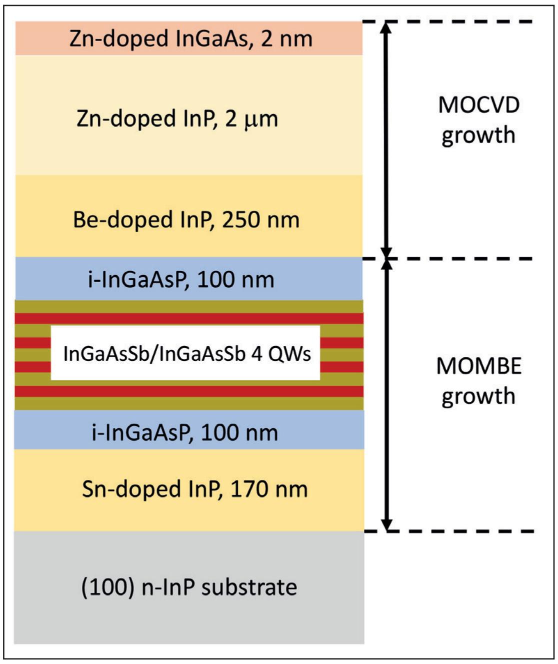
Extending the wavelength of the InP-based laser is far from easy. To reach beyond 2.1 µm with an active region that employs InGaAs quantum wells, strain in this material system must exceed + 1.8 percent. The growth of such structures is challenging, requiring growth temperatures below 500 °C, alongside just a few quantum wells and layers less than 6 nm-thick. Of most concern are defects induced by large strain – they threaten to quash laser emission.
To avoid these issues, the team from NCT has turned to InGaAsSb quantum wells, supressing defect formation with surfactant mediated growth. These engineers are not the first to introduce antimony, which acts as a surfactant during the growth of strained InGaAs wells, but they have stretched the emission further than their peers by cranking up the concentration of this element.

Record-breaking lasers have been realised with a two-step epitaxial process, beginning with the growth of a four-period multi-quantum well active region sandwich by InGaAsP and InP, all grown by metal-organic MBE. After the team studied these structures, they turned to re-growth by MOCVD to add Zn-doped InP and InGaAs layers, prior to the formation of ridge-waveguide lasers. According to team spokesman Manabu Mitsuhara, the strained InGaAsSb lasers produced by NCT, could also be formed by other growth methods, such as MBE and MOCVD, which are capable of growing active regions with sharp interfaces.

Mitsuhara and co-workers studied a pair of samples grown by metal-organic MBE, featuring active regions with different thicknesses. X-ray diffraction determined that both heterostructures have smooth interfaces between the wells and barriers, while simulations of the well-defined satellite peaks suggest that the quantum wells have a strain of +2.3 percent and thicknesses of 6.4 nm in one sample and 8.4 nm in the other. Both samples have 20.6 nm-thick barriers with a strain of -0.23 percent.

Calculations based on the model-solid theory, drawing on photoluminescence measurements and strain value obtained from X-ray diffraction, suggest compositions for the well and barrier of $In_{0.82}Ga_{0.18}As_{0.95}Sb_{0.05}$ and $In_{0.45}Ga_{0.55}As_{0.95}Sb_{0.05}$, respectively.

Using standard processes for making InP telecom lasers, Mitsuhara and co-workers have fabricated ridge-waveguide lasers with a cavity length of 600 µm and a stripe width of 2.5 µm. These lasers, with quantum well thicknesses of 6.4 nm and 8.4 nm, produced several Fabry-Perot modes and had peak wavelengths of 2.190 µm and 2.278 µm, respectively, at 15 °C. Driven at 100 mA, the output power per facet of the longer-wavelength source fell from 5.9 mW to 2.4 mW when its operating temperature increased from 15 °C to 55 °C.



➤ The team from NCT employed a combination of metal-organic MBE and MOCVD for growth of their hetero-structures.

Mitsuhara claims that it should be easy to apply their lasers to absorption spectroscopy, which requires a tunable light source with single-mode operation and an output power of several milliwatts.

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