PICMAGAZINE

CONNECTING THE PHOTONIC INTEGRATED CIRCUITS COMMUNITY

ISSUE IV 2020
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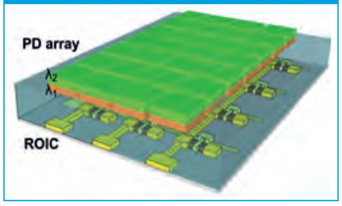
Comb lasers advanced high-performance

Toward high resolution multi-colour imaging



Unique PIC, and MEMS requirements

Invest in photonics to fight future pandemics

Innovation Hub secures €19 million

European Pilot Lines in PICs

EPIC

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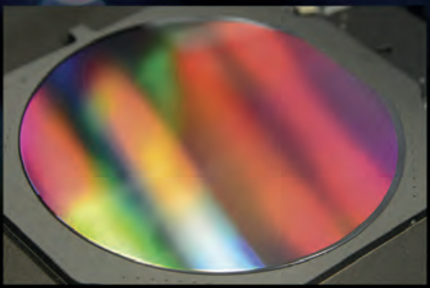
HERCULES



Viewpoint

By Mark Andrews, Technical Editor

Looking forward to brighter days ahead

WE could all use a break. A pause amidst an unforgettable-regrettable year. A break from constraints. A beam of light to brighten short winter days. Take heart – the glass is half full, not half empty – and it is filling more each day. Brighter days are indeed ahead.

After many months of grim statistics, the world recently received a much needed ‘shot-in-the-arm’ as COVID-19 vaccines began distribution in the UK, Europe and now in North America. Vaccines typically require years of development, but by pooling resources and using the latest technology, the world pharmacological community did the almost-impossible in mere months. But even now as grim numbers still grow we have real reason to hope. Instead of just raising our glasses to welcome a New Year, we’ll soon be rolling up our sleeves.

While 2020 had its horrors, it also had heroes. Not Big Screen stars dressed in capes fighting mythical villains; 2020’s heroes wore PPE, scrubs, and risked their lives each day to heal the sick and comfort the hurting. After each harrowing day, they did it all over again: day, after day, after day. Superman? Thank a nurse. Wonder Woman? Hug a doctor. Iron Man? Thank the orderlies, the med techs, the elder care workers and everyone giving their all so that tomorrow will be brighter. And it will. Thank-you to the heroes of 2020 and all who give us hope that we can soon take off our masks and gather with friends (safely) while planning a future beyond grappling with fearsome realities.

We have a great edition of PIC Magazine to share as 2020 winds to a close. We take a look at the role photonics can play in disease detection from Dr. Jürgen Popp, Scientific Director of Germany’s Leibniz Centre for Photonics in Infection Research. EPIC reports on the successes and importance of PIC Pilot Lines across the EU, while EXFO, AEPONYX and MLP share their successes developing automated PIC testing for HVM. We also explore ways to enhance the performance of Silicon Photonics (SiP) with III-V materials and barium titanate.

Here is to brighter days ahead!

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16 Invest in photonics now to fight infectious diseases and future pandemics

The spread of the SARS-CoV-2 coronavirus and resulting COVID-19 pandemic has sadly demonstrated how a new infectious disease poses unparalleled dangers to citizens and healthcare systems alike. The German government has invested €150 million to fund the Leibniz Centre for Photonics in Infection Research on the Jena University Hospital campus to investigate photonic technologies focused on disease detection

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Test requirements for photonic integrated circuits (PICs) are unique in that they must assess performance of both photonic and electronic circuit components. To enable high volume manufacturing, PIC test and measurement must also be fast, repeatable and reliable

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By tackling a bottleneck in bandwidth, multi-wavelength quantum dot lasers are enabling improvements in high-performance computers

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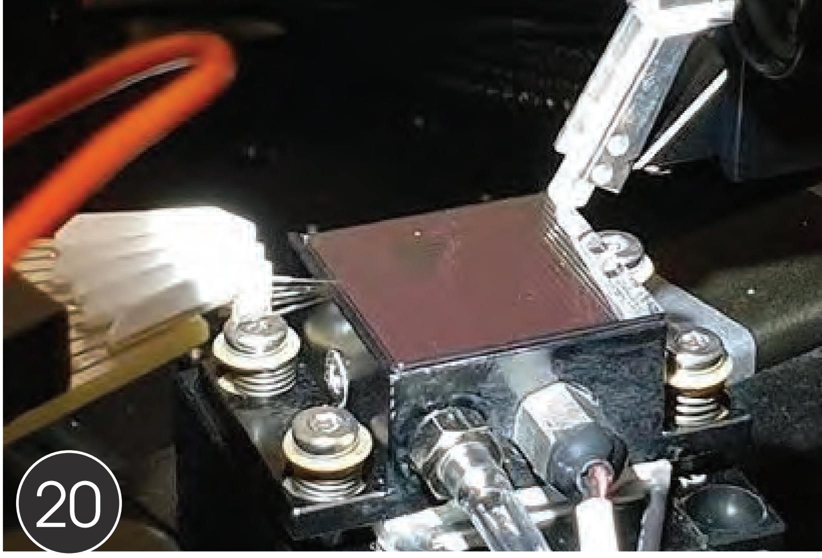

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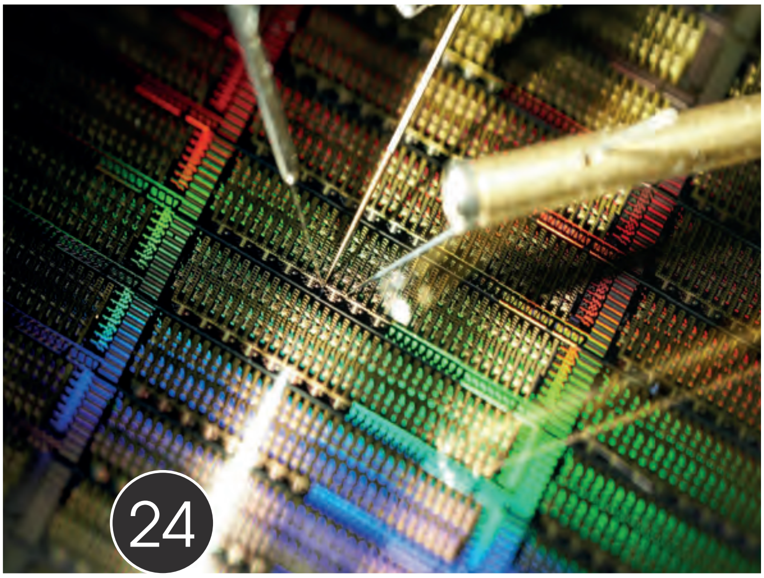

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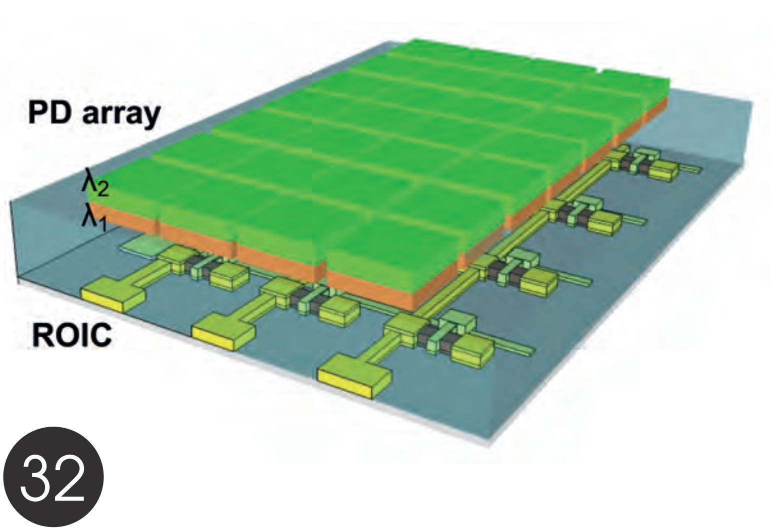

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Fast, accurate and repeatable testing requirements have in the past impeded the rapid roll-out of photonic integrated circuits (PICs) and related components at cost-effective, high volume scale

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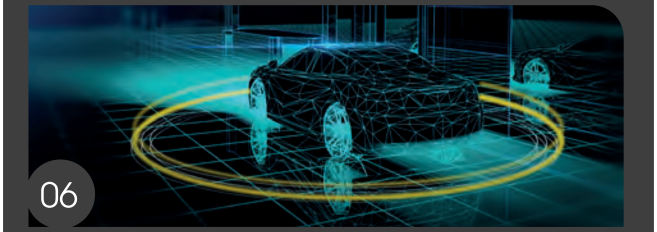

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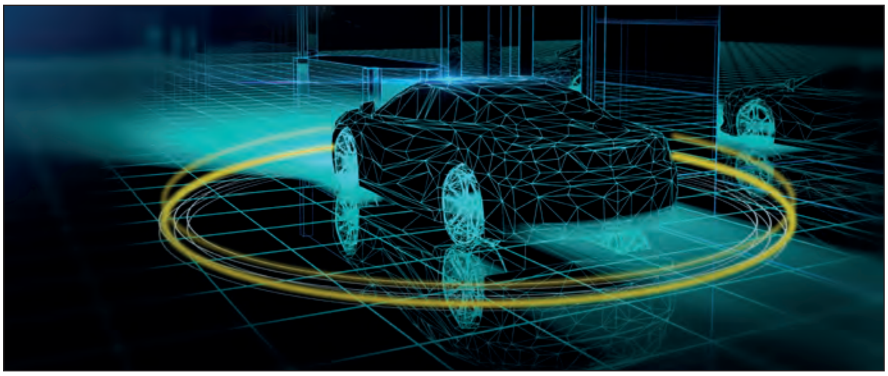
Sivers Photonics gets £325k of quantum LiDAR grant



SIVERS PHOTONICS has received £324,800 of Innovate UK, government funding, for its part in SPIDAR – a quantum project to develop range finding and 3D imaging systems for driver assisted and autonomous vehicles. The project is in collaboration with high-profile, commercial partners Toshiba, Network Rail and Thales UK, amongst others.

Billy McLaughlin, Sivers Photonics MD, said: "The SPIDAR project will develop single-photon, infrared imaging, detection and ranging technology. This technology will be used to sense the proximity of objects and other vehicles for driver safety and self-driving vehicle applications; a market valued at $556 B by 2026.*

"Cameras are used to detect single photon, light particles in the infra-red region of the electromagnetic spectrum. The distance to the detected object or range, is the measured time from the photon's emission, to the object and back again. The photon detector delivers sub-nanosecond precision, detecting single photons from the faintest possible reflections. This technology enables a far greater detection range for 3D cameras than is currently available, enhancing both safety and effectiveness when deployed in real-life applications like vehicle safety."

The total SPIDAR project grant is worth £3.62 M, split between Sivers Photonics and project partners Toshiba Research, Network Rail Infrastructure, Thales UK, Bay Photonics, Heriot-Watt University, Horiba Mira, IQE, University of Cambridge, University of Edinburgh and the University of Glasgow. Sivers Photonics (previously CST Global) is a wholly owned subsidiary of Sivers Semiconductors AB.

CEA-Leti to build quantum-photonics platform

EYEING FUTURE DEMAND for hack-proof digital communication in a quantum-information world, CEA-Leti today announced plans to build a quantum-photonics platform to develop next-generation technologies for key industries that require ultra-secure data transmission. Quantum technology is expected to provide unconditionally safe data encryption required by the finance, health care, energy, telecommunications, defense and other essential industries and sectors.

Funded by Carnot, a French multidisciplinary network that pursues R&D which benefits society, the project will build on CEA-Leti's silicon-photonics platform complemented with new quantum characterization equipment for designing, processing and testing quantum-photonic integrated components and circuits. The institute uses photons to build quantum bits, or qubits, which are the best physical means for quantum communications.

The three-year project will fabricate silicon-photonics circuits that generate single photons, manipulate those photons with linear optical components such as slow and rapid phase shifters and detect them with superconducting nanowire single-photon detectors (SNSPD). The project will build demonstrators for transmitting and receiving information in a quantum-based system to deliver quantum-technology's promise for ultra-secure cryptography. For example, the demonstrators will realize an integrated qubit transmitter, as a circuit generating single photons and entangling them. An integrated qubit receiver will be built to detect the photons.

Beyond these demonstrators, the CEA-Leti team will focus on integrating the qubit transmitter and the qubit receiver on one unique platform to address also quantum computing applications.

"Almost daily, we read about breaches of standard cryptography protocols, with major financial-loss and security-risk implications, and the threat to critical infrastructure, such as power-supply systems," said Ségolène Olivier, R&D project leader at CEA-Leti and coordinator of this project. "With the future advent of quantum computers, the risk will drastically increase as current encryption algorithms will not be safe anymore. Quantum cryptography is the solution to this problem as it is not vulnerable to computing power."

Noting that a quantum system based on single-photon qubits must ensure there is minimal propagation loss of photons to be reliable, Olivier said CEA-Leti's silicon photonics platform has achieved a world-record of low-loss silicon and ultralow-loss silicon-nitride waveguides. "Propagation losses in waveguides directly impact the data rate and reach of quantum communications links, that's why it is so important to build ultralow-loss components and circuits," she said.

CEA-Leti has already demonstrated a generation of entangled photon pairs on its silicon-photonics platform, and has other techniques in-house to address the single-photon detection challenges: CdHgTe avalanche photodiodes (APD) with a world-record speed in photon counting and materials deposition for integrated superconducting nanowire single-photon detectors.

Photonics Innovation Hub secures €19 million

PHOTONHUB EUROPE – a new pan-European photonics digital innovation hub – has been awarded €19 million investment from the EU's Horizon 2020 programme.

PhotonHub Europe will help European SMEs and mid-caps become highly competitive digital businesses through faster and smarter deployment of photonics-based technologies, directly creating over 1.000 new high-tech EU jobs and nearly €1 billion in new revenues and venture capital by 2025.

"Photonics is essential to the functioning of new applications which are powering the new industrial wave – Industry 4.0 – and which are also critical to our ability to fundamentally address the enormous global societal and environmental challenges of our times", said Prof Hugo Thienpont, director of Brussels Photonics (B-PHOT) at the Vrije Universiteit Brussel (VUB) and overall coordinator of PhotonHub Europe.

"European industry needs to be at the forefront in innovating with photonics, making the most of our combined strengths across all parts of the innovation value chain, and working collaboratively across all member states, to support European business innovation and growth. This is the motivation behind the establishment of PhotonHub Europe which is directly building on top of over 15 year of previous European projects and collaborative efforts by all of the organisations involved in developing and integrating the infrastructure necessary for such a major undertaking".

In order to accelerate the uptake and deployment of photonics technologies by European industry, PhotonHub will establish a single photonics innovation hub which integrates all of the best-in-class photonics technologies, facilities, expertise and experience of 53 top competence centres across Europe under one roof as a one-stop-shop solution with open access for any company anywhere in Europe that wants to innovate with photonics.

As a result, PhotonHub will provide European companies, in particular 'non-photonics' SMEs and mid-caps that are first users and early adopters of photonics, with open access and guided orienteering through the PhotonHub front office in Brussels, across a broad range of services and capabilities covering: training and upskilling supports; "test before invest" innovation support; and supports to find investment.

Photonics Training and Upskilling Supports

Training and upskilling supports to companies will cover both technology- and application-specific learning in photonics using lecture-based tutorials, hands-on lab-based training and "Train-the-Trainer" programmes within the hub's 40 Demo Centres and 10 Experience Centres throughout Europe, all coordinated for consistent standards of excellence under the umbrella of the European Photonics Innovation Academy of PhotonHub.

Supports to Find Investment

PhotonHub will help companies innovating with photonics to find investment from suitable sources of venture capital or other private/public sources of growth capital to further boost their capabilities in bringing new photonics and "photonics-enabled" products faster to market.

Cross-Border Added Value and Pan-European Networking

PhotonHub will support cross-border innovation activities of European companies, whilst simultaneously working closely with local photonics hubs representing 18 European regions as additional partners in the consortium to further boost photonics innovation amongst SMEs at a localised level all over Europe.

Commenting on the regional collaboration with PhotonHub Europe, Ziga Valic of Photonics France said: "Photonics is recognised across many European regions as a key digital technology which is central to industrial innovation and prosperity. As such, we are investing strongly at a regional level in developing a vibrant local ecosystem for photonics innovation which integrates all stakeholders from research institutes and innovation labs to SMEs and large enterprises.

"Linking our regional efforts to PhotonHub at the European level we believe is essential as it means we can offer local companies a fast and seamless route to the best expertise and technologies in photonics to match their needs, whether that is to be found locally, nationally or on a cross-border level".

PhotonHub Europe will work with the local photonics hubs from the "lighthouse regions" where photonics is already well established in order to develop best practice models for SME innovation support and to disseminate these best practices widely to support the development of new innovation hubs covering most regions of Europe.

UK CSC launches foundry for quantum photonics

QUANTUM TECHNOLOGIES are on the brink of emerging from the realms of the laboratory and science fiction into a wide range of industrial and consumer products that will affect the way we live, work and spend our leisure time.

Advanced quantum phenomena are being harnessed to create disruptive technologies in areas ranging from ultra-secure communications to highly-sensitive imaging and healthcare diagnostics.

As new applications emerge, widescale market adoption of quantum systems will require a robust, commercial-grade source of quantum photonic components, often based on advanced semiconductor devices.

The adoption of foundry manufacturing concepts, well known in the semiconductor industry, will accelerate mass-market traction.

QuantumFoundry (QFoundry) is a three-year, £5.7 million project that is part-funded by the UK Quantum Technologies Challenge, via UK Research and Innovation. The project will use standard semiconductor techniques to scale up the manufacture of quantum components that are critical to a wide range of novel quantum systems.

Initial areas of focus include VCSELs for commercial grade atomic clocks and atomic magnetometers, and single-photon emitters and detectors for quantum communications, computing, imaging and sensing applications.

The consortium led by the Compound Semiconductor Centre (CSC) and comprising Amethyst Research, Bay Photonics, Compound Semiconductor Applications Catapult, CSconnected Ltd, Cardiff University, Integrated Compound Semiconductors (ICS), IQE, Microchip Technology, National Physical Laboratory (NPL), Toshiba Europe, University of Cambridge and University of Sheffield will deliver a national open-access quantum semiconductor device foundry.

Members of the consortium have already delivered proof-of-concept quantum devices, and they will build on collective capability to create the foundations for robust, scalable quantum component manufacture in the UK to reduce barriers to commercialisation of quantum technologies.

Wyn Meredith, director of CSC commented: “Widescale adoption of quantum systems need a robust, reliable and volume supply of semiconductor components to integrate into products to deliver a return on investment on the science. QFoundry can perhaps be described as the missing piece in pathway to commercialisation, and the project will lay the groundwork towards a new UK quantum component industry.”

Roger McKinlay, challenge director for the Quantum Technologies Challenge, said: “This is part of the UK National Quantum Technologies Programme which is set to make a £1B investment over its lifetime.

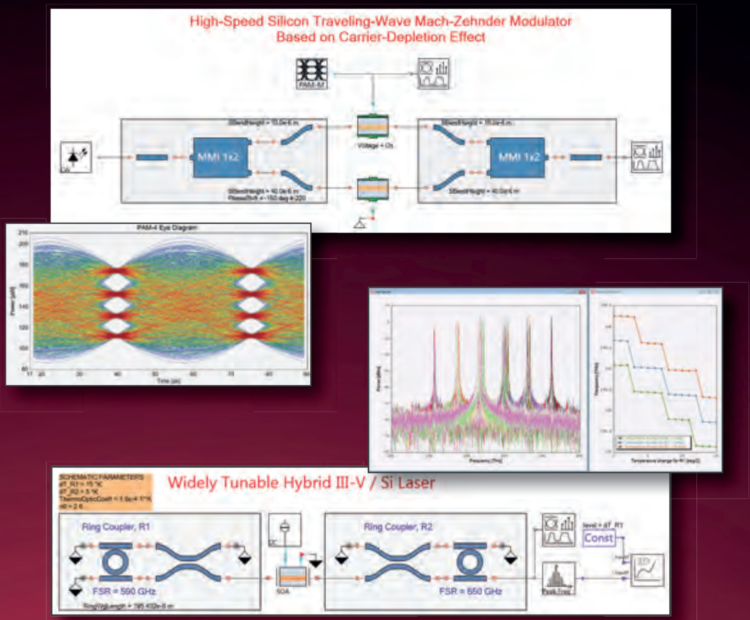
“This impressive team illustrates that the UK can lead in the manufacture of quantum devices, not just the development of the technology. This is not just good business in its own right but also part of a virtuous cycle in which world-class fabrication is underpinning further leading developments in quantum computing, communications, imaging in sensing.”

Hitachi acquires Spanish photonics company

HITACHI HIGH-TECH has bought VLC Photonics, a photonic design house based in Valencia, Spain. VLC is a spin-off from the Universitat Politècnica de València. It has a wide experience with various material platforms (silicon photonics, InP, silicon nitride, PLC, polymer) and offers fabless development services for photonic integrated circuits (PICs) in telecom/datacom, microwave photonics, quantum optics, lidar, bio-photonics and optical sensing markets.

VLC will become a subsidiary company of Hitachi and will continue to provide PIC engineering services as part of the company’s broader offering. Recently internet traffic has been continuing to increase significantly due to the data arising from social media, video streaming services, working from home, IoT and the overall digitization of our economy and environment.

In the optical communications market, higher speeds and increased bandwidth are required to satisfy this growing demand. Meanwhile as demand gets stronger, the market has also had to manage issues of power consumption, size and cost reduction, and manufacturing scalability. Photonic integration provides the means to address all these requirements in a more holistic way than the traditional approach of assembling optical systems from discrete parts. A long-term provider of components and services to the optical communications industry, Hitachi High-Tech is aware of the increasing need of customers for greater integration and innovation. As the foremost independent provider of PIC design, test and engineering services, VLC is in an excellent position to help Hitachi High-Tech serve the new requirements of its existing customers as well as providing a base for the development of new service provisions.


High-Speed Silicon Traveling-Wave Mach-Zehnder Modulator
Based on Carrier-Depletion Effect
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MMI 1x2
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Ring Coupler, R2
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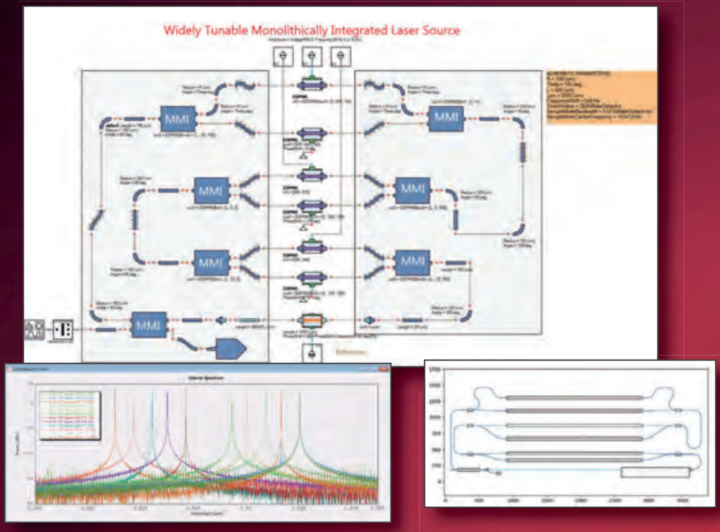
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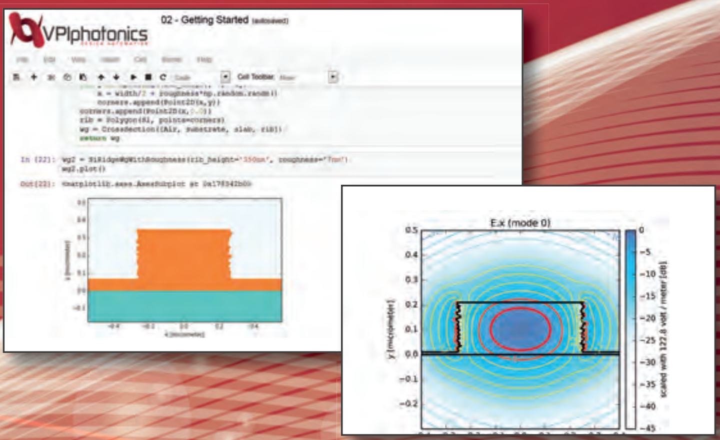
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02 - Getting Started
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Ayar Labs demos ultra-dense optical interconnect

AS PART OF a multi-year technology and manufacturing partnership, Ayar Labs has successfully demonstrated its patented monolithic electronic/photonic solution on Global Foundries (GF) next generation photonics solution based on its 45nm platform.

This is an industry first and key milestone in providing chip-to-chip optical connectivity at scale for data-hungry applications such as artificial intelligence, high performance computing, cloud, telecommunications and aerospace.

“As collaborators, we’ve incorporated their requirements for PDK and process optimisations while providing early access to our next generation process. Together, we will unlock a larger market opportunity and realise chip-to-chip optical I/O solutions that will enable higher bandwidth and faster connection for high performance compute applications.”

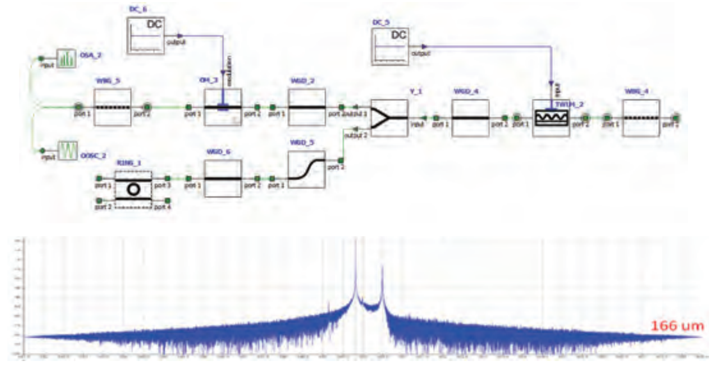
The two companies began working together in 2015 with a commitment to collaborate and commercialise differentiated silicon photonics solutions for greenfield applications that would require extreme bandwidth density (high data throughput in a small physical package) at low latency and high energy efficiency.

“Ayar Labs has been perfecting our micro-ring based monolithic electronic/photonic solution for nearly a decade. But the true commercial potential is realized when coupled with a 300mm semiconductor fabrication process that delivers the performance, reliability, and cost advantages that we and our customers require,” says Charles Wuischpard, CEO, Ayar Labs. “This is yet another industry-first result that solidifies our leadership for this market opportunity.”

“Ayar Labs is an important partner of Global Foundries,” says Anthony Yu, VP of silicon photonics at GF. “As collaborators, we’ve incorporated their requirements for PDK and process optimizations while providing early access to our next generation process. Together, we will unlock a larger market opportunity and realize chip-to-chip optical I/O solutions that will enable higher bandwidth and faster connection for high performance compute applications.”

Over the last 18 months, Ayar Labs has been working with select semiconductor manufacturers, systems builders, and end users on co-design partnerships. The company is now announcing an expanded sampling program of its next generation chiplet developed on GF’s latest silicon photonics manufacturing process that will be available to a broader group by request at ayarlabs.com/starterkit/

Mark Wade, president and CTO of Ayar Labs, will be sharing details of this industry first demonstration at ECOC 2020 as part of his presentation on ‘Silicon photonic chiplets for chip-to-chip communications’ on Tuesday, December 8, from 16:20 – 16:40 (CET).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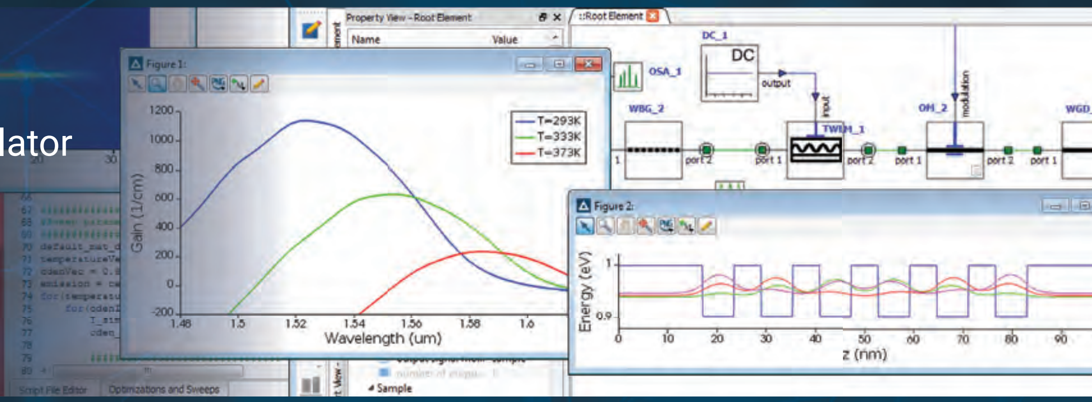
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T=373K
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Wavelength (um)
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200
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1.56
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DC_1
DC
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TWLM_1
OH_2
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Figure 2:
Energy (eV)
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70
80
90
Script File Editor
Optimizations and Sweeps
Sample

NeoPhotonics adds modulator and receiver for 100+ Gbaud systems

NEOPHOTONICS, a maker of photonic integrated circuit-based lasers, modules and subsystems for bandwidth-intensive, high speed communications networks, has announced the addition of Class 60 versions of its Coherent Driver-Modulator (CDM) and Intradyne Coherent Receiver (Micro-ICR) to its suite of high bandwidth coherent components designed to address the next generation of 100+ Gbaud systems.

These new Class 60 Coherent components extend the highest speed over distance performance of our existing Class 50 products by increasing the 3 dB bandwidth from 50 GHz to 60 GHz. The Class 60 suite is said to improve on the currently shipping Class 40 components, and allows increasing symbol rates from the current 64+ Gbaud rate to the higher 100+ Gbaud rates.

These NeoPhotonics components work together to enable customers to implement single wavelength data transmission near one Terabit per second over datacenter interconnect (DCI) distances, and long-haul 400~500Gbps transmission.

Higher symbol rates increase data capacity while maintaining superior optical signal to noise ratio (OSNR) and reach performance, thereby enabling the highest speed over distance use. These new components are available in compact form factor packages suitable for use in pluggable modules and compact daughter cards. NeoPhotonics Class 60 CDM and Micro-ICR are mechanically compatible to their Class 40 counterparts, and are a natural upgrade path for achieving the higher symbol rates (100+ Gbaud) in order to support 800Gbps and above data rates per wavelength applications.

The Class 60 suite comprises two components. First there is the Class 60 CDM: NeoPhotonics Class 60, polarisation multiplexed, coherent driver modulator (CDM) features a co-packaged InP modulator with four linear, high bandwidth, differential drivers, and is designed for low V-Pi, low insertion loss and a high extinction ratio. The compact package is designed to be compliant with the form factor of the OIF Implementation Agreement #OIF-HB-CDM-01.0.

Second, there is the Class 60 Micro-ICR: NeoPhotonics Class 60 High Bandwidth Micro-Intradyne Coherent Receiver (Micro-ICR) is designed for 100+ Gbaud symbol rates, more than tripling the rate of standard 100G ICRs. The compact package is designed to be compliant with the OIF Implementation Agreement OIF-DPC-MRX-02.0.

These components are designed to work together with NeoPhotonics ‘Nano’ ultra-narrow linewidth external cavity tunable laser, which cuts the size approximately in half compared to current Micro-ITLAs, while featuring industry leading linewidth and low phase noise with low electrical power consumption.

AXT completes first tranche of investment in China

AXT, a manufacturer of compound semiconductor substrates, has announced that the first tranche of the private equity investment in its wafer manufacturing company in China, Beijing Tongmei Xtal Technology has been fully funded.

The first tranche investment totals approximately $22.5 million. Three funds within the Haitong Private Equity Group make up the first tranche investors: Liaoning Haitong New Energy Low-Carbon Industry Equity Investment Fund, Liaoning Haitong New Kinetic Energy Equity Investment Fund Partnership and Haitong Innovation Securities Investment.

AXT previously announced on November 16, 2020 a strategic plan to access China’s capital markets and progress to an initial public offering by Tongmei on the Shanghai Stock Exchange’s Sci-Tech innovAtion boaRd (the “STAR Market”). To qualify for a STAR Market listing, Tongmei is required to have multiple independent shareholders. The first major step in this process is engaging reputable private equity firms in China to invest funds in Tongmei. In exchange for approximately a 7.14 percent minority interest in Tongmei, private equity firms will invest approximately $50 million. The second tranche of approximately $26.5 million is expected to fund in January 2021. The second tranche investment documents have not yet been executed.

“We are pleased to have completed the first tranche funding so quickly,” said Morris Young, CEO. “This is an exciting time for our company as the applications and customer opportunities for which we have been preparing over the last two years are now taking shape. The materials we produce are proving to be an essential part of many of the technologies that will define advancements in telecommunications, networking, healthcare, consumer products, and other verticals for many years to come. We believe that our success to date in positioning ourselves for an IPO of Tongmei on the STAR Market reflects the strong market demand for our products and our future growth, as well as our well-established presence in China. We appreciate The Haitong Group’s enthusiasm for our business and its cooperation throughout this process. We look forward to continuing to build a long and positive relationship.”

The process of going public on the STAR Market includes several periods of review and, therefore, is a lengthy process. Tongmei does not expect to accomplish this goal until mid-2022.


TRAINING
DEVELOPMENT
SKILLS

European Pilot Lines

in photonic integrated circuits

The value, practicality, and performance of photonic technologies has led to key roles within telecom and datacom systems. Manufacturers see many additional opportunities for photonics in myriad applications beyond data. But the challenge of taking new ideas from concept to manufacturing is daunting. Enter the Pilot Lines system that has been instituted to level the playing field so EU companies can better compete in the growing, multi-billion-euro global photonics marketplace.

BY ANA GONZALEZ, R&D MANAGER & PIC EXPERT AT EPIC

THE POSSIBILITY of integrating different optical components such as couplers, interferometers, beam splitters, spectrometers and focusing lenses together in semiconductor chips has attracted attention and interest by companies that see the potential to develop smaller, low power and more efficient photonic products. Even as the optical communications field is the main driver of present-day photonic integration, there are other applications of the technology that have demonstrated ways in which photonic integrated circuits have huge potential, such as the development of point-of-care biosensors for clinical diagnosis, highly miniaturized 3D sensors like LiDAR and Optical Coherent Tomography (OCT) as well as interrogators for fibre sensing.

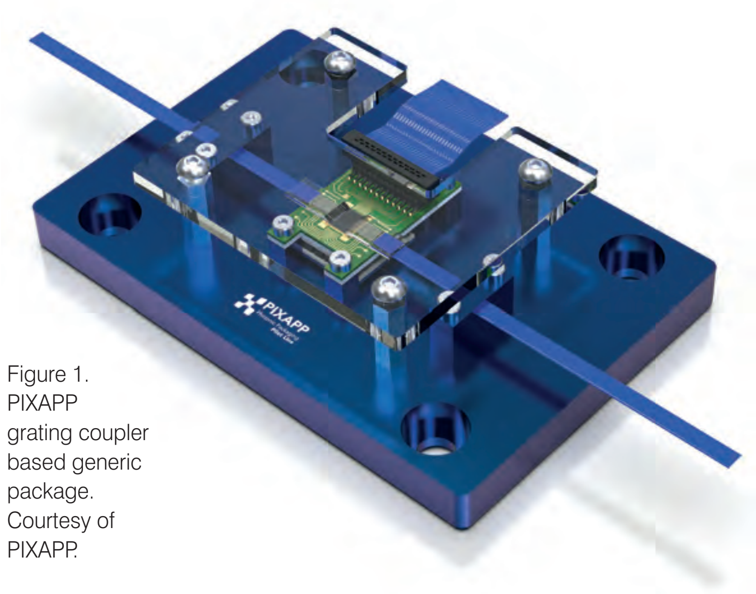


Figure 1. PIXAPP grating coupler based generic package. Courtesy of PIXAPP.

However, there are still challenges related to the commercialization of photonic integrated circuits (PICs) that hinder their introduction in new products. These challenges involve the need to develop tools and processes to scale up PIC production in terms of chip fabrication at the foundries, packaging of photonic chips and automated testing at all the production levels. To face these challenges, various European Pilot Lines have seen created starting in 2016 to scale up manufacturing of innovative photonics components and systems by the EC together with Photonics21. This article takes a brief look at the work of the Pilot Lines in photonics in developing mature processes across the different levels of the supply chain to ramp up production of PIC-based products.

Enabling SME market success

In addition to the optical communications market where PIC solutions are already commercially available, there are other sectors in which photonic technologies can also have a big impact such as the medical, automotive and industrial (process

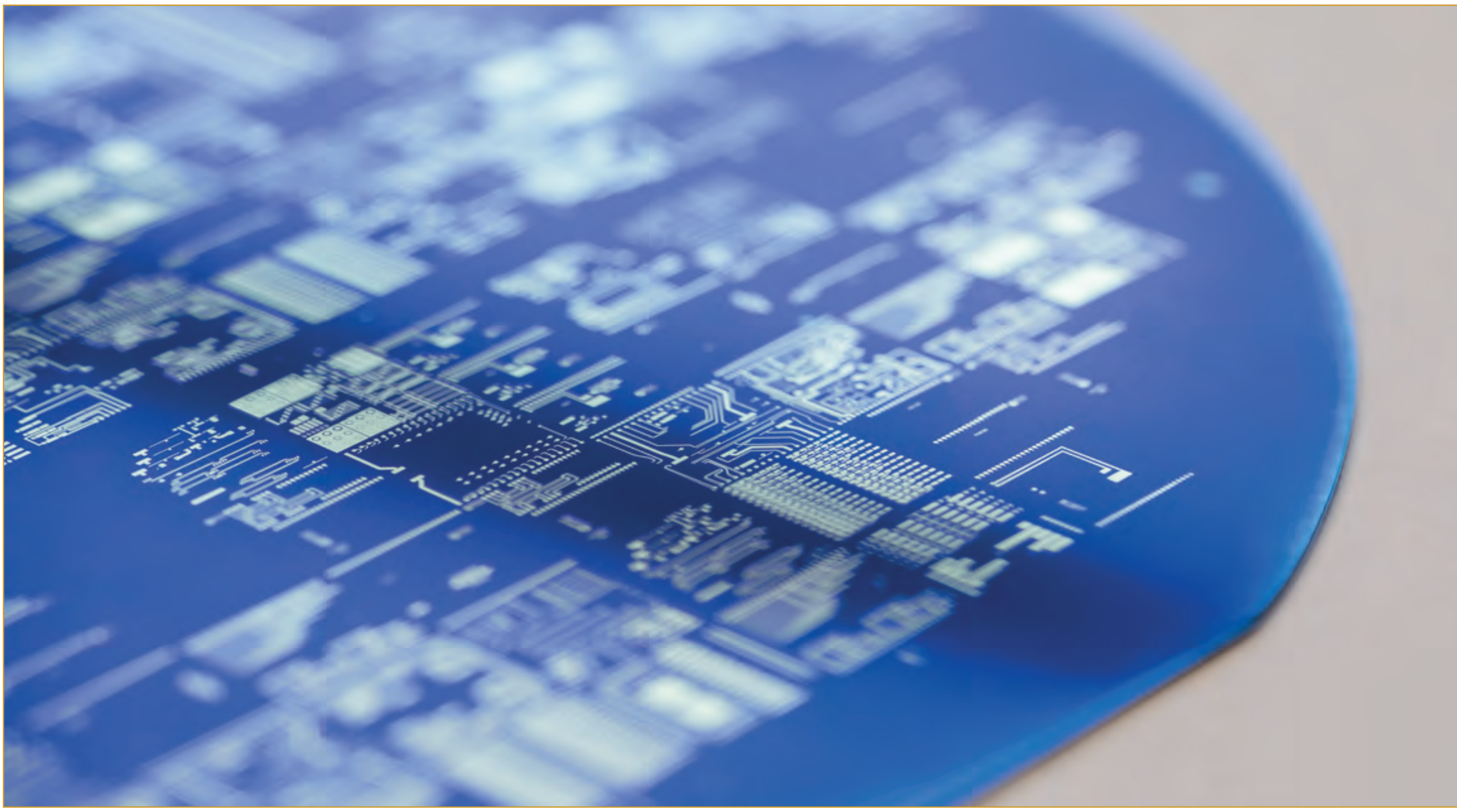


Figure 2. InP photonic integrated circuit wafer. Courtesy of Smart Photonics.

monitoring) markets. While small and mid-size enterprises (SMEs) make the most significant contribution to photonics innovation in Europe, compared to typically large companies in China and the US, the small size of European photonics companies means they face a number of barriers for scaling up production such as: lack of expertise and R&D; the absence of an advanced, cost-effective manufacturing infrastructure; difficulties finding investment and a fragmented regulatory structure.

As a counter measure, the European Commission (EC) incorporated Photonics21 in 2013 as a "Public Private Partnership" (PPP) within the framework of Horizon 2020 and committed €700 million over the next seven years to scale up the manufacture of key photonics technologies in Europe. Around half of this funding was allocated to improve access to start-up and growth financing together with projects designed to bring photonics into Europe's education system, and the establishment of various European Pilot Lines to accelerate innovation and the uptake of photonics technology for a rapid translation into new products and services.

Cost-effective production requires large volumes

When thinking about integration, miniaturization, and wafer-level manufacturing, it is clear we are thinking about applications needing large-volume production for mass markets. Disposable biosensors for user-friendly diagnosis, LIDAR for automotive (taking into account that several LiDAR systems could be required per car) and transceivers for access technologies are examples of emerging PIC markets. These opportunities will require a coordination effort to define design rules, standards and processes, across all the different levels of the supply chain, taking into account the specifications and needs of the different applications. Pilot Lines in Photonics have expended considerable effort in that direction, making processes compatible and organizing the main actors for PIC development to work together to create a solid supply chain.

The development of standardised photonic packaging processes is key to increasing access and reducing the cost of manufacturing photonic devices. In 2017, PIXAPP was created with a budget of €15.8 million to provide a range of standardised photonic packaging technologies that could be scaled to high volumes along with training in optical, electrical, and mechanical packaging technologies. The PIXAPP Pilot Line offers a menu of packaging processes to its users which cover optical, electrical, thermal, mechanical, and micro-fluidic processes. These building blocks allow standardised manufacturing processes to be used across the entire supply chain. PIXAPP works with design houses, foundries, and companies providing packaging services and components; PIXAPP also works with companies providing automation tools to ensure these building blocks are suitable for pilot level assembly.

PIXAPP building block technology is based on the organization's reference PICs. These reference devices have been designed to meet different design rules that make it easier to develop packaging

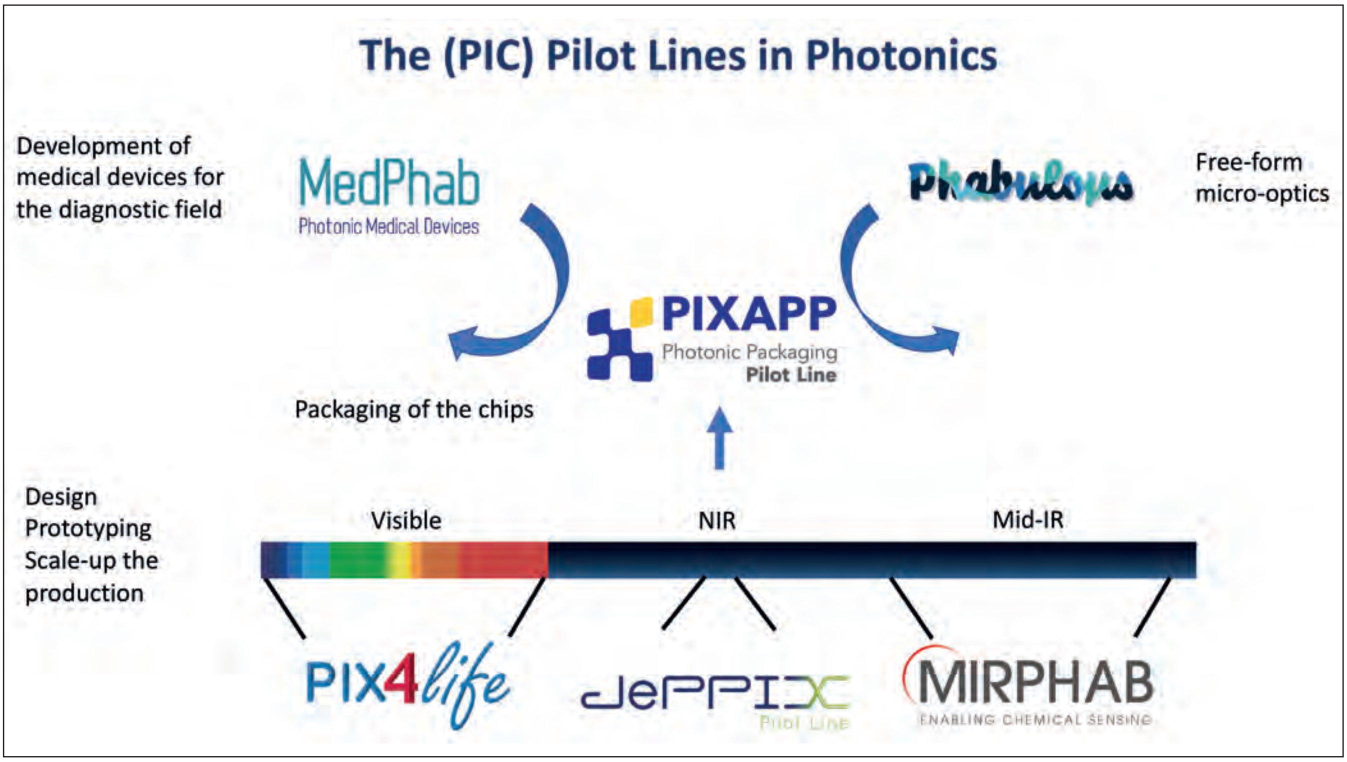


Figure 3. Pilot Lines in Photonics for PIC technologies.

processes compatible with ramping-up production. They are a joint effort across each of the PIC providers in PIXAPP to produce PICs in the major photonic platforms (InP, SOI, SIN) with standard designs for electro-optical I/O ports and packaging assembly steps. These PICs are key in the development of the PIXAPP building blocks and are used to optimise packaging processes as well as being a basis for designing generic materials and sub-components used for scalable packaging.

As a result of this work, PIXAPP offers different packaging solutions: 1) the Prototype Packaging Platform (See Figure 1), intended for telecom/datacom, LIDAR and other sensing applications, which is compatible with Indium Phosphide, Silicon or Silicon Nitride PICs from multi-project wafer (MPW) services; 2) the Pilot Packaging Platform, which includes the High Speed Gold Box, the Biosensor Package and the Fibre Sensing Interrogator Package, for companies needing pre-commercial production. Different applications require different wavelengths Regarding the fabrication of the chips, a given application could require InP or silicon-based chips, and their fabrication requires different processes, equipment and facilities. Launched in 2016 was PIX4Life which, with a budget of €10.2 million, aimed to ramp up manufacture of optical life science systems based on silicon nitride (SiN) photonic integrated circuit technology for applications in the visible range (400-1000nm). SiN is transparent for visible and near-infrared wavelengths, which makes it possible to make SiN waveguides with very low propagation loss for applications in healthcare, sensing, imaging, LiDAR and quantum computing. Other applications include biosensors, cytometers, DNA sequencers, gas sensors, microscopes and medical imagers. SiN is also widely used in semiconductor device fabrications, which makes it highly compatible with CMOS technology. PIX4Life offers a library of mature (bio-) photonic building blocks and prototyping manufacturing solutions using a cost sharing model, i.e. MPW runs.

JePPIX became the second chip manufacturing Pilot Line. Launched in 2019, powered by InPulse with a budget of €17.3 million, the JePPIX Pilot Line was established to provide companies with direct access to state-of-the-art manufacturing of PICs based on indium phosphide (See Figure 2) from proof of concept to industrial prototyping and pre-production. InP is used to produce lasers, photodetectors, and modulators because, as a compound semiconductor wide bandgap material, InP is the most effective material for the generation of laser signals and the detection and conversion of those signals back to electronic form. InP PICs allow the integration of hundreds of optically active and passive functions on the same chip and can handle the high-speed transmission of very large volumes of data, with applications such as fibre optic communications, biomedical devices, next generation mobile products, portable devices, astrobiology, and quantum computing.

PICs at the core of other technologies

Other Pilot Lines are focused on PICs at the core of the technology as well as the production of the PIC packaging. An example is the MIRPHAB Pilot Line, based on Mid-InfraRed (Mid-IR) technologies, that was launched in 2016 with a budget of €16 million. MIRPHAB was established to scale up products based on miniaturized Mid-IR spectroscopic sensors, including PICs acting as the spectrometer by using arrayed waveguide grating (AWG). The Mid-IR light in the 3- 12 μm wavelength band interacts strongly with molecular vibrations that present unique adsorption spectrums that give superior detection capabilities and unambiguous detection of chemicals in gas and liquids allowing high sensitivity and real-time detection. A different case is PHABULOUS, which develops processes linked to PIC production in order to couple light into waveguide structures. PHABULOUS was set up in 2020, with a budget of €17.6 million, to help mature manufacturing processes and increase manufacturing readiness of free-form micro-optical structures and functionalities. Micro-optics is key for the packaging and assembly of PICs; in this context, PHABULOUS is fundamental to completing the supply chain for PIC packaging.

Last but not least, MedPhab was created in 2020 with a budget of €17.1 million. MedPhab marked a change of strategy. Instead of focusing on a single technology, the project was designed to ramp up the manufacture of devices for a particular application field, namely, medical diagnostics that would leverage the best qualities of fibre optics, microfluidics, surface functionalisation, instrumentation, opto-electronic integration, miniaturisation for micromodules and wearables applications. MedPhab was chartered to include PIC and non-PIC complementary technologies as a means to create optimized solutions for a given application.

Conclusion

The Pilot Lines in Photonics offer a complete range of services for the manufacture of PIC-based products by focusing on developing standardized processes compatible with large-volume manufacturing.
They present a solid and understandable menu of technologies and standardized processes along the supply chain including software companies, design houses, packaging companies and enterprises making automation equipment (see Figure 3).

The Pilot Lines cover a ‘missing gap’ for the commercialization of PIC devices, focused on serving the needs of European SMEs developing the next generation of photonic products based on PICs.
Note: This content reflects only the authors’ view and the European Commission and Photonics 21 are not responsible for any use that may be made of the information it contains. The projects PIXAPP, MedPhab, JEPPIX, MIRPHAB, PIX4Life and PHABULOUS have received funding from the European Union’s Horizon 2020 research and innovation programme.

For their grant agreement information, please visit:
www.photonics21.org and https://cordis.europa.eu/en

Invest in photonics now

to fight infectious diseases and future pandemics

The spread of the SARS-CoV-2 coronavirus and resulting COVID-19 pandemic has sadly demonstrated how a new infectious disease poses unparalleled dangers to citizens and healthcare systems alike. The German government has invested €150 million to fund the Leibniz Centre for Photonics in Infection Research on the Jena University Hospital campus to investigate photonic technologies focused on disease detection. Scientific Director, Dr. Jürgen Popp, details the urgency behind new photonics research initiatives and how to better prepare for potential future pandemics.

BY DR. JÜRGEN POPP, SCIENTIFIC DIRECTOR FOR THE LEIBNIZ CENTRE FOR PHOTONICS IN INFECTION RESEARCH

STRONG INVESTMENT IN PHOTONICS will help us fight infectious diseases that kill an unimaginable number of people and prepare us against future pandemics. By harnessing photonics – technologies that are based on light – we are producing solutions in fields as varied as next-generation farming, the environment, transport, industry and healthcare.

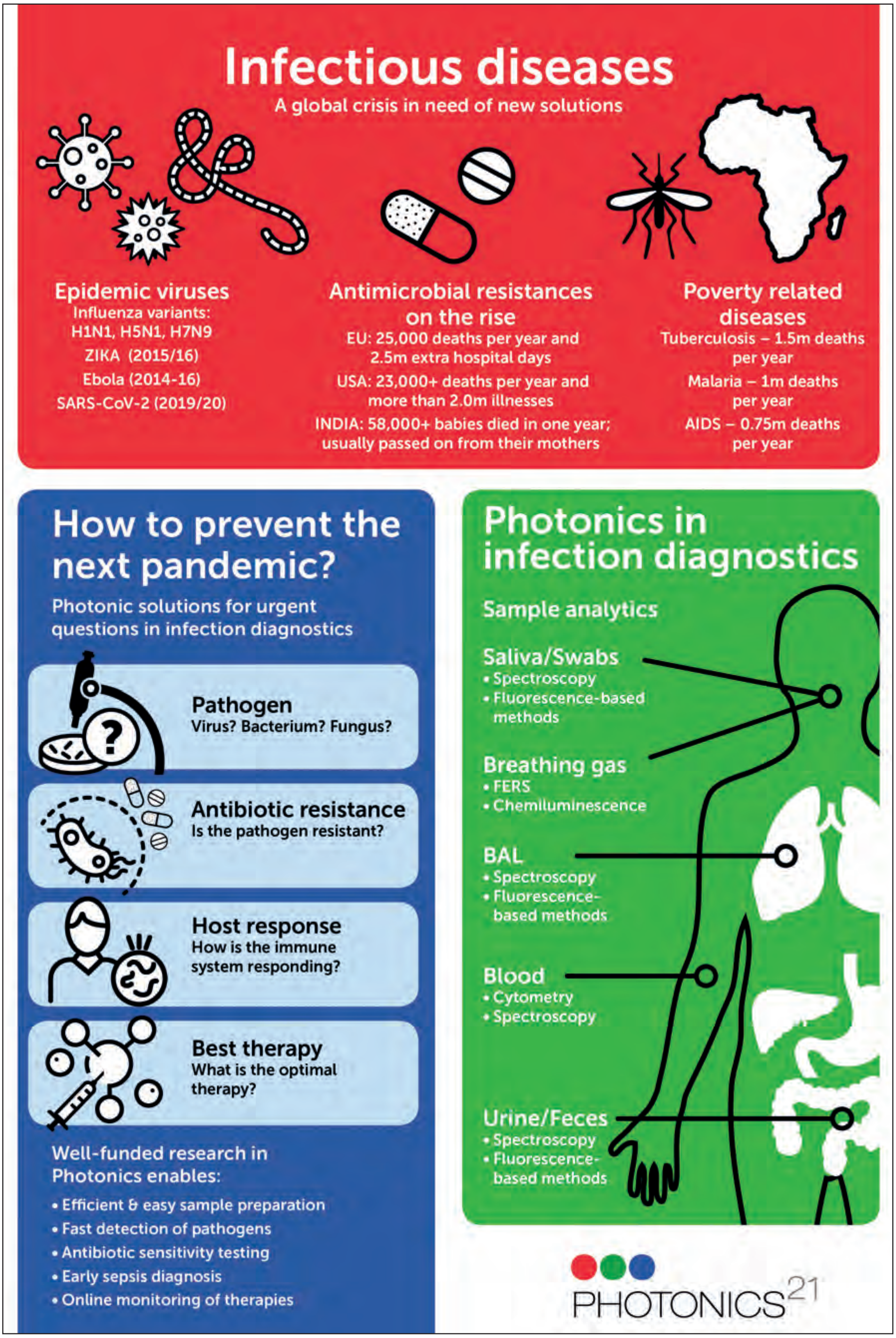
- Light offers promising new solutions to tackle infectious diseases that kill millions of people every year.
- Urgent action is needed from the EU and governments to invest in photonics technologies
- South Korea invests €2.8 billion in photonics per year; China invests €1 billion, whereas the entire EU photonics investment is €100 million p.a.
- A proper investment will prepare us for the next pandemic

Light technologies are recognised as revolutionary and beneficial to a number of sectors: driverless cars, 5G and Green technologies are all made possible by the generation, detection, manipulation, emission, transmission, modulation, processing, switching, amplification, and sensing of light.

The threat of infectious diseases and antimicrobial resistance is just one case to illustrate that now is the time to commit to strong investment in photonics. Fast, clean and precise, photonics can build advanced diagnostics, pervasive monitoring and innovative e-health applications that can detect body signals, symptoms and diseases at very early stages.

Detecting with light

COVID-19 has shown us that we, as a species, have been unprepared for a dangerous pandemic in many regions of the world. Nations have lacked the necessary capacities to test for infectious diseases, meaning responses have been delayed and adequate measures not taken at appropriate times. It is in this critical time period – the testing and initial response phase – that determines our ability to control or respond adequately to a threat. And it is in this crucial



Infectious diseases

A global crisis in need of new solutions

Epidemic viruses
Influenza variants:
H1N1, H5N1, H7N9
ZIKA (2015/16)
Ebola (2014-16)
SARS-CoV-2 (2019/20)

Antimicrobial resistances on the rise
EU: 25,000 deaths per year and 2.5m extra hospital days
USA: 23,000+ deaths per year and more than 2.0m illnesses
INDIA: 58,000+ babies died in one year; usually passed on from their mothers

Poverty related diseases
Tuberculosis – 1.5m deaths per year
Malaria – 1m deaths per year
AIDS – 0.75m deaths per year

How to prevent the next pandemic?

Photonic solutions for urgent questions in infection diagnostics

Pathogen
Virus? Bacterium? Fungus?

Antibiotic resistance
Is the pathogen resistant?

Host response
How is the immune system responding?

Best therapy
What is the optimal therapy?

Well-funded research in Photonics enables:

- Efficient & easy sample preparation
- Fast detection of pathogens
- Antibiotic sensitivity testing
- Early sepsis diagnosis
- Online monitoring of therapies

Photonics in infection diagnostics

Sample analytics

Saliva/Swabs
- Spectroscopy
- Fluorescence-based methods

Breathing gas
- FERS
- Chemiluminescence

BAL
- Spectroscopy
- Fluorescence-based methods

Blood
- Cytometry
- Spectroscopy

Urine/Feces
- Spectroscopy
- Fluorescence-based methods

PHOTONICS21

Established test protocols for identifying infectious diseases are accurate, but often require trained personnel and days-long laboratory analysis. Photonic technologies offer fast, accurate and portable alternatives

phase where photonics can provide unique solutions like no other technology owing to its speed and the rapid time it can deliver information. Photonics can deliver instantaneous information about the health status of a patient to determine whether they are suffering from a condition that is caused by a virus or a bacterium. Indeed, one of the unique selling points of light technologies is that results can be determined on-site, in-situ without having to send samples to a laboratory and await analysis – all of which can take days or sometimes weeks.

Infectious diseases

Infectious diseases can have a number of causes, including bacteria, viruses, fungi, or even parasites, and can be transmitted from person-to-person, or animal-to-person. There are many infectious diseases that pose a danger to our species, like Influenza, AIDS / HIV, Malaria, Tuberculosis, SARS, Ebola or Zika. This serious threat requires drastic, urgent solutions and has been highlighted by COVID-19 this year.

With the global pandemic of 2020 caused by SARS-CoV-2, COVID-19 will be added to the three infectious diseases that account for the top ten leading causes of death worldwide, including lower respiratory infections, diarrheal diseases, and tuberculosis. Even before COVID-19, according to the World Health Organisation, the situation was worse in low-income countries in 2018, with five infectious diseases – lower respiratory infections, diarrheal diseases, HIV/AIDS, malaria, and tuberculosis – being a leading cause of death among the top ten.

Antimicrobial resistance

Declared by the World Health Organisation as one of the top 10 global public health threats facing humanity, Antimicrobial Resistance (AMR) poses a serious threat to humanity. Antimicrobials – which include antibiotics, antivirals, antifungals and antiparasitics – are medicines used to prevent and treat infections and infectious diseases. AMR occurs when bacteria, viruses, fungi and parasites change over time and no longer respond to medicines, making infections harder to treat and increasing the risk of disease spread, severe illness and death. Currently, the WHO estimates 10 million people could die from antimicrobial-resistant (AMR) infections globally by 2050 if the prescription or treatment situation does not change fundamentally.
To tackle future pandemics, medical and health practitioners will need to be equipped with next-generation specialist tools that provide instantaneous diagnostic information that is inexpensive and easy to deploy and should operate at a point of care to the patient.

Photonics projects currently tackling infectious diseases

At the time of writing, in Europe, the Photonics Public Private Partnership is funding many research projects to develop tools and techniques for infection diagnostics. The CoNVat consortium, for example, is developing an ultrasensitive laser sensor that detects coronavirus at the earliest point of infection from a saliva or nasal swab in minutes.

Originally developed to look for bacterial infections or cancer biomarkers, the new ultrasensitive detector uses photonics to detect infections in patients with a small amount of the virus and will diagnose in real-time with high specificity from a low concentration sample. Looking at tiny molecules, the new point-of-care detector examines virus antigens using miniaturised chips – or 'nanophotonic biosensors' – from a simple nasal or saliva swab.

Similarly, the RAIS consortium is making a bold bid to reduce the mortality rate from sepsis by more than 70% with their new detector using photonics to identify E. coli bacteria from a tiny drop of blood, producing a while-you-wait diagnosis in less than thirty minutes. Programmed to detect proteins and E.coli, one of the deadly bacteria that can cause the human body to go into septic shock, the detector then uses light to look for specific biomarkers (the tell-tale signs or an indicator of a disease) that are as small as few nanometres in size, or 1 / 1,000,000th of the thickness of a single human hair. The rapid 'microarray' detector looks at a small blood sample taken from a thumb or forefinger. The patient's blood sample is then separated in a centrifuge so that a clinician can examine the plasma, the part of the blood sample where all the proteins are contained.

Projects using spectroscopy and imaging for fast diagnosis of infection and sepsis

A powerful method for diagnosis of infection and sepsis has been researched within the EU-funded project “HemoSpec.” From a small amount of blood from the patient, the photonic-based algorithm can differentiate patients with sterile inflammation, infection and sepsis with high accuracy.

The algorithm is based on valuable information of the leukocyte’s activation state that can be extracted in a non-destructive and label-free manner using Raman spectroscopy. The technology is currently in translation together with the industry. In order to provide the basis for a future decentralised application of biophotonic technologies such as Raman spectroscopy as a novel diagnostic tool in hospitals and doctor’s offices, the EU COST action “Raman4Clinics” brought spectroscopists, clinicians and device manufacturers from all over Europe together to perform a large scale cross-laboratory study. This study assessed the comparability of Raman spectroscopic configurations of 35 Raman spectroscopic devices with different configurations in 15 institutes within seven European countries. Statistical data analysis played an important role in achieving comparability.

The European Union is currently funding the Innovative Training Network (ITN) “IMAGE-IN: Imaging Infections” within the Marie Skłodowska-Curie Actions (MSCA) to educate the next generation of scientists who can actively advance imaging technology for medical application, in particular, to develop a new photonics-based method for fast diagnosis of difficult-to-treat infections, but also for non-invasive treatment monitoring.

In further national funded projects, spectroscopists advance in close collaboration with physicians and live science researchers optical-spectroscopic methods for fast antibiotic susceptibility testing (AST). The aim is to reveal the infection-causing bacterial pathogen and its antibiogram within three hours directly from a minimal amount of the patient’s sample. Ideally, the patient sample is easily accessible, such as a patient’s urine or blood.

The joint research project ReHwIN focusses on nosocomial urinary tract infections that account for up to 30 per cent of all nosocomial infections in Germany. The final photonic analysis system will combine microfluidic processing of a urine sample with a miniaturised and sensitive Raman spectroscopic readout platform and data analysis with artificial intelligence. The project InfectoXplore tackles bloodstream infections which are associated with high morbidity and mortality rates and require rapid therapy; otherwise, they can lead to sepsis. Within InfectoXplore, positive blood cultures will be analysed and a targeted and personalized photonics-based diagnostic algorithm will be developed that enables a tailored antibiotic therapy as quickly as possible.

Step up funding

While Europe has a wealth of researchers working on cutting edge photonics techniques, we cannot simply rest on our laurels. We need to ensure we are prepared against the next pandemic with a collective commitment to fund photonics.

> The technology is currently in translation together with the industry. In order to provide the basis for a future decentralised application of biophotonic technologies such as Raman spectroscopy as a novel diagnostic tool in hospitals and doctor’s offices

Photonics is a global industry predicted to be worth a staggering €696 ($829 USD) billion by 2025. In parts of the world, photonics is recognised as having enormous potential and leverage. The China central government (has recently) increased its investment in photonics every year by 40%, to reach €1 billion in 2020 while the South Korea government spending in photonics increased to €2.8 billion per year. While these figures sound impressive, we must recognise that the EU only commits €100 million to photonics every year – a tenth of the China equivalent.

Just recently, three of the world’s most eminent scientists criticised the European Commission’s intention to drastically cut photonics funding over the next seven years. In an open letter to the European Commission, the Nobel laureates criticised the decision to make a 30% reduction in funding support by the European Commission for a future Photonics Partnership 2021-2027 in Horizon Europe.

Digital innovation which drives economic growth and creates jobs all across Europe, as well as critical healthcare, will be at risk if the budget to fund enabling photonics technologies is slashed. In short, photonics is a key enabler for a wealth of next-generation technological developments, as well as for humanity to mount an adequate response to future pandemics and health crises.

Rather than stall, policymakers should recognise the threat pandemics (which are caused by infectious diseases) are capable of and how adequate photonics funding can see us prepared for a future outbreak.

For the sake of defending ourselves against future pandemics, now is the time to commit to a programme of strong investment in photonics.

Next-generation test solution addresses unique PIC, MEMS requirements

Test requirements for photonic integrated circuits (PICs) are unique in that they must assess performance of both photonic and electronic circuit components. To enable high volume manufacturing, PIC test and measurement must also be fast, repeatable and reliable. EXFO, AEPONYX and MLP joined forces to address adding MEMS components to an already daunting list of requirements.

BY LAWRENCE VAN DER VEGT, EXFO SUBJECT MATTER EXPERT, WITH CONTRIBUTIONS FROM PHILIPPE BABIN, AEPONYX CEO, AND ROE HEMENWAY, PH.D., MAPLE LEAF PHOTONICS CHIEF TECHNICAL ADVISOR

PHOTONIC INTEGRATED CIRCUIT (PIC) testing faces mounting challenges as two key forces come into play – advancement of core component technology, and the growing need to ramp up volume component manufacturing as network bandwidth requirements increase exponentially. These trends will continue to gain momentum as 5G, video streaming, video conferencing, Internet of Things (IoT), and automotive connectivity drive incremental bandwidth demand.

To keep pace, component vendors need innovative test solutions that enable quick design-fabrication-test cycles to accelerate time-to-market for advanced technology. Three industry innovators – EXFO, AEPONYX, and Maple Leaf Photonics (MLP) – have collaborated to address this challenge. These companies, an optical test equipment manufacturer, a components manufacturer, and an integrated electro-photonics probe system developer, created a solution to address a PIC test challenge that combines silicon photonics, MEMS-based switches, and optical waveguides in one device. Their effective solution achieved a new milestone that sets the stage for future advances in PIC design and testing.

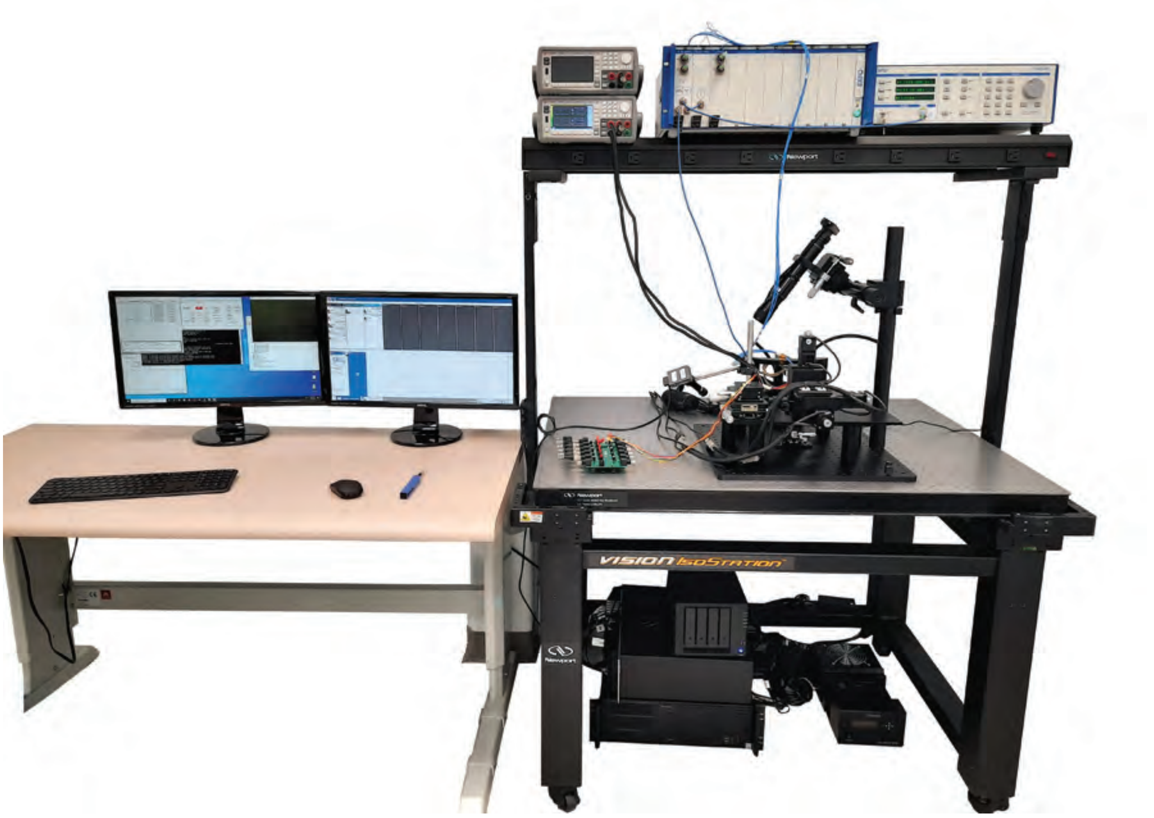
The need for speed and accuracy

AEPONYX is a PIC inventor and micro-optical switch leader creating chips for fiber optic access to the cloud. The company needed to find a solution for faster test processing of its advanced chips that combine silicon photonics, MEMS switches, and waveguides in one device. This presented a unique challenge because AEPONYX is the first company to combine silicon nitride waveguide photonics and planar MEMS on a single chip, requiring the test solution to cover both optical and electrical probing. The company also faced a deadline: high volume production needed to ramp up soon, so AEPONYX needed a solution that could test hundreds of thousands of devices for use both in development and production stages.

Specifically, AEPONYX needed a fully automated opto-electrical probing system, with ultra-fast optical test instrumentation, capable of generating the large set of data needed for device characterization. It was no small undertaking. As Philippe Babin, CEO of AEPONYX said, AEPONYX was striving to “master the art of silicon nitride photonics.”

Steps to collaboration

To tackle their unique testing requirements, AEPONYX began a pathfinding development effort with industry and university partners. Ultimately the company established a collaboration with MLP, an optical probe station system developer, and EXFO, an optical testing leader. The challenge was to design an integrated solution for high-speed electrical and optical testing



The MLP and EXFO fully automated opto-electrical probing system meets AEPONYX PIC test challenges.

that jointly leveraged all the unique capabilities of the MLP probe station and EXFO's optical test equipment.

MLP began by analyzing the AEPONYX design requirements and defining the type of testing that would be needed from EXFO. Combining EXFO's hardware with MLP's unique die and wafer-level testing approach enabled an efficient, scalable, and fully automated test setup.

The integration necessitated customized firmware specifically adapted by EXFO that allowed autonomous device-to-device displacement and locking based on optical signal quality. This solution provided fully automated measurements.

The combined EXFO and MLP technologies delivered an effective, production-ready machine that met the requirements of automated testing for devices made of silicon photonics, MEMs, and electronics. AEPONYX can now derive critical test data with this advanced system. In fact, accurate statistics are being delivered even faster than anticipated, which in turn accelerates AEPONYX product development. The solution is currently in use for prototyping at AEPONYX and is expected to soon move into full-scale production.

Innovation at work

Here is a closer look at what each company contributed to the challenge of developing a fully automated opto-electrical probing test solution.

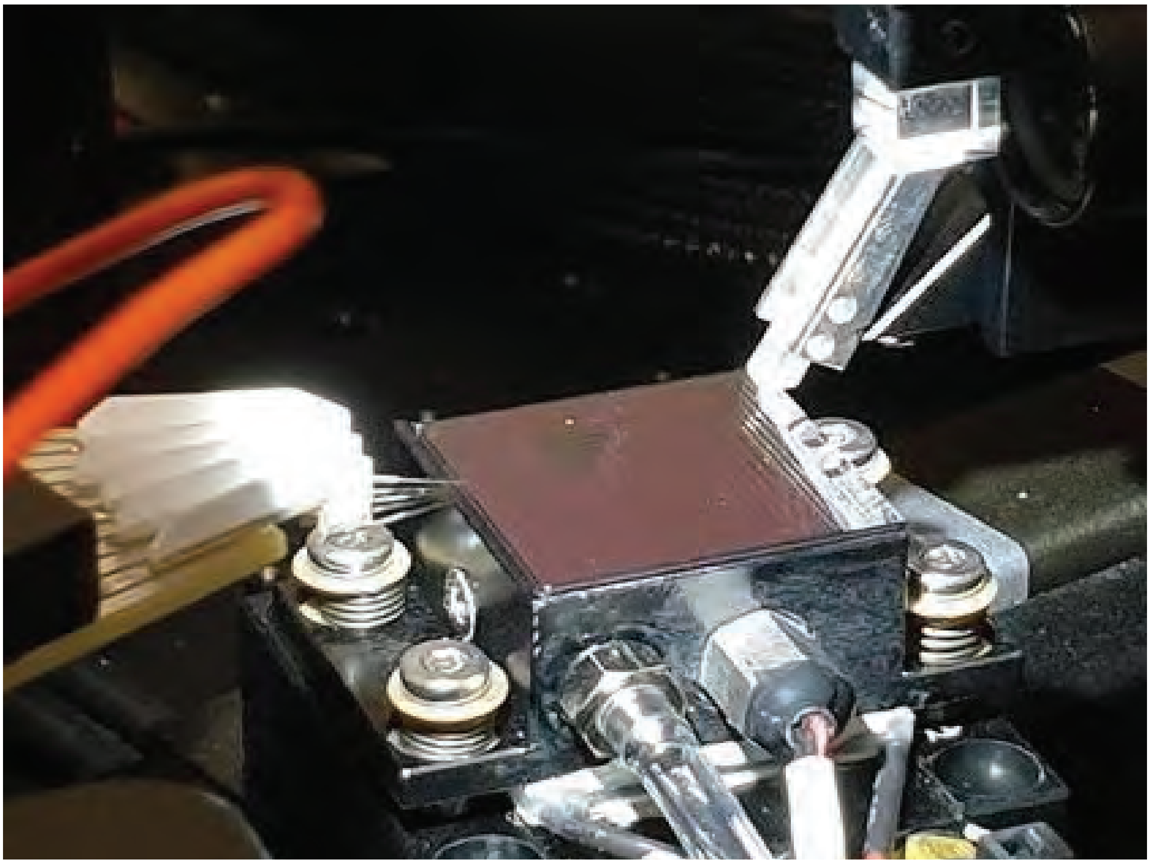
AEPONYX

AEPONYX is a photonics innovator with a growing portfolio of 11 patents and 15 other patent-pending devices. The company believes their optical chips will advance telecom, cloud datacenters, and compute functions with tunable transceivers and optical switches.

The AEPONYX leadership enabled the company to be the first to combine silicon photonics and planar MEMS on a single chip. This innovation drove the need for the fully automated opto-electrical probing system.

Babin says he is delighted with the impact of the innovative probing system on AEPONYX' business processes and the company's ability to produce cost-effective devices. For the broader industry, he foresees this solution potentially changing PIC testing for component manufacturers as others begin to face similar testing challenges.

> The new test system resulting from the EXFO, AEPONYX, and MLP collaboration dramatically increases test speed by more than 10 times compared to previous technologies.



The tester is probing both electrical and optical functions on the AEPONYX Silicon Nitride plus MEMS device.

MLP

MLP's mission is to simplify PIC testing. The company brings together motion, photonics, and electrical controls in a way that solves significant challenges faced by companies bringing next-generation integrated photonic solutions to market. MLP's Chief Technical Advisor, Roe Hemenway, says MLP helps reduce the complexity experienced by users in a world of multi-parameter testing required for electro-photonic circuits, thus speeding 'time to insight,' as he describes it.

MLP's Optical Probe Station solutions are scalable, customizable, and cost-effective. Their specialized modular architecture and API provide the tools needed for users to essentially control their own destiny and develop highly customized test recipes involving many instruments and parameters. Real time graphical result displays help ensure error-free testing.

MLP's innovative motion controls provide orchestrated probe head motion for speed and precision in critical 3D optical alignments. In certain modes, the system coordinates high-speed, on-the-fly measurements conducted while probe head elements remain in motion, eliminating the standard slow cycle of step, stop, measure, and repeat.

AEPONYX' need for a highly accurate and efficient source-detector combination coupled with precise optical alignments and test orchestration catalyzed the collaboration between MLP and EXFO. It was the ability of each company to provide flexible and customized approaches that contributed to a successful outcome. Coupling EXFO's hardware with MLP's unique wafer disc heatmapping process enabled the creation of a highly efficient, scalable and fully automated custom-tailored test setup addressing the specific needs of AEPONYX.

EXFO

"One size fits all" does not apply in the PIC industry, a fact that was particularly evident when collaborating to meet AEPONYX' unique requirements. EXFO provides advanced, automated PIC test instrumentation that is virtually unrivalled in the industry because of its fast, accurate, and reliable results. But even with industry-leading PIC test solutions, silicon photonics testing requirements can be unique, demanding customization at many different levels.

AEPONYX' goals demanded specific hardware features to work flawlessly with a wafer disc handler in a fully automated setup. This necessitated hardware features such as a multichannel, ultra-fast detector response time synchronized with the optical probe head that needed to be able to keep up with a fast-scanning, high dynamic range tunable laser source while measuring highly sensitive parasitic PIC devices. The test solution also needed to guarantee a high wavelength accuracy and repeatability during the entire measurement process.

The combination of EXFO's CTP10 and T100S-HP enables swept laser testing of passive optical components at a picometer resolution and at high speed, even under the most stringent conditions.

The CTP10 can output an analog electrical signal used as a closed-loop feedback signal by the actuator driver, ensuring that the lowest possible time is required to find the optimum position in and out of the wafer disc PIC under test. Customization involved making changes to the CTP10 firmware to accommodate MLP's heatmapping feature, delivering the test capabilities needed for AEPONYX high-speed, high-volume, ultra-accurate testing.

EXFO's technology enables continuous wavelength sweeping (up to 100nm/s @ 1pm optical resolution) supported by the T100S-HP high dynamic range in excess of 100dB, coupled with the ultra-high measurement and data processing speeds of the CTP10. This delivered low acquisition times and excellent S/N ratio – as low as 10s for 120nm wavelength sweeps every 10mA over a 50mA current sweep.

The CTP10 facilitates optical synchronization between the sweeping tunable laser source and a known wavelength reference, addressed by the built-in, all-optical wavelength referencing engine against which the incoming signal is being compared during the scanning process. That in turn is used to synchronize the source and optical detectors, guaranteeing a wavelength accuracy of better than +/-5pm with excellent repeatability in the order of 1pm, transparent from the laser scanning speed.

MLP's Roe Hemenway describes the following highlights of EXFO's solution that made it ideal for this project:

- wide dynamic range and tunability of the laser source
- continuous laser sweep speed with trigger
- expanded spectrum of testing, avoiding bottlenecks
- superior system performance based on optical rather than electrical synchronization
- speed of measurement and data processing from the CTP10 at 1 million samples/second per detector
- ability to manage multiple ports simultaneously.

Outcomes of a new industry milestone

Philippe Babin says AEPONYX can now meet the challenge of testing his company's devices in volume because the solution combines a leading-edge probing solution and equipment system. AEPONYX testing is now under way using this solution on a 24/7 basis. Access to massive amounts of highly accurate data is helping the company accelerate its innovations and shorten the time to mass production, thanks to the collaboration between three forward-looking companies. Testing silicon photonics and planar MEMS on a single chip with both optical and electrical probing is now a reality.

About the authors:

Lawrence Van Der Vegt
Subject Matter Expert, EXFO

Lawrence is an optics veteran; he earned his Bachelor's degree in Electrical and Computer Engineering in the Netherlands and has held various key Directorial positions at optical T&M companies in the Netherlands and the United States. He is currently active as a Subject Matter Expert on behalf of EXFO, involved in passive and active component testing driven by PIC technologies.

Roe Hemenway
Chief Technical Advisor, Maple Lead Photonics

Roe Hemenway applies his optical physics knowledge in innovative silicon and III-V OEICs for high speed communication links and novel optical network architectures. He earned a Ph.D. in applied physics from Stanford University where he invented a compact high speed silicon integrated light modulator and has recently advanced the passive assembly of DFB lasers and silicon WDM photonic ICs. While at Maple Leaf Photonics, he has co-developed modular automated probe systems ideally suited to integrated photonic research and development. He has 35 years of R&D experience in optical communications technology at AT&T Bell Labs, MIT Lincoln Labs, DiCon Fiberoptics, Corning, Inc., Macom Technology Solutions and now MLP. Roe has published over 100 technical papers and has 14 patents.

Philippe Babin
President of AEPONYX Inc.

Philippe Babin holds a Bachelor's degree in Electrical Engineering and an MBA in Business Administration from the University of Sherbrooke. He began his career in 1994 with C-Mac Microcircuits Inc. as a process engineer and subsequently held various management positions, including Director of Substrates Manufacturing, contributing to the 600 percent growth in revenues of one the most profitable business units of the EMS division. Philippe Babin joined Media5 Corporation in 2001 as head of research and development. Within this company, he successively headed product line management, sales engineering, sales and marketing and was ultimately appointed general manager, where he orchestrated complete business turnarounds. Before joining AEPONYX with the co-founders, Babin started his own sales and marketing agency in 2012 in the field of telecom and IT.

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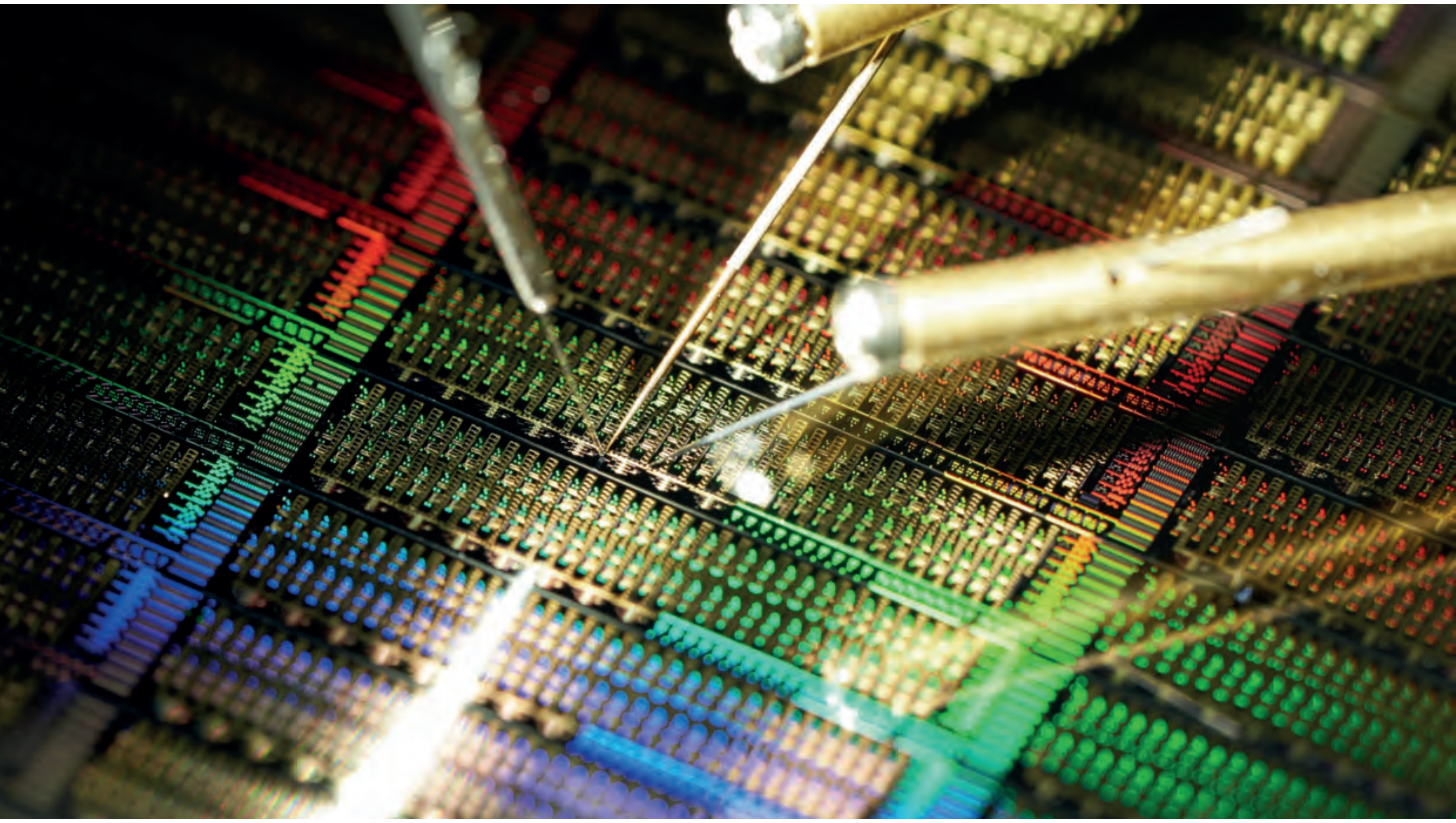


Comb lasers advance high-performance computers

By tackling a bottleneck in bandwidth, multi-wavelength quantum dot lasers are enabling improvements in high-performance computers

BY GEZA KURCZVEIL, DI LIANG AND RAY BEAUSOLEIL FROM HEWLETT PACKARD ENTERPRISE

GROWTH IN DATA is occurring at a phenomenal rate. Now it takes just two years to produce 90 percent of all the data on the internet. That has major implications, particularly as it comes at a time when the performance of single cores has stagnated (see Figure 1 (a)).

To make headway, efforts are no longer directed at trying to increase the clock speed of single cores, but are focused on the construction of processors with more and more interconnected cores, and limited private memory on one socket. This new architecture makes much sense, given that memory is cheap, the opposite of what it was when the first computers were being built. In future, high-performance computers will feature a massive pool of memory at the centre, surrounded by many compute nodes located at the periphery, with all nodes having access to the full memory pool (see Figure 1 (b)).

A key requirement for this new high-performance computer architecture is a massive communication link for the massive pool of memory. Without this, there would be insufficient throughput of data between memory and compute nodes.

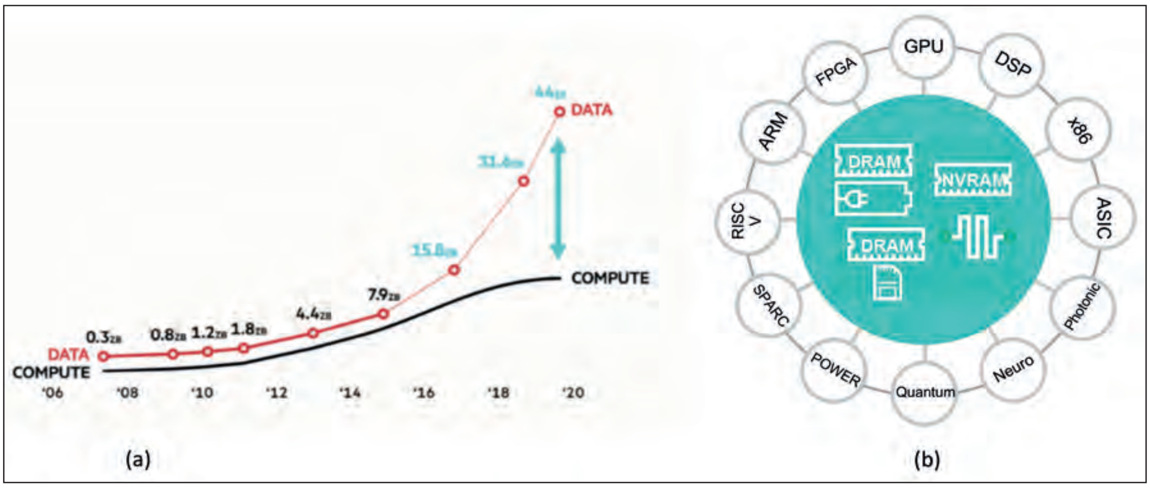


Figure 1. (a) While memory has gotten cheaper over time and there has been an exponential rise in the generation of data, single-thread performance has stagnated. (b) In memory-driven computing a massive pool of memory is at the centre of the architecture, and application-specific compute nodes are placed at the periphery. Each compute node has access to the full memory pool.

One option for the data link is electronic interconnects, such as copper wires. However, they suffer from significant losses, high power consumption, and cross-talk at higher frequencies. A far better alternative is optical interconnects, which address all the weaknesses of wires while allowing the transmission of multiple wavelengths. Data can be transmitted through these links using a technology known as wavelength division multiplexing, which avoids any crosstalk between channels. It is a well-established approach for routing internet traffic when distances and bandwidths are large enough to justify the cost – and as deployment has increased, prices have fallen, making these links common-place in applications where distances are on the order of just a metre. As that's a length scale found in high-performance computing, optical links are already used for rack-to-rack connections.

High-performance computers require aggregated data rates of terabits per second. Today, this rate is out of the reach of a single laser, so the aggregated data rate is sliced up between many lasers, each making an equal contribution. Although individual lasers can transmit at above 200 Gbit/s, data rates of only up to 20 Gbit/s are actually used, to minimise energy consumption.

A common approach for operating these lasers is amplitude modulation. But this has a downside, producing sidebands above and below the original optical carrier wavelength (see Figure 1 (c)). Due to this, the sidebands of one channel have to be sufficiently separated from those of the neighbouring channels to minimise crosstalk. When driving a laser with amplitude modulation at a data rate of 50 Gbit/s,

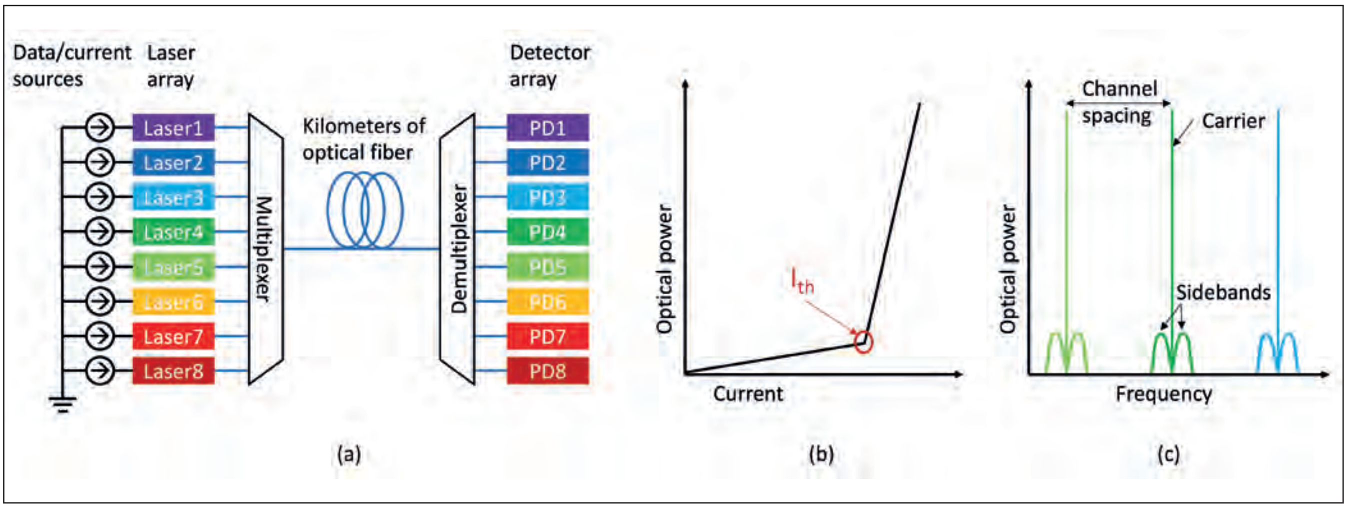


Figure 2. (a) A typical optical link consisting of several single-wavelength lasers. Data are encoded on the optical signal by turning each laser on and off. (b) The output power of a laser as a function of injection current. Once data are encoded onto a laser signal, sidebands are generated. As long as the sidebands of neighbouring channels do not overlap, there is no crosstalk between channels. This is accomplished by limiting the modulation speed.

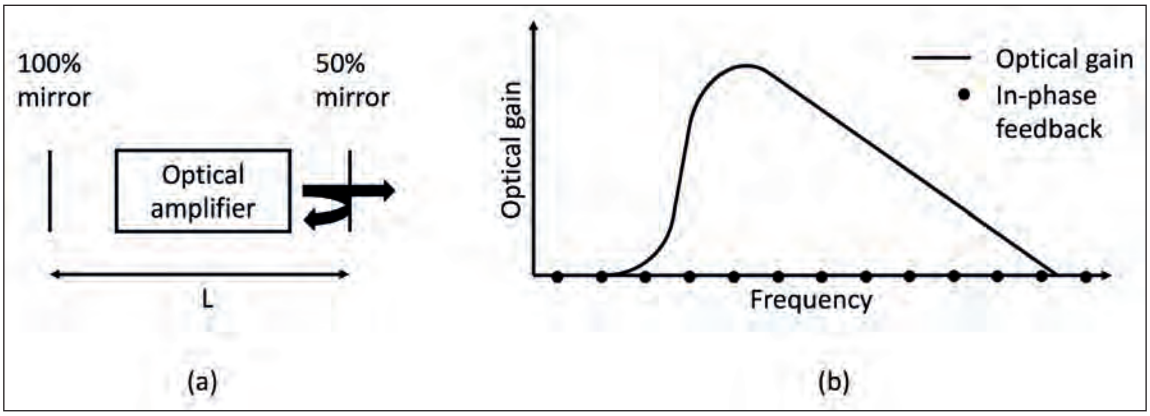


Figure 3. (a) A basic laser cavity contains an optical gain amplifier, surrounded by a pair of mirrors. (b) Lasing occurs at frequencies where light experiences a positive net gain and the feedback from the mirrors is in phase with the light in the cavity.

there needs to be a 3.5 THz channel spacing to minimise crosstalk.

To transmit data using wavelength-division multiplexing, signals from a number of lasers are united by an optical multiplexer, routed through a fibre, and sent to a demultiplexer that returns the data back to a collection of signals at different wavelengths. Photodetectors then convert all of these signals into electrical signals, which is the form required by today's processors and memory. Note that this scheme, which works very well, is particularly attractive for links with low-to-medium volumes of traffic, because it allows unused channels to be turned off, saving power.

Unfortunately, wavelength-division multiplexing is not easy. There are often imperfections in the laser production process, resulting in variations in the lasing wavelength. Addressing this requires active monitoring and tuning. If there are many channels, and the spacing is below 100 GHz – this is the case in dense wavelength division multiplexing – variations in wavelength can create significant problems. In such situations, rather than using many single-wavelength lasers, it is better to use one laser that provide multiple wavelengths – a comb laser.

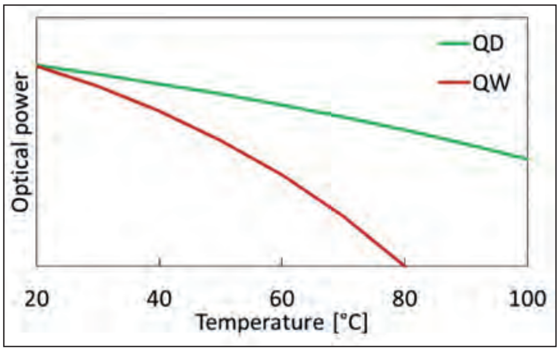


Figure 4. As the temperature of the laser junction increases, optical output power decreases. Due to the three-dimensional confinement of electrical carriers, the power drop in quantum-dot lasers is far smaller than in traditional quantum-well lasers. This makes quantum-dot lasers especially attractive for applications where temperature control is impossible or limited.

Comb credentials

A key difference between a conventional, single-wavelength laser and that with a multiple wavelength comb is the reflectivity of the mirrors. Conventional lasers need an additional bandpass filter inside the cavity – or at least a narrow-band mirror – to ensure single-wavelength lasing, while comb lasers employ a more straightforward design, tending to consist of a long cavity and broadband mirrors (see Figure 3(a)). For cleaved lasers, which can be formed with cleaved facets, the cavity can be 0.5 mm or longer, depending on the desired channel spacing.

With a comb laser, the spacing between the lines is fixed. Although changes in temperature shift the entire comb to either higher or lower wavelengths, once one knows the wavelength of one of the comb lines, one knows the wavelengths of them all. That's because the channel spacing is determined lithographically, and it is therefore a prescribed, controllable design parameter.

Given the great simplicity of the design of the comb laser, one may wonder why anyone would ever go to the trouble of making a single-wavelength laser. The reason is that when a comb laser is built with the most commonly used optical gain medium – a stack of quantum wells – this device is impaired by an intrinsic material property known as mode partition noise. This impediment produces random fluctuations in optical power for every comb line. Although these fluctuations, occurring on a nano-second timescale, do not alter the total optical power, they are a show-stopper for error-free data transmission. That's because it is not possible to transmit an optical 'one' while the power of a comb line has randomly dropped to zero.

So why have comb lasers suddenly risen in popularity, given these issues? Ironically, the recent success has nothing to do with comb lasers. Instead, progress has been driven by the development of a relatively new gain medium, quantum dots. Researchers in Japan pioneered these low-dimensional structures, developing a laser with greater tolerance to temperature variations. By switching from wells to dots they were able to increase the confinement of electrical carriers, with early experimental work verifying an increase in high-temperature gain stability

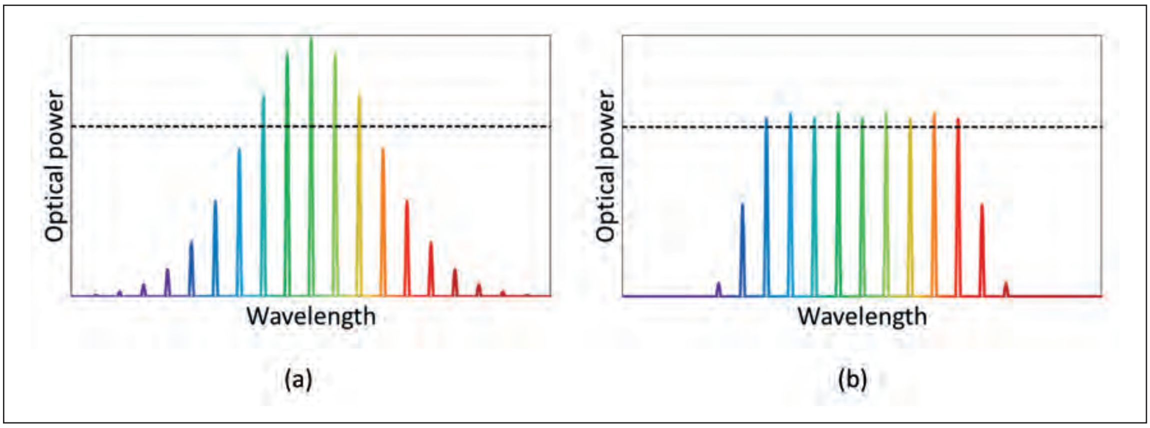


Figure 5. (a) Some comb lasers exhibit a Gaussian distribution of amplitudes. The dashed line indicates a hypothetical power level for noise-free data transmission. Comb lines with less power cannot be used, so they reduce the device efficiency. (b) Quantum-dot-based comb lasers produce a more rectangular optical spectrum. This device has the same total power as the one in (a). Note that more channels satisfy the power requirement for noise-free data transmission.

(see Figure 4). After this success, it took a few more years until a collaboration between researchers in Germany and Russia investigated the topic of mode partition noise in quantum dot comb lasers. This work revealed that the introduction of dots quashed the partition noise in these devices.

Not all comb lasers are created equally. Some are more practical than others for data communication, because they combine a low mode partition noise with a flat comb that ensures that all channels have similar signal-to-noise ratios. Poor candidates for high-performance computing include lasers with frequency combs generated in SiN resonators, as they show a Gaussian distribution of comb line amplitudes (see Figure 5 (a)). The good news, for reason yet to be understood, is that the combs from quantum-dot lasers produce flat spectra with a relatively uniform power over a large number of comb lines (see Figure 5 (b)). However, not all comb lasers are suitable, as there are problems with pulsed variants (for details see the box "The problems of pulsed comb lasers").
Encoding independent data streams on each comb line is not as straightforward as for a single-wavelength laser. Turning the laser on and off by modulating its injection current encodes the same data stream on all the comb lines, which is inefficient.

Instead, our team at Hewlett Packard Enterprise has the comb laser on at all times (see Figure 6) and places several micro-ring modulators outside of the laser – we have one for each comb line (see Figure 7 (a)). This approach exploits a key characteristics of micro-ring modulators, a wavelength dependent loss (see Figure 7 (b)). By adjusting the voltage of the *p-n* junction of the micro-ring, we shift the wavelength of maximum loss, which is the resonance wavelength. To generate an optical 'one', we tune the resonance wavelength away from the comb line; and to produce a 'zero', we line-up the resonance wavelength with the comb line.

Our micro-ring modulators are compact, with a diameter of around 10 μm. With proper design, they can transmit data at 50 Gbit/s. The full-width-half-maximum of the micro-ring's resonance is ideal, being wide enough to capture an entire comb line, but narrow enough to allow neighbouring comb lines to be transmitted without any loss in optical power. Selecting the resonance wavelength of the micro-ring is relatively easy, as it can be tuned by adjusting the

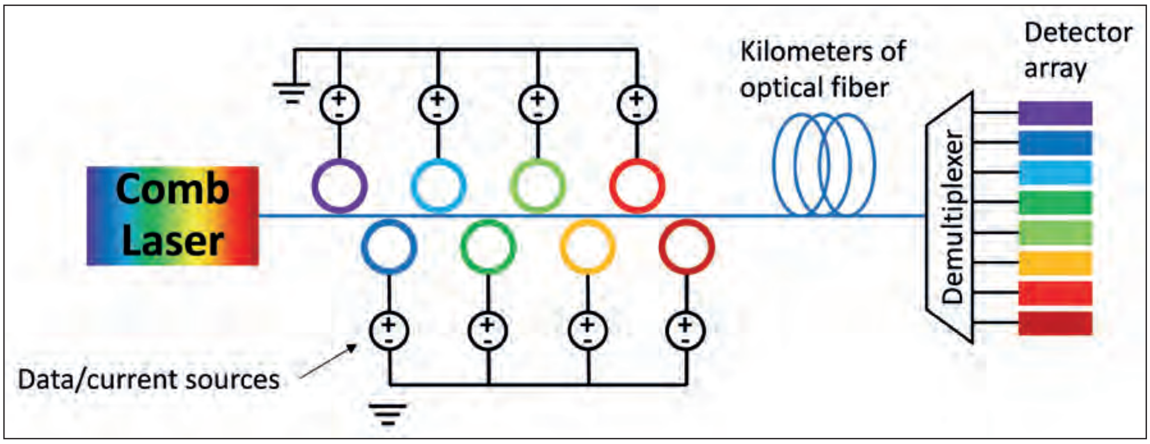


Figure 6. An optical link based on a comb laser. Rather than directly modulating the laser, external modulators are used to encode data on individual comb lines.

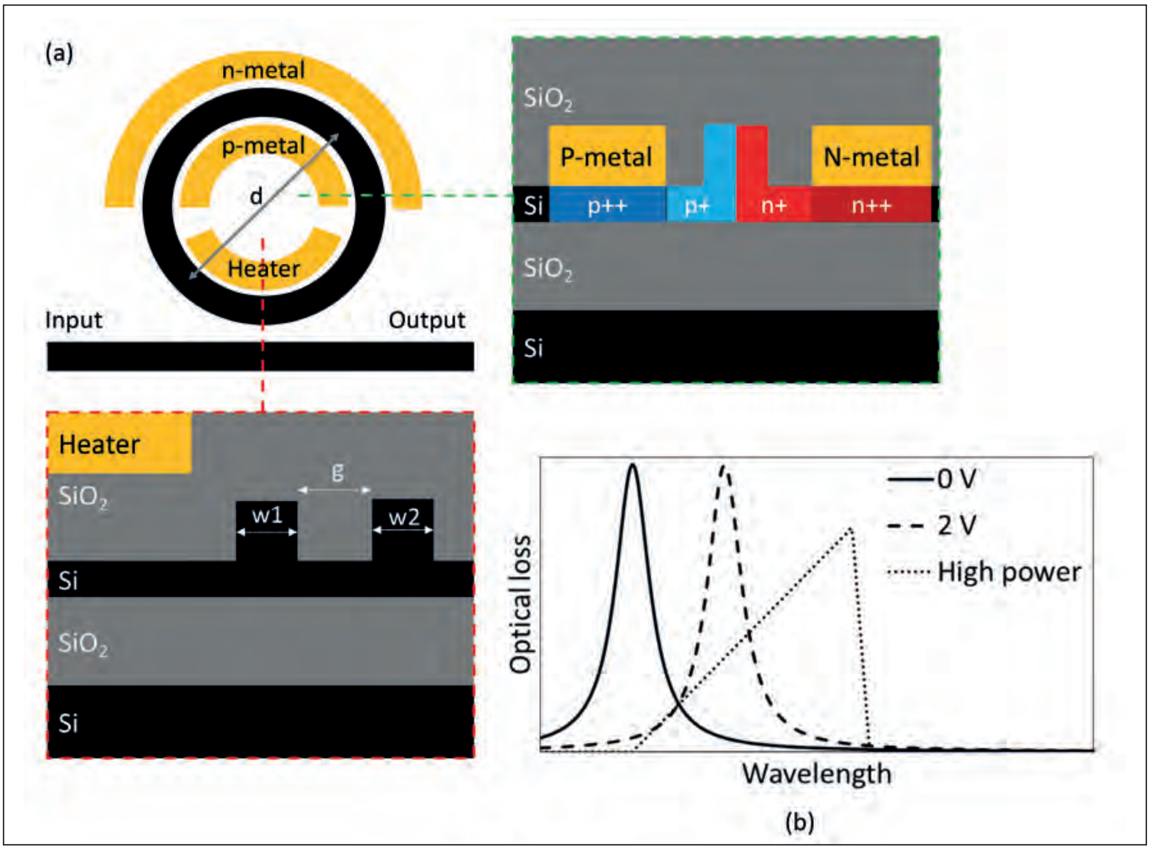


Figure 7. (a) Top-down and cross-sectional diagrams of a micro-ring modulator. (a) The wavelength-dependent loss of a ring modulator has a resonance that can be engineered using parameters *d*, *g*, *w1*, and *w2* in (a). In addition, it can be tuned using a power-hungry heater. Data are encoded by applying a voltage across the *p-n* junction. (b) The shape of the modulator's resonance becomes highly distorted at high optical powers, making pulsed lasers less desirable as a light source.

diameter of the ring, its inner width, and its thickness. One of the constraints of micro-ring modulators is that they impose a limit on optical power. If it is too high, non-linearities degrade the contrast of the resonance, and in turn lower the signal-to-noise ratio of the encoded data (see Figure 7 (b)). Due to this restriction, it is far better to operate comb lasers with a constant optical power. Fortunately, that's a great operating regime for this class of laser, thanks to its gain recovery characteristics.

There will always be a shift in the lasing wavelength of the comb laser, even if the micro-ring is perfect. What's needed is some form of tuning or tracking to maintain a line-up between the ring's resonance wavelengths and the temperature-shifted comb lines. One option is to apply a voltage to the *p-n* junction, but this results in excess optical loss, in the form of free-carrier loss.

The common way to avoid this is to use a resistive heater to locally change the ring's temperature. In turn, this shifts the refractive index of the cavity, and can deliver large changes to the resonance wavelength. However, resistive heaters are wasteful, requiring up to tens of milliwatts to shift the wavelength by just a nanometre. We prefer a more energy-efficient approach, using a capacitor to tune the resonance wavelength. With our design, a layer of semiconductor material is placed on top of the micro-ring, and inserted between is a 20 nm-thick layer of dielectric, such as SiO_2 or Al_2O_3 (see Figure 8). Electrodes are added to the silicon and the semiconductor to form a metal-oxide-semiconductor capacitor. When a voltage is applied to this device, sufficient electrons and holes accumulate at the dielectric interfaces to produce a change in the refractive index of the micro-ring, and its resonance wavelength. As the current flowing through the capacitor is incredibly small – it is only around 100 fA – the resulting tuning is 10^{-9} mW/nm, giving an increase in efficiency of nine orders of magnitude compared with a resistive heater.

To manufacture these comb lasers in high volume, using a high yield, low-cost process, they must be integrated on silicon substrates. Our short-term solution is to take GaAs-based epitaxial wafers, which contain our quantum dot structures, and use a molecular bonding technique to attach them to silicon-on-insulator wafers. We then selectively remove the GaAs substrate to leave a 1-2 μm-thick epitaxial stack on silicon, and process this material in the same way that is used to produce conventional GaAs lasers. However, we have the benefit of using much larger, stronger wafers.

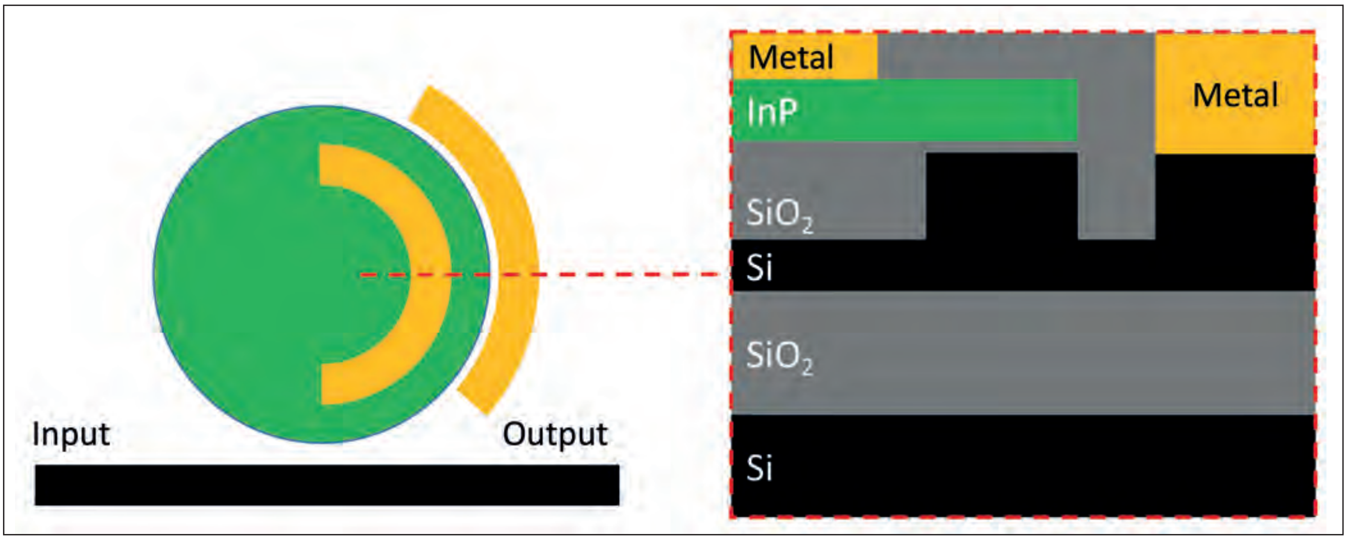
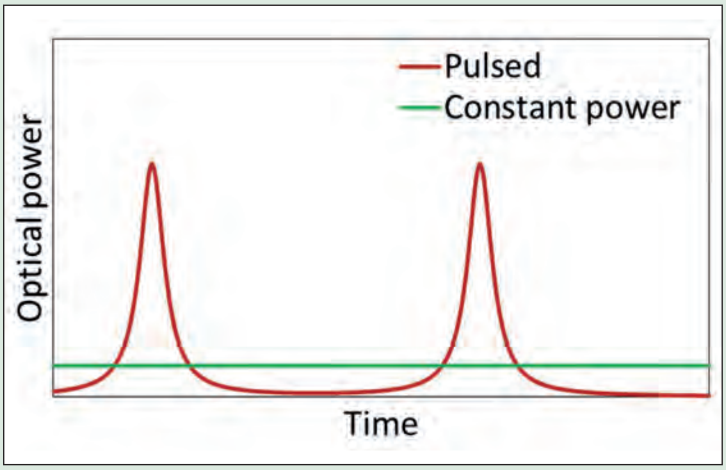


Figure 8. A MOS tuner provides much more efficient resonance tuning than a thermal tuner. When a voltage is applied to the contacts, charges accumulate at the SiO_2 layer, which is between the silicon and the InP. Charge accumulation is sufficient to change the refractive index and thus the resonance wavelength. However, since no current flows through the capacitor, power consumption is negligible.

The problems of pulsed comb lasers

WHEN COMB LASERS produce a pulsed output, or are temporally modelocked, the average optical output power is constant, but the energy of one period is compressed (see figure below). This can cause two problems. One potential issue is that the higher instantaneous power, contained in pulses typically as short as 2 ps, accelerates device failure, such as catastrophic optical mirror damage.

This is particularly problematic in comb lasers, as a failure impacts all channels. The second issue is that the high output power of the peaks impairs the contrast of the resonance, and ultimately reduces the signal-to-noise ratio of the encoded data.



Pulsed lasers are a form of comb laser that emit periodic pulses. The two devices shown here have the same average power, but the pulsed laser has a much higher peak power than the constant-power laser. The presence of pulses can have unwanted consequences such as reduced laser reliability and reduced signal-to-noise ratio of the encoded optical data.

A great strength of this process is that the silicon layer in these lasers provides both a mechanical substrate and an optical waveguide (see Figure 9 (a)). Silicon is ideal for waveguiding – it has a far lower optical loss than those made with GaAs or InP systems, and it allows us to make: high quality laser mirrors; MOS tuners for near zero-power tuning; and vertical grating couplers, which allow rapid, wafer-level device testing. With this approach we have fabricated comb lasers operating up to 100 °C (see Figure 9 (c)), and variants that provide 14 channels for error-free, high-speed modulation (see Figure 9 (d) and (e)).

Longer term, our plan is to produce comb lasers by growing quantum-dot-containing layers directly on silicon. This is far from easy, due to the large lattice mismatch between silicon and GaAs. Left unchecked, this results in a high density of defects that drag down device reliability, and can even kill lasing operation in an instant. Some groups have turned to thick buffer layers to reduce the strain in the quantum dot layers, but this hampers efficient coupling of light from the quantum dot layers to the silicon. Due to this, teams that have made devices that are based on direct growth of quantum dots on silicon have only used silicon as a mechanical carrier.

While comb lasers are very attractive, we are not advocating their use in every optical link. Since all channels in a comb laser are always on, comb lasers are only attractive for dense wavelength division multiplexing links that have a high volume of traffic at all times. Use a comb laser with many channels in a link with little traffic, and lots of power will be wasted by the unused channels, because they cannot be turned off. For links with low and medium levels of traffic, using an array of single-wavelength lasers may offer a more energy efficient solution.

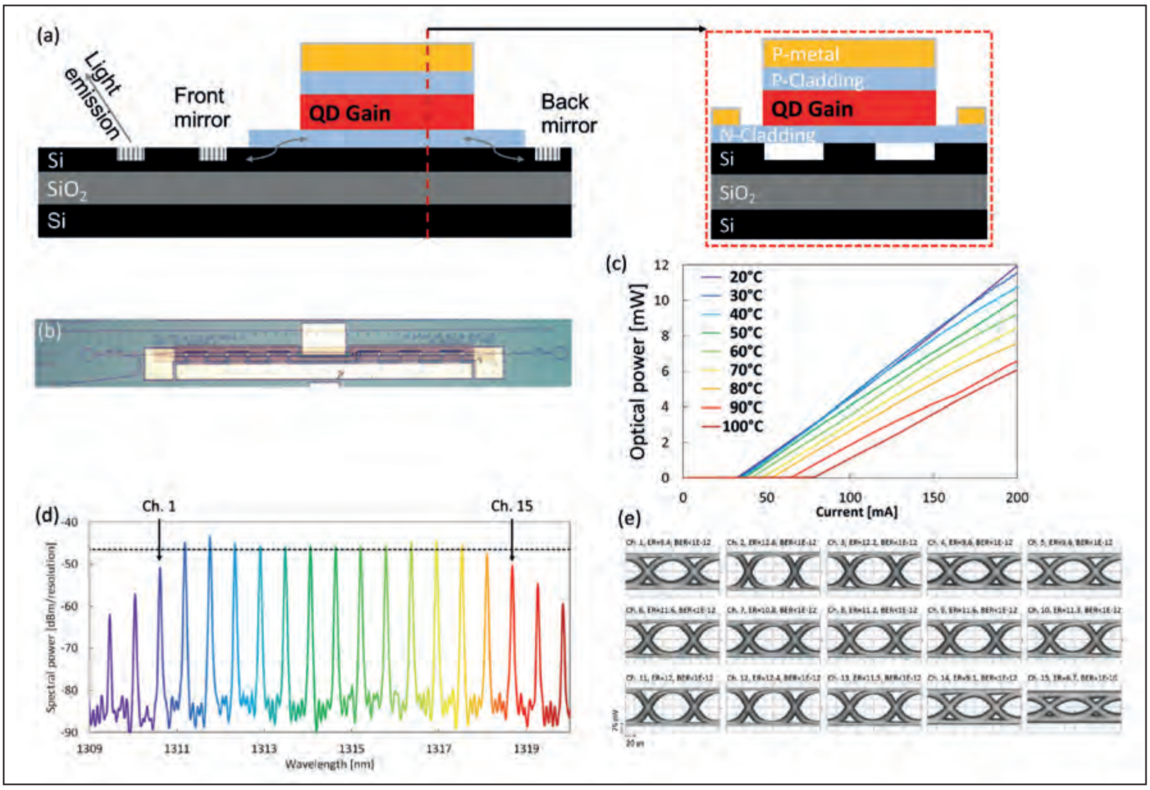


Figure 9. (a, b) Cross-sectional diagrams of a quantum-dot comb laser on a silicon-on-insulator substrate. Thin epitaxial layers between the top silicon and the quantum-dot gain allow efficient transfer of light between them. (b) Top-down photograph of a fabricated comb laser on silicon using wafer bonding. (c) Optical output power as a function of current and temperature showing excellent high-temperature performance. (d) Optical spectrum of a comb laser showing multiple comb lines with a quasi-rectangular shape. 12 comb lines within 3 dB of the peak (dashed line) are observed. (e) Eye-diagrams and bit-error-ratios (using an external modulator) showing error-free performance in 14 of the 15 channels that were measured (the bit error rate is no more than 10^{-12}).

There are two remaining challenges to overcome before comb lasers are ready to light up the next generation of high-performance computers. The first of these is device reliability. Since all channels are created in one laser, when a device fails, it impacts all channels. One way to partly offset this risk is redundancy. The second challenge is to devise an effective approach to increasing the number of channels. Although the spacing between the channel is inversely proportional to the length of the laser, making a laser longer is not a recipe for success. What happens is that as the channel spacing gets narrower, the individual channel rate has to be reduced to maintain a low cross-talk between the channels. The upshot is that there is no increase in the aggregated bandwidth.

A more promising solution is to increase the width of the optical window for the comb lines. The upper limit for this is determined by the gain bandwidth of the optical amplifier, which is typically 50 nm wide. Through engineering, this has the potential to be increased to more than 100 nm. However, even for 'regular' optical amplifiers with a 50 nm gain bandwidth, the combs that result are typically just 15 nm wide. At present, the reason for this is unclear, but several hypotheses have been suggested. One possible explanation is spatial hole burning, and another is group velocity dispersion – that there is imperfect mode spacing of a comb, resulting from a wavelength-dependent refractive index. If either of these are the cause, they can be addressed by engineering. Analytical models are being developed to help understand the impact of these phenomena, and experiments are underway to verify the models. When success follows, we shall be a step closer to implementing the efficient, high-speed optical links required to maintain progress in high-performance computing.

Further reading

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Toward high resolution multi-colour imaging

Wafer bonding opens the door to the fabrication of multi-colour, high-resolution imagers

BY SANGHYEON KIM, DAE-MYEONG GEUM FROM KOREA ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY, WON JUN CHOI FROM KOREA INSTITUTE OF SCIENCE AND TECHNOLOGY AND EUIJOON YOON FROM SEOUL NATIONAL UNIVERSITY

DEPLOYMENT OF PHOTODETECTORS is on the rise. Those operating in the visible spectrum are now a key feature in smartphones, and variants detecting in the infrared are being used in surveillance and the development of autonomous cars.

Product designers are selecting photodetectors that operate within a particular spectral domain to retrieve specific information. Detectors of visible light provide visual information our eye can see. Meanwhile, those operating in the infrared, where our eyes cannot see, offer details of the height of an object, or some chemical information – this is crucial in many applications.

Recently, there has been great interest in simultaneous detection across different spectral regions. The development of multi-wavelength photodetectors promises to revolutionise sensing and imaging applications, such as gas detection, medical diagnostics, industrial surveillance and time-of-flight sensors. By constructing overlapping images at different wavelengths, it is possible to generate more informative, more accurate, and more creative information.

Downsides of multi-colour photodetectors, including those that have been recently reported and those that have been commercialised, are bulkiness and use that is restricted to the lab. The only approach to making them that has been commercialised is packaging-based integration. This involves the positioning, in a vertical plane, of a silicon photodetector for the visible and an InGaAs variant for the infrared. With this geometry, when light is separated by a diffraction grating, the differing spectral domains are directed at appropriate detectors (see Figure 1). However, adopting this approach hampers the production of compact, high-resolution imaging devices – the detectors are relatively large, and alignment accuracy is limited by the mechanical alignment between the silicon and InGaAs photodetectors.

One alternative is epitaxy-based integration. With this approach, multi-colour photodetectors are formed by growing multiple active regions. This addresses the issue of bulkiness, but due to lattice mismatches between the different sections, the photodetector is impaired by high power consumption and degraded material quality.

Additional alternatives involve transfer printing and adhesive bonding. But they are compromised by limited vertical and horizontal alignment, as well as a low pixel density.

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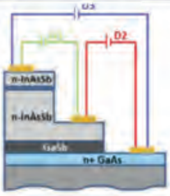
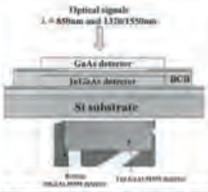
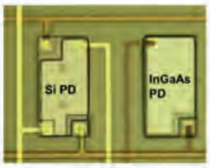
Structure				
Integration method	**Epitaxy** **[C. Xie et al, *IEEE J. Sel. Top. Quantum Electron* (2018)]**	**Adhesive bonding** **[S.W. Seo *et al, IEEE PTL* (2003)]**	**Transfer printing** **[L. Menon *et al, IEEE Photonics Journal* (2016)]**	**Packaging** **[*Hamamatsu*]**
Material quality	▲	●	●	●
CMOS process compatibility	●	▲	▲	X
Alignment accuracy (pixel density)	●	▲	▲	X
Simultaneous detection	▲ **(Voltage tunable)**	●	●	●
Throughput	**High**	**Medium**	**Medium**	**Low**

Figure 1. There are many different methods to fabricate multi-colour photodetectors.

A far better way forward, pursued by our partnership between researchers at Korea Advanced Institute of Science and Technology (KAIST), the Korea Institute of Science and Technology (KIST), and Seoul National University (SNU), is the monolithic integration of visible and infrared photodetectors. Employing wafer bonding and epitaxial lift-off techniques, this enables high-resolution, multi-colour imaging.

Multi-colour capabilities

At the heart of our fabrication process is the wafer bonding technique. This low-temperature, low defective process allows us to unite different materials without having to address concerns relating to lattice mismatch (see Figure 2).

We select GaAs as the light-absorbing material for visible wavelengths, and use InGaAs for infrared detection. Both detectors are formed by epitaxy: GaAs substrates are used for the growth of visible detectors, and those made from InP are used to make detectors operating in the infrared. To separate the GaAs photodetector from its native substrate after the wafer bonding step, we insert a sacrificial AlAs layer between the device and its substrate.

After growing both types of epiwafer, we deposit a layer of Y_2O_3 on both of them. This oxide is inserted because it is a suitable bonding material, and it has good material stability in the presence of HF, an acid used in the epitaxial lift-off process. After this, we undertake mesa isolation to enhance the speed of the epitaxial lift-off process (this process is detailed in our previous article, published in the June 2017 edition

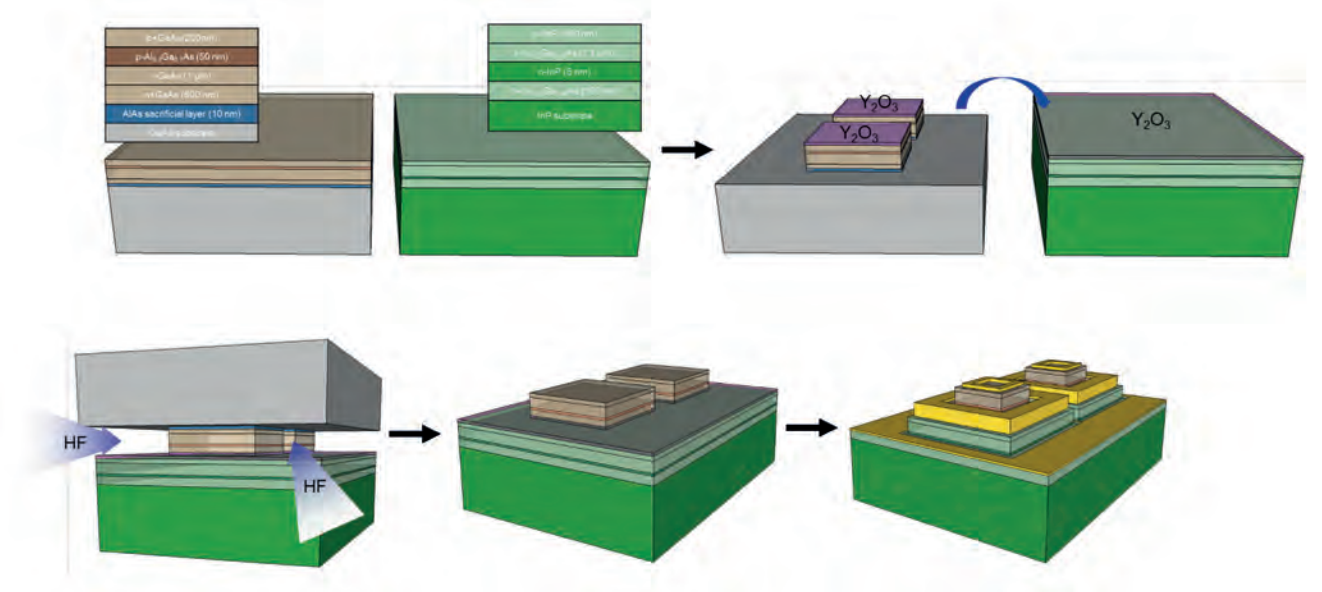


Figure 2. Process flow for multi-colour photodetectors made from GaAs and InGaAs using wafer bonding and an epitaxial lift-off process.

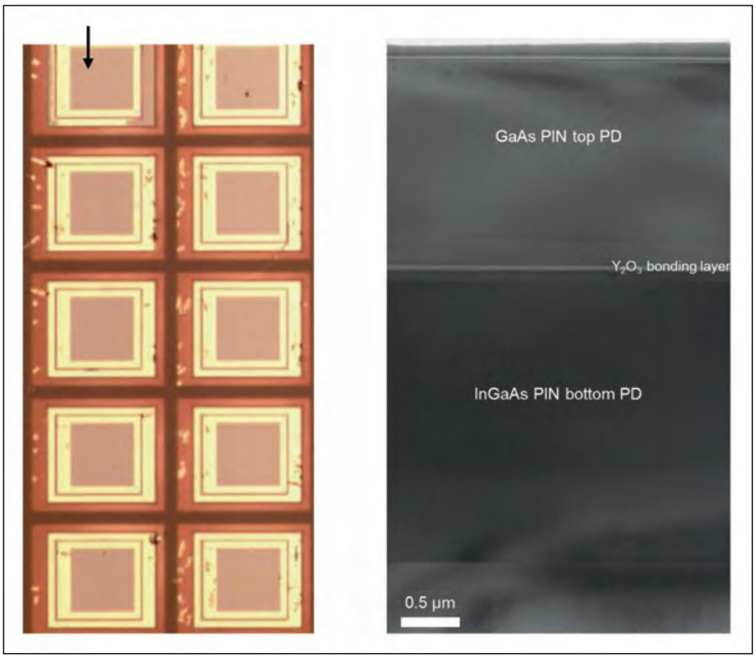


Figure 3. Photographic top-view image and cross-sectional transmission electron microscopy images of the fabricated stacked GaAs visible photodetector and infrared InGaAs photodetectors. These images reveal the good bonding, and also the high material quality after the bonding.

of *Compound Semiconductor* magazine). The two samples are then bonded together, and the resultant entity dipped in HF acid to separate the GaAs donor substrate from the stack of materials that contains the GaAs photodector, the InGaAs photodetector and the InP substrate. Finally, using standard semiconductor process technology, we undertake metal formation and mesa isolation.

Note that with our approach we form pixels after wafer bonding, using photolithography and etching. This allows us to use a small pitch, and create a high-resolution photodetector (see Figure 3 for microscopic top-view images of fabricated pixels). One of the merits of the multiple pixel array, formed by vertically stacking two photodetectors, is that it delivers twice the resolution of a conventional approach.

Scrutinising our structures with cross-sectional transmission electron microscopy highlights the good bonding quality and material quality between the layers made from GaAs, and those made from InGaAs. The quality of our stacked material is very high – it is nearly as good as the as-grown sample – and it leads to good electrical and optical performance for the fabricated photodetectors.

Optical performance

We have broken new ground by demonstrating vertically well-aligned, multi-colour photodetectors formed from typical semiconductor processes. They detect from 400 nm to 1650 nm, a range so broad that it cannot be realised with a single absorbing material (see Figure 4). Measurements of photoresponsivity show similar levels for GaAs and InGaAs photodetectors, highlighting the excellent match between this pair of materials.

The insulating Y_2O_3 film between the two photodetectors enables independent operation. Visible light is absorbed in the top GaAs photodetector, while infrared light passes through it and is absorbed in the bottom InGaAs photodetector. Simultaneous measurements from a single device, shown in Figure 5, demonstrate that we have made a promising step towards the fabrication of a high-resolution, multi-colour imager, formed from high-quality III-V light absorbing layers.

Our next goal, the fabrication of imagers, requires

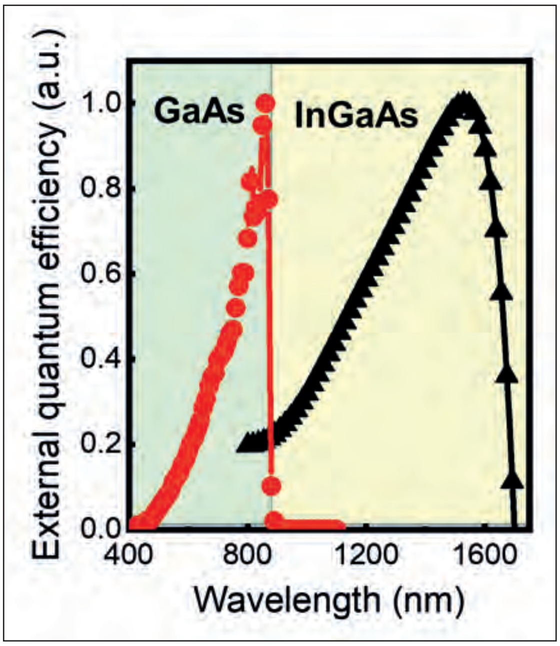


Figure 4. The external quantum efficiency of the fabricated multi-colour photodetectors, highlighting very broad band absorption from 400 nm to 1650 nm.

> We have broken new ground by demonstrating vertically well-aligned, multi-colour photodetectors formed from typical semiconductor processes. They detect from 400 nm to 1650 nm, a range so broad that it cannot be realised with a single absorbing material

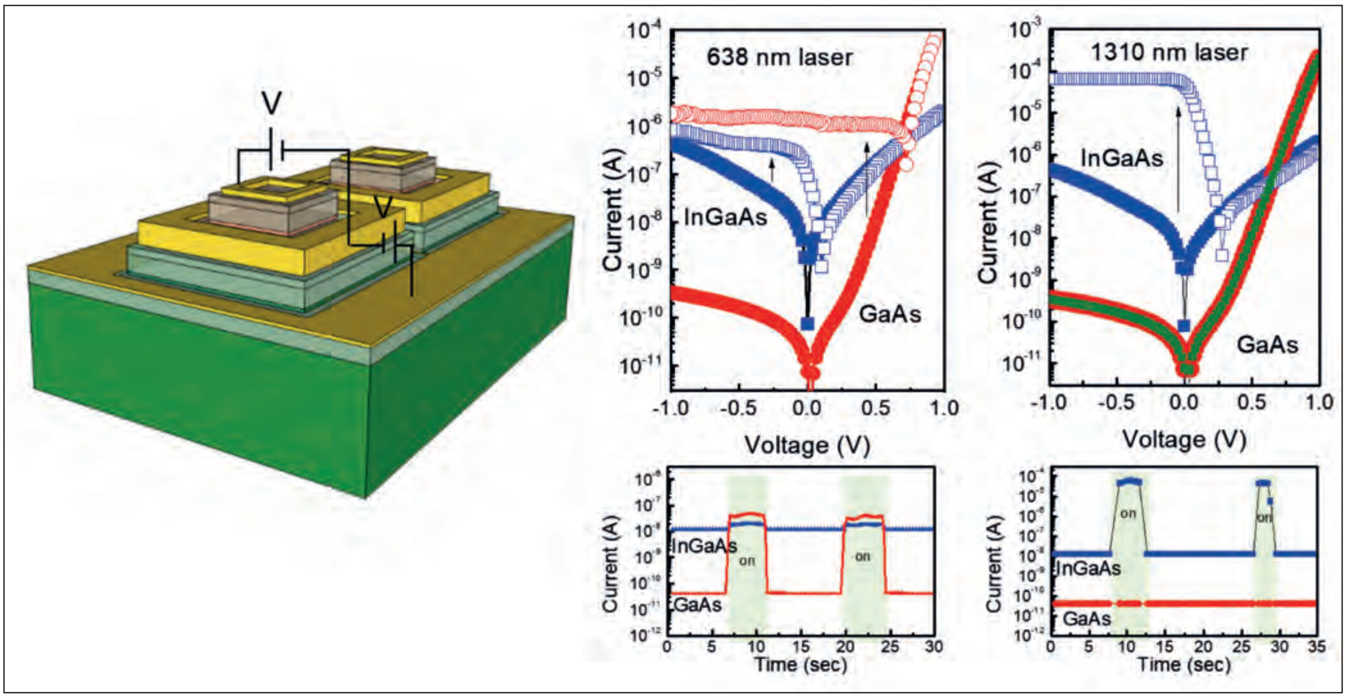


Figure 5. An illustration of the stacked multi-colour photodetectors, and plots of the photoresponse of photodetectors to visible and infrared excitation

the hybrid integration of photodetectors with readout integrated circuits (ROICs).

Often the integration is accomplished with indium bump bonding. This is quite a complicated process that includes thick indium deposition, reflow, flip chip bonding, and epoxy underfill. What's more, it involves mechanical alignment between III-V imagers and ROICs, limiting pixel resolution.

We are pursuing a slightly different approach to integrating multi-colour imagers on ROICs. After forming the ROICs, our intention is to bond the first absorbing materials and then the second absorbing materials, processing them using mesa formation, metallization and so on. With this approach, we can draw on the benefits of lithography, which delivers the very precise alignment needed to form high resolution pixels.
Our efforts have enabled us to make great progress towards the fabrication of multi-colour photodetectors. Combining light absorbing layers of GaAs and InGaAs by wafer bonding offers many advantages over conventional integration methods, including good material quality, CMOS process compatibility, precise alignment accuracy between pixels, and simultaneous broad band detection.

When we realise our next milestone, the fabrication of high resolution, multi-colour imagers, our success will open up many new markets. That's because there is a tremendous opportunity to develop many promising applications enabled by our technology, such as artificial vision sensors with coloured image recognition functions.

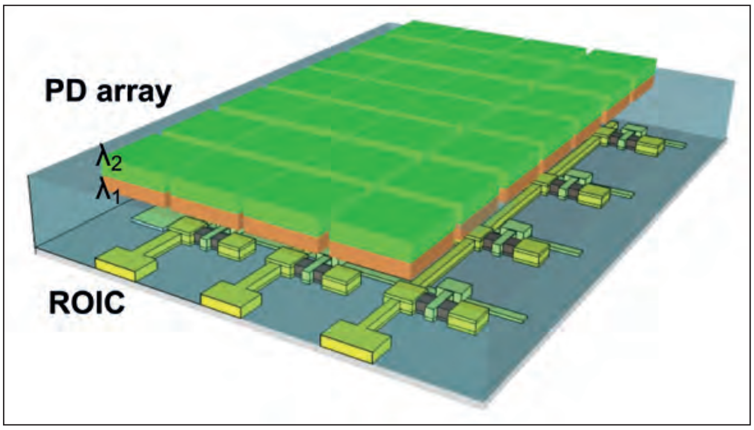


Figure 6. A potential integration method for making multi-colour photodetectors on ROICs.

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Enhancing silicon photonics with III-Vs and barium titanate

Heterogeneous co-integration of barium titanate and III-V semiconductors on a silicon photonics platform enables efficient optical transceivers and novel neuromorphic devices

BY PASCAL STARK AND BERT JAN OFFREIN FROM IBM RESEARCH EUROPE AND STEFAN ABEL FROM LUMIPHASE AG

RECENTLY GLOBAL DATA TRAFFIC has been increasing at a compound annual growth rate of more than 25 percent. Due to this exponential rise, worldwide data traffic is tipped to reach 400 Exabytes per month in 2022. To cope with this hike in growth, which shows no sign of slowing, there needs to be a rapid scale-up in data transmission capacity and speed.

The lion's share of the traffic occurs within datacentres, where data is routed through optical fibres over distances from a few metres to a few kilometres. Inserted at the interfaces between optical fibres and the electronic domain, involving computing and routing units, are high-speed optical transceivers (see Figure 1) – they are the most critical element in optical communication links.

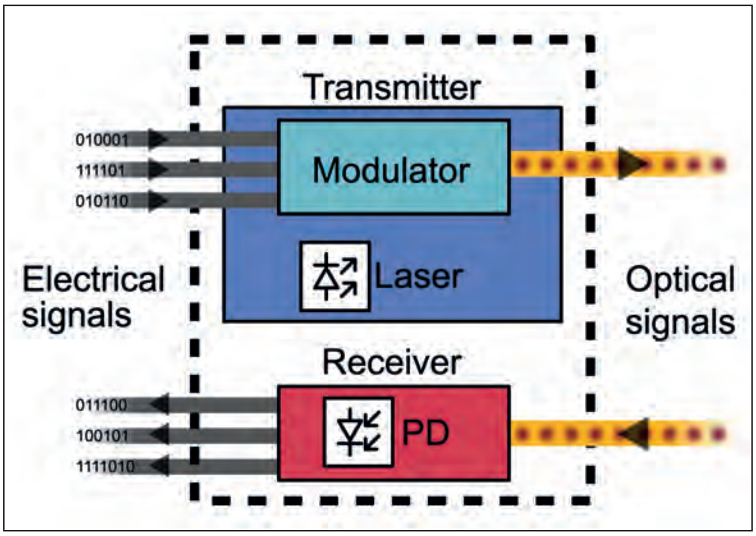

Figure 1. An optical transceiver provides an interface between electrical and optical communication channels. The transmitter converts electrical signals into optical signals. Vice-verse, the receiver is used to convert optical signals into electrical signals.

There are two parts to the optical transceiver: the transmitter and the receiver. The transmitter contains a high-speed electro-optical modulator, which encodes input signals onto an optical carrier by a continuous-wave laser diode. After encoding, the optical signal is transmitted over an optical fibre. When the optical signals reach the transceiver, they are converted from the optical domain to the electrical domain with a photodetector.

Our team at IBM Research Europe has been pioneering a platform that paves the way to compact, high-bandwidth, power-efficient optical transceivers. At the heart of our technology is the co-integration of barium titanate (BTO), selected for its extremely strong electro-optic switching properties, with ultra-thin III-V technology, which provides a gain material for light emission, on a single silicon photonics platform. Lumiphase further develops such efficient switching products based on BTO photonic technology for commercial exploitation.

Here we detail how we integrate these different functional materials onto a silicon photonics platform. To fully unleash the functionality of all the layers, we have taken much care to ensure that we transfer light with low loss between different photonic layers. Efforts have also been directed at developing devices for potential applications such as optical transceivers and novel neuromorphic photonic architectures.

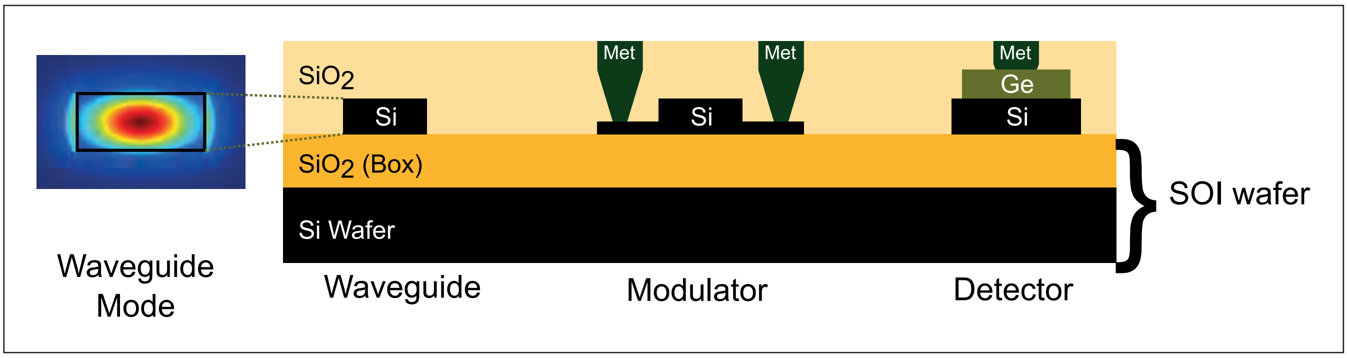

Figure 2. A silicon photonics platform with a waveguide, electro-optic modulator and germanium photodetector. Devices are fabricated on a silicon-on-insulator wafer (SOI). The waveguide mode shows the electric field intensity (red depicts high intensity, blue is for low intensity) in the waveguide (black box).

Silicon photonics: power and flexibility

The foundation for our work is silicon photonics. It offers efficient routing, manipulation, detection and modulation of light at telecommunication wavelengths, which span the range 1.3 µm to 1.55 µm. Today, silicon photonics is a mature photonic integrated circuit (PIC) technology, suitable for high-volume, low-cost production in CMOS foundries. Most commercial platforms are limited to the integration of PICs with optical components, such as waveguides, modulators and detectors, but also approaches to combine electronic and photonic integrated circuits (EPICs) are being developed. These approaches bring on-board electronic circuits, such as drivers, amplifiers, or control electronics, monolithically co-integrated with photonic components. Our technology is compatible with both PIC and EPIC platforms.

Silicon photonics is based on guiding light in silicon waveguides clad by SiO_2. Manufacturing this technology in state-of-the-art processing facilities enables the production of waveguides with propagation losses below 1 dB/cm. Due to the high refractive index contrast between silicon and its native oxide, light is well confined in the waveguides, enabling the realisation of low-loss bends with radii below 10 µm. In addition to waveguides, there are many other passive building blocks in silicon photonic circuits, including: splitters and combiners; low-loss waveguide crossings; tapers; reflectors, which may be based on Bragg gratings; and Echelle gratings. Thanks to many years of research and development, various structures have been established, including passive filters that provide wavelength multiplexing and demultiplexing on photonic chips.

It is also possible to produce some active components with silicon photonics. One example is the electro-optic modulators based on the plasma dispersion effect in silicon. Injecting or depleting carriers creates an electrically induced change in the refractive index. Instead of solely changing the real part of the refractive index, there is also a shift in the imaginary part, due to the plasma dispersion effect. As designers of advanced modulators do not welcome this change in absorption, it must be avoided to boost the performance of future generations of silicon photonic modulators.

Two of the biggest drawbacks of silicon are that it cannot emit light; and that it is transparent at telecommunication wavelengths, making it unsuitable for efficient high-speed photodetectors. To equip circuits with these functionalities, direct-bandgap materials such as III-Vs are co-integrated with silicon. The most common approach for light detection is to add germanium, integrating this on silicon waveguides used for advanced photodetection. Far more challenging is the monolithic integration of the light source.

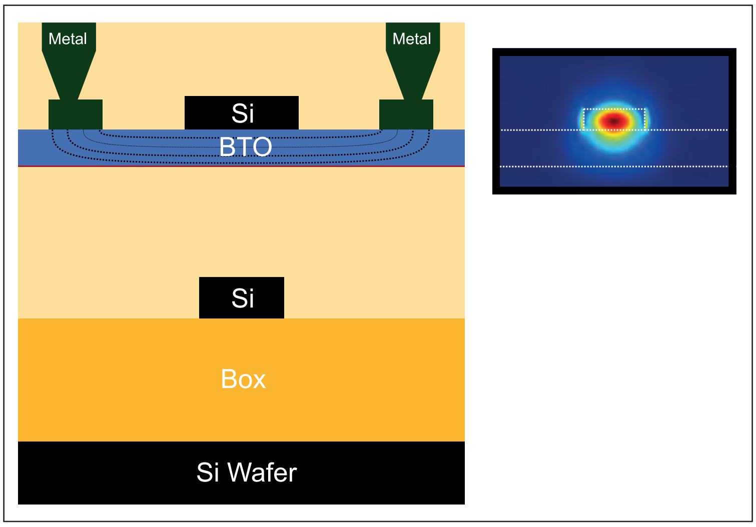

Figure 3. Cross section of a hybrid BTO/silicon device integrated on a silicon photonics platform. The refractive index of the BTO film (blue layer) can be tuned by applying an electric field (dotted lines). The inset shows the electrical field intensity of the optical mode in a hybrid silicon/BTO device. A large fraction of the optical power overlaps with the barium titanate film.

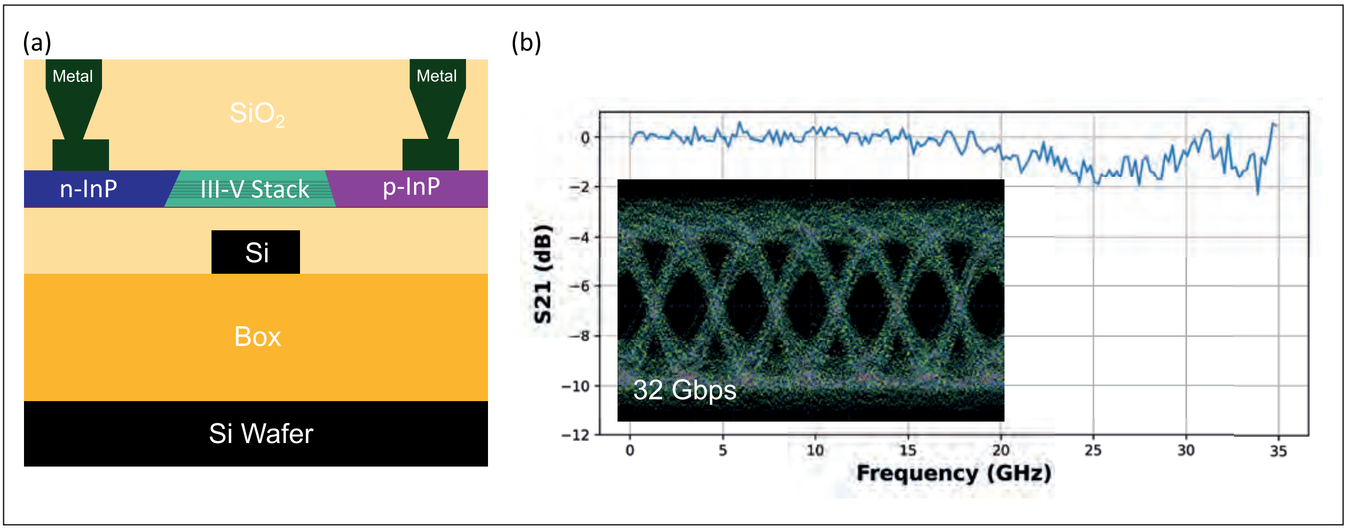

Figure 4. (a) Ultra-thin, CMOS compatible III-V integration on a silicon photonics platform. (b) Frequency response of a III-V photodetector. The inset shows an eye-diagram of the detector operated at 32 Gbit/s (NRZ signal) without using digital signal processing.

Roles for barium titanate and III-Vs

A novel material for improving the performance of silicon photonics is the ferroelectric oxide barium titanate (BTO). It is blessed with one of the largest known Pockels coefficients – this means that it produces one of the most significant changes in refractive index upon application of an electric field. Additional merits of the Pockels effect in BTO are that the refractive index changes are ultra-fast, its static power consumption is extremely low, and it tunes purely the real part of the refractive index, without any absorption.

Exploiting all these strengths enables the construction of ultra-small, energy-efficient, fast modulators, optical switches, and tuning elements, operating by modulating the phase of an optical wave but not its amplitude. Note that there is no Pockels effect in silicon and realizing these functions directly in silicon through the plasma dispersion effect leads to much less favourable properties.

We integrate BTO by loading large silicon-on-insulator (SOI) substrates into an MBE chamber and epitaxially growing a thin film of this oxide. Subsequent low-temperature molecular wafer-bonding allows us to transfer the BTO films to a silicon photonics wafer. By limiting the thermal budget, we ensure that the integration of BTO is compatible with CMOS foundry processes, enabling co-integration with CMOS circuits. That is a major asset for high-speed applications, because monolithic co-integration limits unwanted capacitive effects.

The next step in the fabrication process involves the etching of silicon waveguides into the silicon film on top of the BTO to create hybrid silicon/BTO devices (see Figure 3). The etched silicon waveguide guides the light, while a large fraction of the optical power overlaps with the underlying BTO film. Using this architecture, we have constructed Mach-Zehnder interferometers that offer efficient modulation and provide an excellent value for the figure of merit known as $V_\pi L$ – it is 0.2 Vcm, which is about one order of magnitude smaller than a typical silicon photonic modulator based on the plasma dispersion effect. As BTO modulators are field driven, they can also be used as low-loss switches, requiring a switching power of only about 100 nW.

As regular readers of this magazine know, III-Vs have been used for several decades to make high-performance lasers, as well as excellent photodetectors with bandwidths reaching more than 100 GHz. One option for integrating III-Vs with silicon is to employ the wafer bonding technique used to incorporate BTO films. However, today's III-V stacks are often relatively thick, making them incompatible with the CMOS/silicon photonics process.

To use wafer bonding, III-Vs would have to be integrated on a CMOS/silicon photonics wafer in a dedicated fabrication line after completion of CMOS/silicon photonics processing. This effectively rules out direct co-integration with CMOS circuits.

To overcome this limitation we have been exploring the use of an ultra-thin hybrid III-V platform that is fully CMOS compatible. This approach involves lateral injection or collection of carriers in and out of the multi-quantum-well stack. Using ultra-thin stacks, we have built III-V photodetectors with a large bandwidth on a silicon photonics wafer (see Figure 4).

Creating co-integration

Each of the materials that we use has its particular strengths. Silicon holds the key to low-cost photonic circuits, BTO brings efficient modulation, and III-Vs offer efficient light emission and detection. To bring

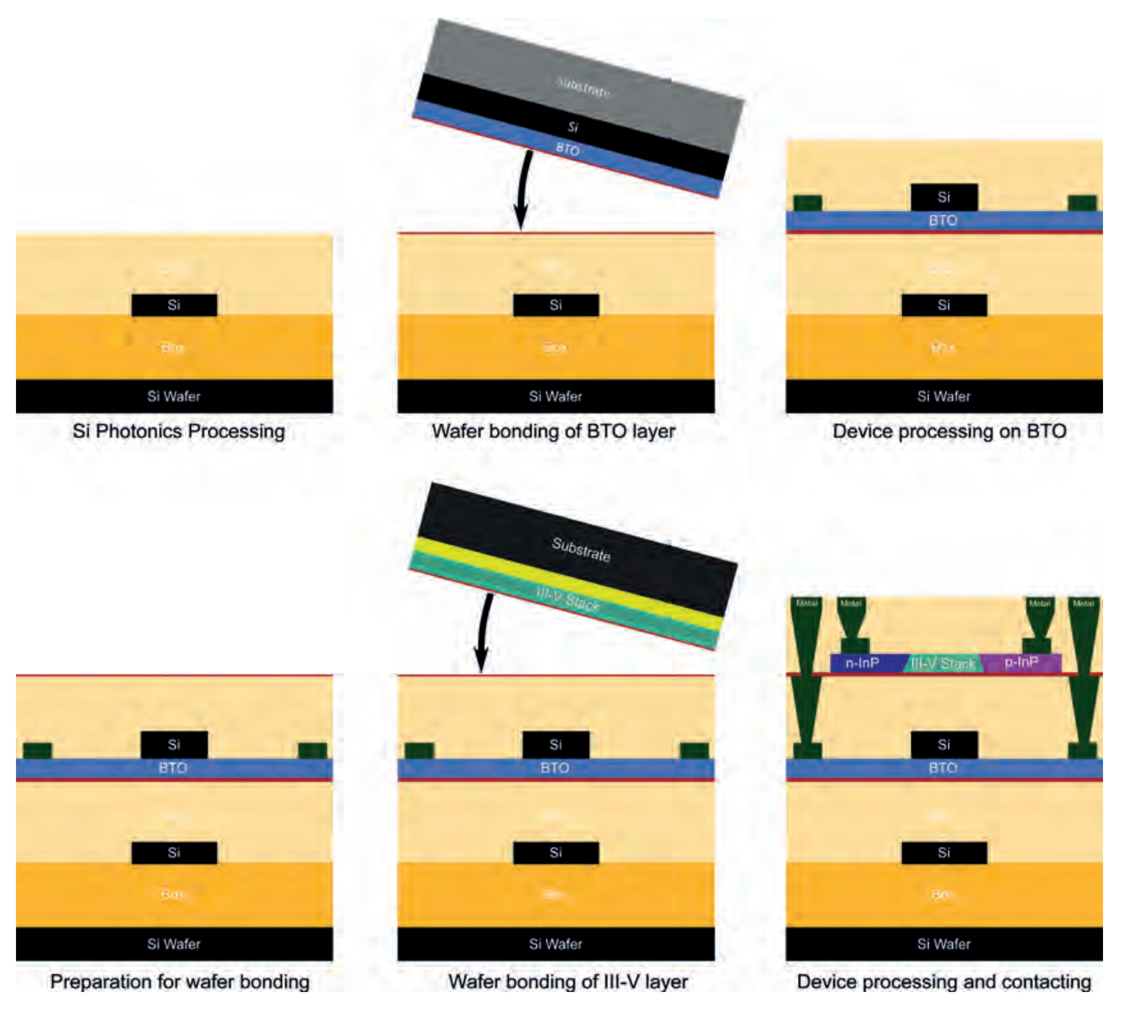

Figure 5. Co-integration of BTO/silicon and III-V technology on a silicon photonics wafer involves the following steps: (1) Processing a silicon photonics wafer and depositing a thin SiO_2 layer on it. Preparing the SiO_2 surface for molecular wafer bonding by chemical mechanical polishing (CMP). (2) Using molecular wafer bonding to integrate a BTO/silicon film on top of the silicon photonics wafer. (3) Defining devices on the BTO/silicon layer. (4) As in step 2, depositing a thin SiO_2 layer and preparing its surface for molecular wafer bonding. (5) Using molecular wafer bonding to integrate a III-V layer on top of the stack. (6) Processing devices in the III-V layer and contacting devices in both co-integrated layers.

them all together in a single photonics platform we begin by fabricating a silicon photonic wafer with a planarized top surface, before transferring a single-crystal BTO layer onto the planarized surface and defining waveguides. Final steps involve bonding a III-V photonic layer, and subsequent processing to create active/passive devices (see Figure 5 for details).

To leverage the benefits from all three classes of material, we use waveguide tapers to ensure a low optical loss when transferring light between the layers. The efficiency of these tapers is enhanced by employing an inverse direction on neighbouring layers. For example, to couple light from the silicon photonics layer to the BTO/silicon layer, we slowly decrease the width of the silicon photonics waveguide (taper down) while increasing the width of the BTO/silicon waveguide width (taper up).

Reducing the silicon waveguide width leads to a decrease in the effective optical mode index and an increase in the mode size along the waveguide taper. This goes hand-in-hand with increasing the width of the BTO/silicon waveguide, which increases the effective mode index in the BTO/silicon waveguide.

As both waveguides are separated by only a thin SiO_2 cladding, there is a small overlap between the silicon and BTO/silicon modes. This overlap propels the optical mode towards the region where the effective mode index is the largest. Consequently, the mode in the silicon waveguide is first converted into a hybrid mode propagating in both the silicon and BTO/silicon waveguides, prior to full transfer to the BTO/silicon layer. This process is incredibly efficient, allowing nearly 100 percent of the light to be transferred from the lower to the upper layer.

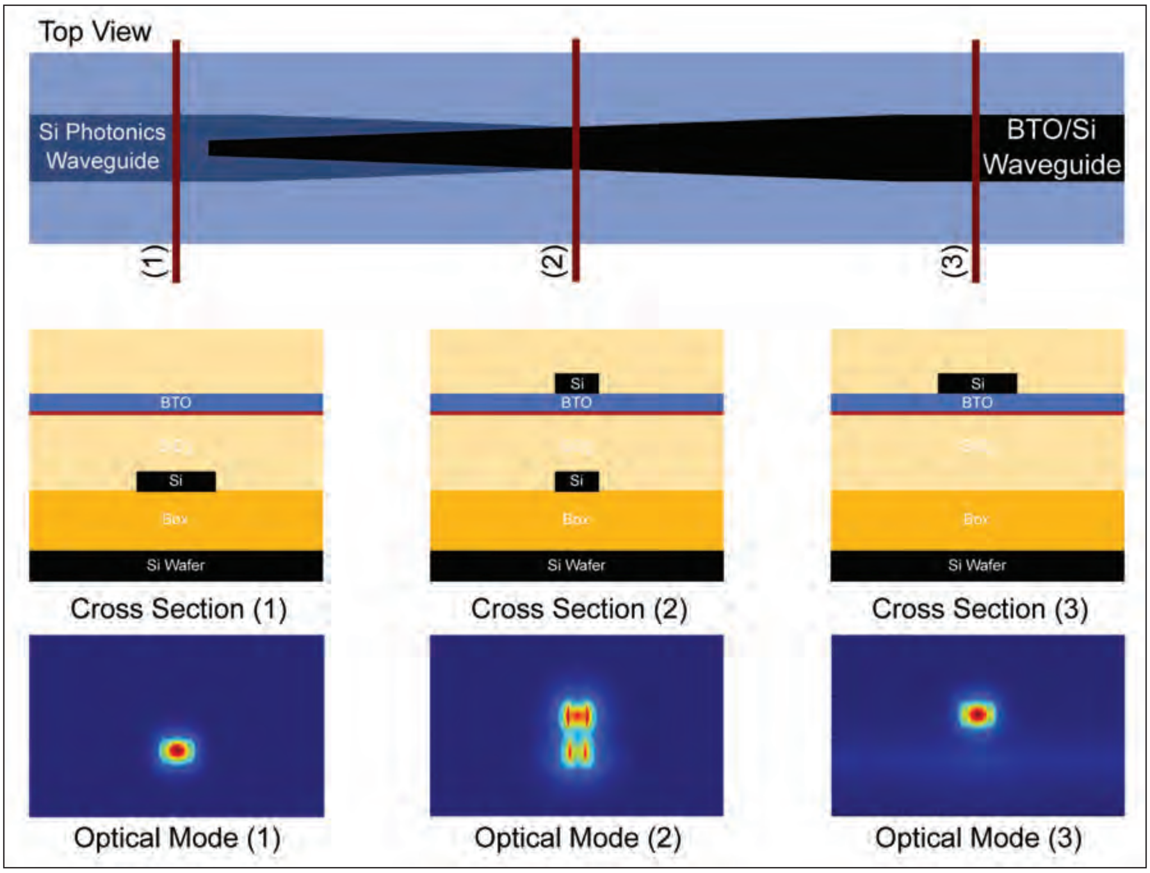

Figure 6. Inverse tapers on consecutive layers couple light between the layers. Shown here is a top view and corresponding cross sections and optical modes along a coupler between silicon and BTO/silicon. The mode is first guided in the silicon photonics waveguide. In the tapered section the mode converts into a hybrid mode, before it transfers to the BTO/silicon waveguide.

We have formed co-integrated structures by combining silicon photonic devices, formed on a 220 nm-thick layer of silicon sitting on 2 μm-thick buried oxide, with a BTO/silicon stack containing 100 nm-thick BTO and an intrinsic 250 nm-thick InP layer. Our entity features passive photonic elements on all photonic layers, demonstrating the simple building blocks of our concept. If we were to include active components, they would be realised with a similar process flow.

Within this structure, a low-loss intrinsic InP layer provides the III-V material stack. InP could act as a potential seed layer for subsequent III-V growth steps required for active III-V devices. This demonstrator, made using the process steps described previously, showcases successful co-integration of all the materials, with separate silicon, BTO/silicon and InP waveguides on different layers (see Figure 7).

We have extracted the coupling loss between the different layers using structures with a varying number of interlayer coupler pairs. To ensure waveguide propagation losses are identical, we kept the total waveguide length in each layer constant for all measurements. That allowed us to extract separate coupling losses for the coupler between silicon and BTO/silicon, and that between BTO/silicon and InP. For these couplers, both based on linear tapers, coupling losses were 0.48 dB and 0.34 dB, respectively. These values equate to power transmissions of 89.5 percent and 92.5 percent (see Figure 8).

Increasing coupling

This level of coupling is good enough for applications that require light to be transferred only a few times between the layers. But it is insufficient for optical transceivers or advanced photonic circuits. So we need to increase the coupling efficiency, a goal that can be met by addressing the two major loss mechanisms: the mode transfer loss, caused by the mode conversion between the waveguides; and propagation loss, attributed primarily to sidewall roughness.

One of the keys to increasing coupling is to optimise the length of the tapers. At first glance, a very long taper is ideal, providing a small mode transfer loss, due to slow mode conversion – in the best case this process can be virtually loss free. However, long tapers are not a panacea, because they lead to a larger propagation loss in the waveguides in the coupling region, and they occupy a larger chip area.

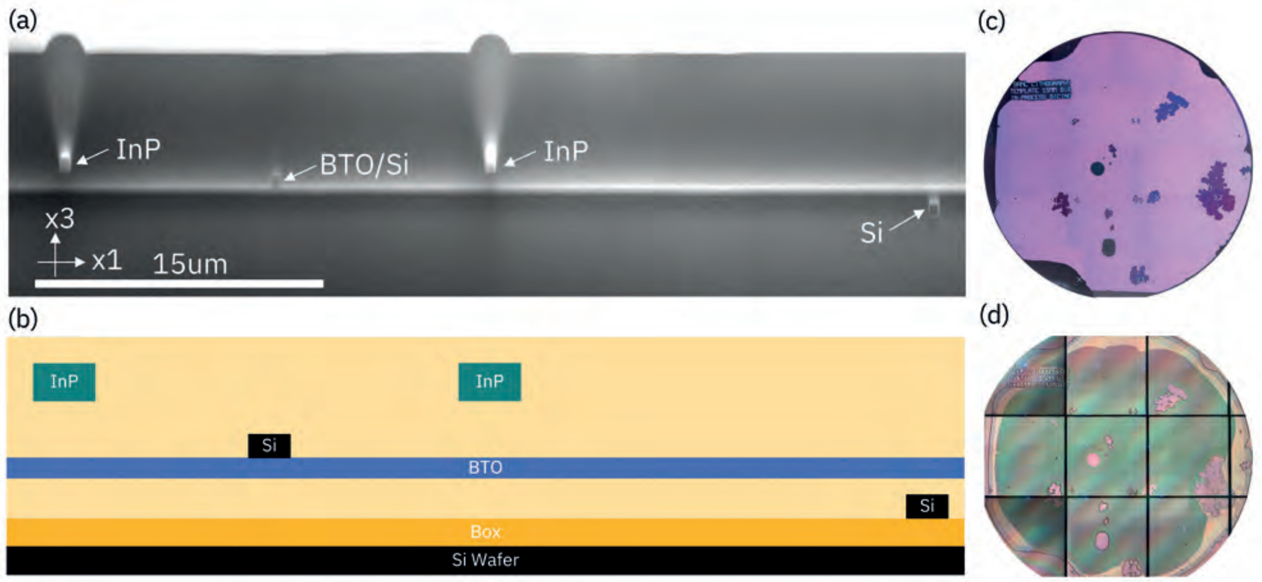

Figure 7. (a) and (b) Co-integrated waveguides in silicon, BTO/silicon and InP. (c) Wafer bonding of BTO/silicon (pink) on the silicon photonics acceptor wafer. Some defects, seen as dark areas, appeared during wafer bonding. (d) Wafer bonding of an InP layer (green colour) on top of the BTO/silicon layer. Defects in the BTO/silicon layer are transferred to the InP layer.

The sweet spot is the use of tapers that are as short as possible, but long enough to ensure that mode conversion is almost loss free. In our experiments, we have found that the coupling loss decreases with increasing coupler length (see Figure 8 (b)). This implies that we are yet to reach a taper length where propagation length dominates over mode transfer loss.

Coupling loss can be reduced even further by optimising the shape of the tapers. We have investigated this through simulation, considering optical modes in many equally distributed cross sections along the coupler structure (see Figure 9 (a)). Our studies consider the mode overlap between consecutive sections. When the mode overlap is large, the mode does not change much. However, when the overlap is small, there is a significant change in the mode field profile.

Based on these insights, mode transfer loss may be minimised by ensuring that the sections with a small mode overlap are longer, so that the mode field profile changes its shape slowly over the section length. On

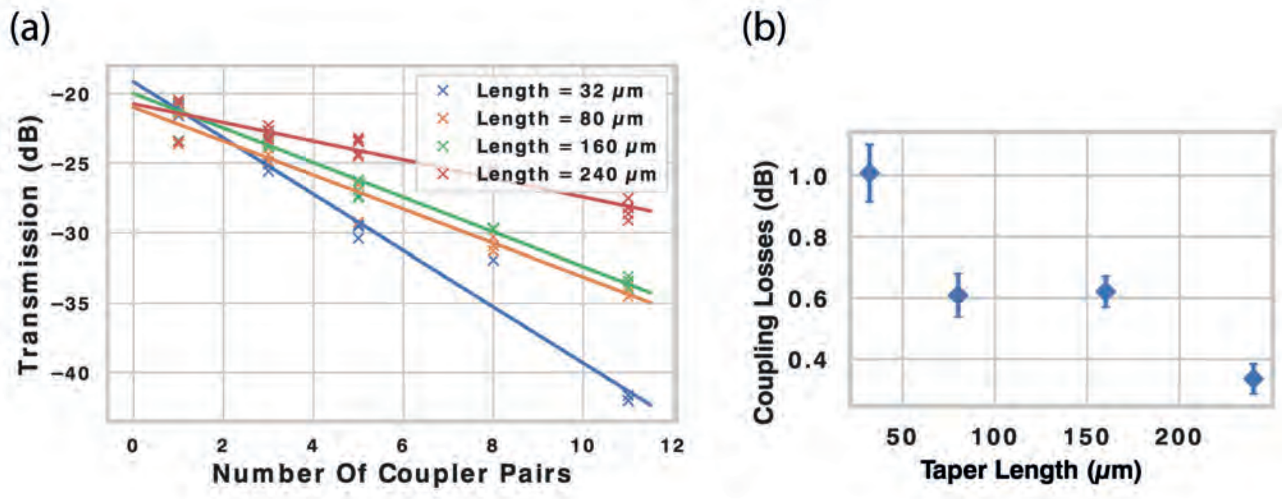

Figure 8. (a) Transmission as a function of the number of coupler pairs for different taper lengths for couplers between BTO/silicon and InP. (b) Coupling loss for BTO/silicon and InP couplers as a function of taper length

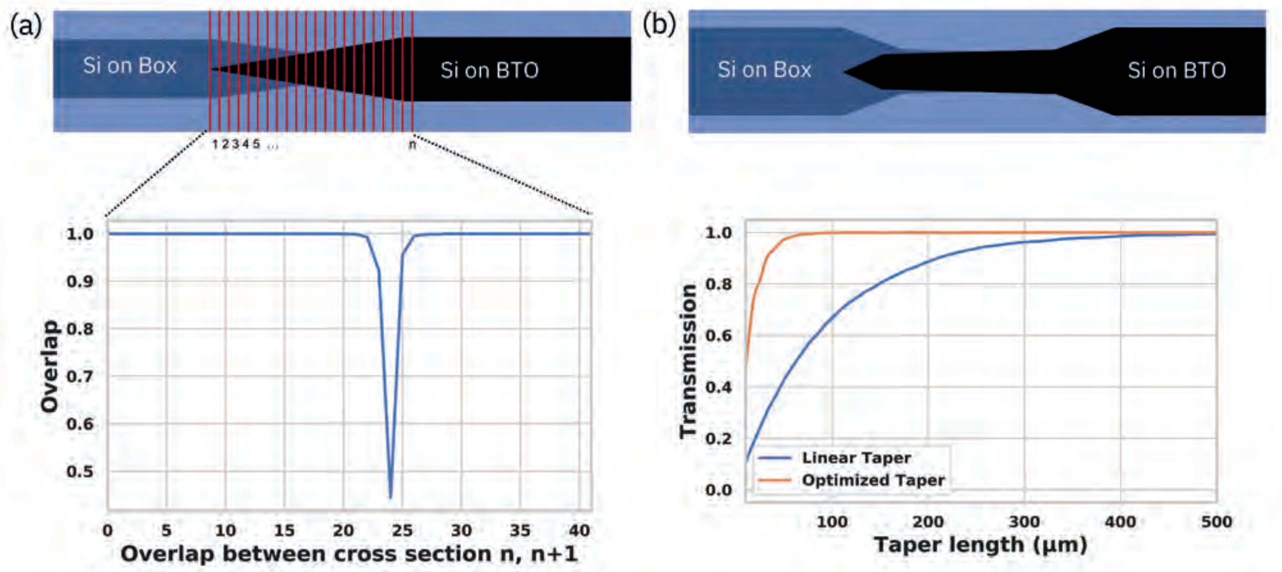

Figure 9.(a) Simulations of optical modes in 42 cross sections (red lines) along the taper. Mode overlap between consecutive sections were computed. (b) Simulated transmission for light coupling from silicon to a BTO/silicon layer as a function of taper length. A transmission value of 1 means that the mode is transferred without any loss. Using the optimised taper shape, a transmission exceeding 99.5 percent is realized for 90 μm-long tapers.

the other hand, sections with a large mode overlap can be shortened, helping to trim propagation loss.

Drawing on mode overlap calculations, we have designed a taper containing three linear sections with different taper slopes. Using Lumerical Mode simulation software, we have found that the mode transfer efficiency exceeds 99.5 percent for 90 μm-long optimised tapers. Switch to a linear taper, and a length of 500 μm is required to deliver a similar performance. Or, to put in another way, by adopting an optimized shape we can slash the length of our taper by a factor of six while maintaining the mode transfer efficiency.

Targeting applications

Data centres and long-haul communication systems are generating strong demand for fast optical transceivers that are power- and cost-efficient. Using our platform, we can form high-performance transceivers from efficient transmitters and receivers. Efficient transceivers are formed by generating continuous-wave optical signals with a III-V laser, subsequent modulation with a BTO/silicon electro-optical device, and turning to a silicon photonics platform to efficiently route, filter and multiplex the signals. If available, we can deploy electronic circuits for the integration of drivers for the laser and modulator. On the receiver side, we use a germanium-silicon photodetector – or, if we require a higher bandwidth, variants made with III-Vs. Here, the roles for silicon photonics circuits could include providing optical filters and demultiplexing circuits. In EPIC platforms, amplifiers and analogue-to-digital converter circuits might also be integrated.

It is clear to see that armed with a platform featuring multiple functional layers, it is possible to combine the strengths of the existing silicon photonic ecosystem with novel functionalities for modulation, emission, and detection. This expansion in functionality also opens the door to radically new fields of applications, such as optical neuromorphic computing. We

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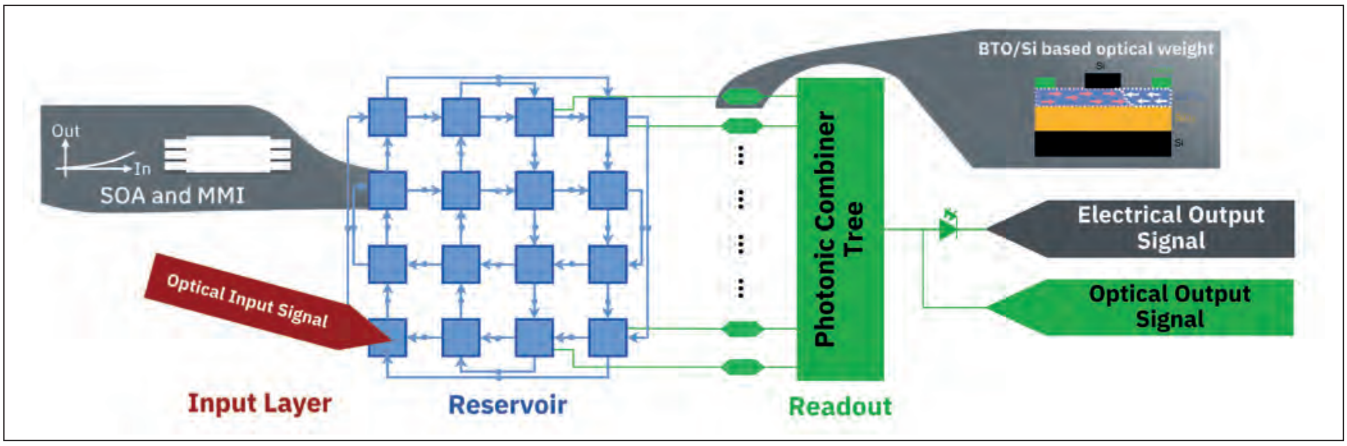

Figure 10. Concept for an all-optical reservoir computing system. Silicon photonics is used to route and mix signals between different nodes (blue squares). Semiconductor optical amplifiers (SOA) based on III-V technology provide a non-linear response at each node. Barium-titanate-based optical weights at the output of the reservoir tune signals, before they are united through a photonic combiner tree. The output signal is converted to the electrical domain using a III-V based photodetector.

have started to consider this opportunity, exploring integrated, all-optical reservoir computing systems based on our co-integration platform (Figure 10). These reservoir computing systems are a special type of neural network, in which only the synaptic weights at the output layer are trained, while weights within the network are random but fixed.

Realising such networks requires the building of various blocks that are not available in standard silicon photonics. They include ultra-compact optical non-linearity or non-volatile optical weights. The good news is that semiconductor optical amplifiers based on III-V technology provide the required non-linear optical response, while BTO/silicon switches, which store their state in the ferroelectric domain configuration of the BTO film, can be used to form non-volatile optical weights. Applying large electric pulses tunes the domain configuration, which is retained for up to several days after the state is set. Uses of optical reservoir computing systems include compensating fibre-optic dispersion and performing Boolean operations, prior to the conversion of optical signals into the electronic domain by a transceiver.

Our efforts have shown that by co-integrating BTO/silicon and III-V technology with silicon photonics we have created a very versatile photonic platform with novel optical building blocks. Results on this platform, featuring low-loss interlayer coupling, demonstrate for the first time the combination of three complementary but powerful technology platforms in a scalable, efficient manner. This multi-functional photonic platform enables not only efficient optical transceivers, but further exciting new applications, such as optical computing and signal processing.

○ We would like to thank Daniele Caimi, Felix Eltes, Yannick Baumgartner, Youri Popoff and Norbert Meier for their support for the fabrication of the coupling demonstrator. This project has received funding from the EU-H2020 research and innovation program under grants no. 688003 (DIMENSION), 688579 (PHRESCO) and 780997 (plaCMOS).

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PI´s fast alignment testing technology adds benefits of ACS controls

Fast, accurate and repeatable testing requirements have in the past impeded the rapid roll-out of photonic integrated circuits (PICs) and related components at cost-effective, high volume scale. Physik Instrumente has pioneered fast optimization technology and has added new algorithms and alignment-enabled controls from ACS to achieve productivity gains for large-format optic and photonic production processes.

BY SCOTT JORDAN, HEAD OF PHOTONICS; SENIOR DIRECTOR, NANOAUTOMATION; PI FELLOW, PI (PHYSIK INSTRUMENTE)

PHYSIK INSTRUMENTE'S (PI's) fast optimization technology has proven to dramatically improve production economics in processes as diverse as photonics wafer probing, device packaging, and chip testing and even laser and optical equipment manufacturing. The combination of speed, nanoscale performance and industrial robustness is reducing costs and improving yield worldwide.

Now the flexible combination of PI´s industrial stages and new alignment-enabled controls from ACS address additional tough throughput and yield challenges for photonics production. Large-format production processes can now be addressed, with each mechanism contributing intelligent alignment for test and assembly. This opens new possibilities for hyper-efficient systems architectures.

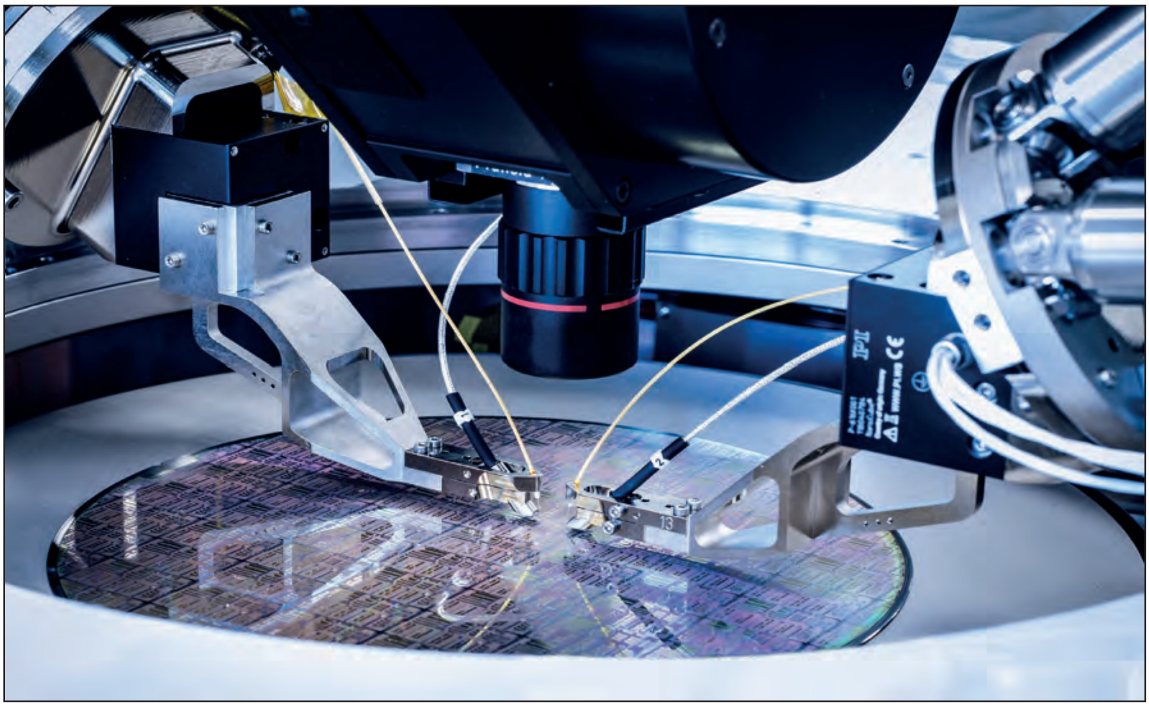


Image 1: The double sided fiber alignment systems from PI enables simultaneous positioning of input and output fibers for chip testing and wafer probing. (PI image)

PI's unique optimization functionality is firmware-based, offers the unique option of parallel alignment across multiple inputs, outputs and degrees-of-freedom, and can improve process throughput by a factor of 100 or more compared to legacy approaches.

Background

Alignment automation emerged three decades ago. In an era dominated by single-mode pigtailing applications, it was an enabler that helped eliminate costly manual submicron-alignment processes during device test and assembly.

The photonics world has advanced, though. Wafer-based photonics now drives the industry. Adoption volumes are orders of magnitude higher than in the 1997-2001 photonics boom, and the devices are quite different.

For example, multiple I/Os necessitating multiple degree-of-freedom optimization, with each coupling frequently presenting non-Gaussian multimode cross-sections and interactions across channels, inputs and outputs, and DoFs. While these challenges can often be met with legacy alignment techniques, the minutes-scale times required present serious challenges for production economics.

PI's unique, fifth-generation optimization technology, now well-proven in the field after its 2016 introduction, allows simultaneous alignment across channels, I/Os and DoFs, even when they interact due to optical or geometric crosstalk. The throughput improvement of this parallelism can often exceed a factor of 100, as PI routinely demonstrates in live demonstrations at conferences. So, for example, an array-device alignment that previously took a few minutes can often now be achieved in a second or less.

PI's first implementations of this technology were in fast piezo stages and hexapods. Now its key functionality has been extended to ACS controls, bringing the benefits of ground-breaking productivity to large-format applications as diverse as photonics wafer probing, device packaging, and chip testing and even laser and optical equipment manufacturing.

Moreover, the algorithms offer seamless compatibility with today's photonic devices, which often prove challenging for legacy approaches. For example, there is no implicit assumption of circular symmetry embedded in the algorithms. That posed no issues in 1997, but can be highly sub-optimal for latter-day photonic devices. It can practically be stated that these systems can virtually "optimize anything," which is definitely not the case for the decades-old approaches still commonly offered.

Deeper Dive

Two alignment techniques are most useful today: area scans, and gradient searches for fast optimization and tracking.

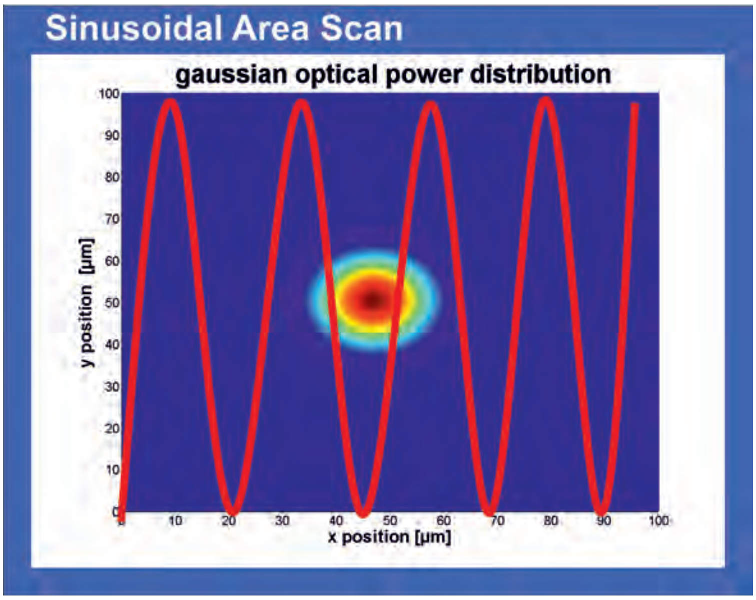


Image 2: In the case of the sinusoidal scan routine the defined surface is scanned continuously without vibration-inducing acceleration or deceleration phases. Surface, starting point, line distance, and success criteria can be defined by the user. (PI image)

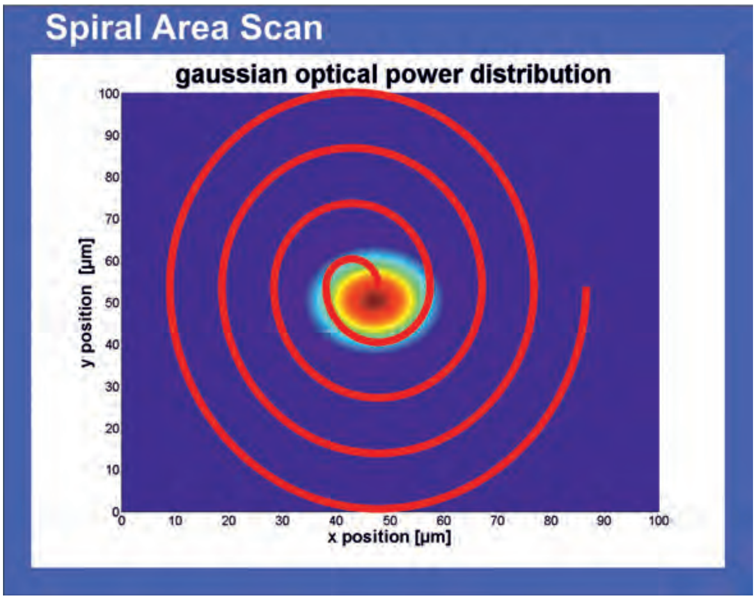


Image 3: In the case of the spiral scan routine, a defined area is scanned helically, whereby either a constant angle or a constant path velocity is maintained. Its selectable operating frequency helps to avoid system resonances. (PI image)

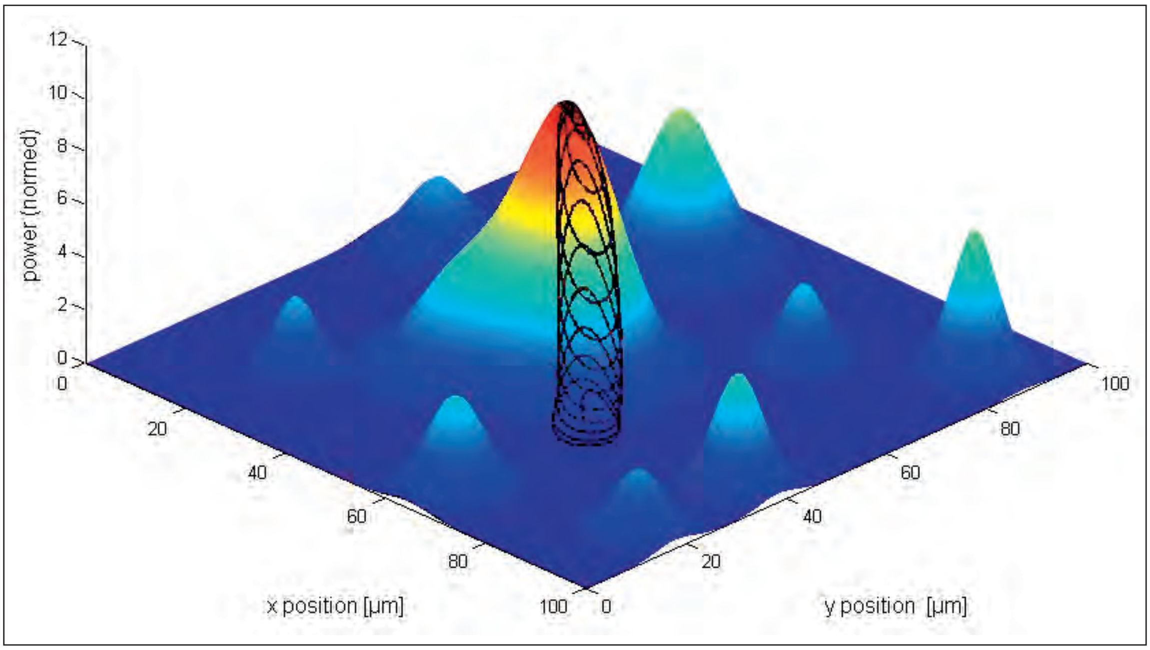


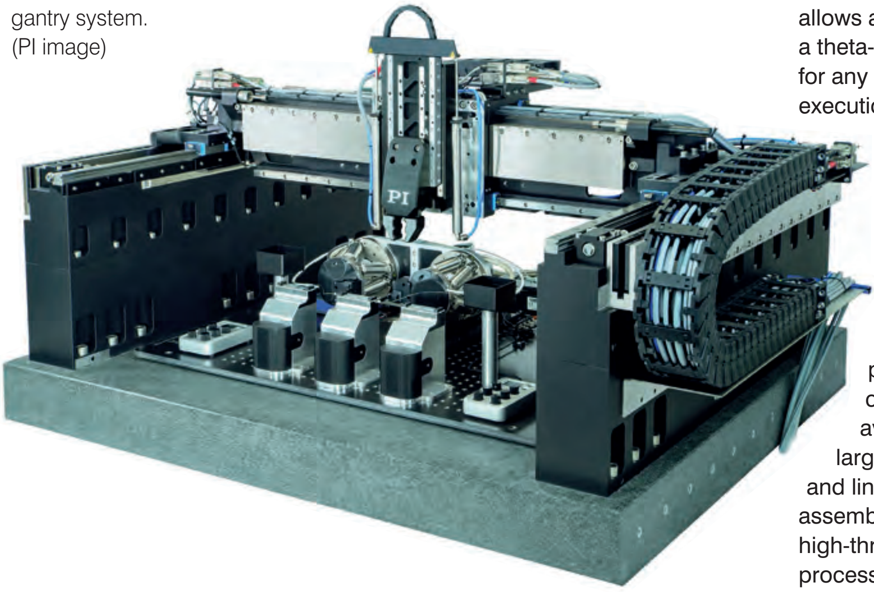
Image 4: Ground-breaking results can be achieved with the unique implementation of the gradient search algorithm. If the light signal is present, this gradient search makes it possible to find the signal maximum in typically less than 1 second. (PI image)

Area Scans

A good example of a legacy approach to an area scan is a classical raster or serpentine scan, which sweeps one axis, then increments its orthogonal axis, and repeats until the area is covered. Variations on this theme are common, including stepwise hill-climbs. But these approaches pose fundamental issues today. The stopping-and-starting adds settling time and causes vibration throughout the system, and the linear acquisitions can lead the system to actually de-align in common situations of asymmetric coupling profiles.

By comparison, PI's firmware-based area scans use smooth, continuous sinusoidal and spiral patterns of selectable frequency. System resonances can easily be avoided, allowing the non-stop scan to proceed without vibration. The result is considerably higher speed. Add built-in modelling in some controllers, and the system can determine the peak (or even the centroid of a top-hat coupling) with good accuracy and speeds down to a few hundred milliseconds.

Image 5: Example of an automation subsystem for multi-channel automated photonic-device assembly tools, based on the proven double-sided F -712 HA2 alignment system and PI´s multi-axis gantry system. (PI image)



Gradient Search

The digital gradient search was first developed in 1987 and, until now, has been mostly unchanged in its implementation through four subtle generations of the technology. A small, circular motion causes the coupling signal (or other figure-of- merit) to vary, and this variation can be analyzed in phase and amplitude to determine the instantaneous gradient. This allows a fast and direct path to optimum, with tracking possible for appropriate mechanisms.

PI's radical fifth-generation approach builds on this classical foundation to enable multiple gradient searches to proceed in parallel. For example, this allows an XY lock-on to be performed at the same time a theta-Z optimization runs – an essential combination for any array-device alignment. This fast, parallel execution replaces the time-consuming iterative loop of separate XY and theta-Z alignments that was formerly required. One step, instead of dozens.

Breakthrough

Since 2016, firmware-based fast-area scan, gradient search, and parallel gradient search technologies have been implemented in PI's powerful piezo nanopositioner and hexapod controllers. Now fast alignment functionality is available for ACS controls. Combined with PI's large industrial stages (including spindle-driven and linear-motor stages, gantries and air-bearing assemblies), this forms a foundation for especially high-throughput applications involving large-area processing, such as when devices are processed in

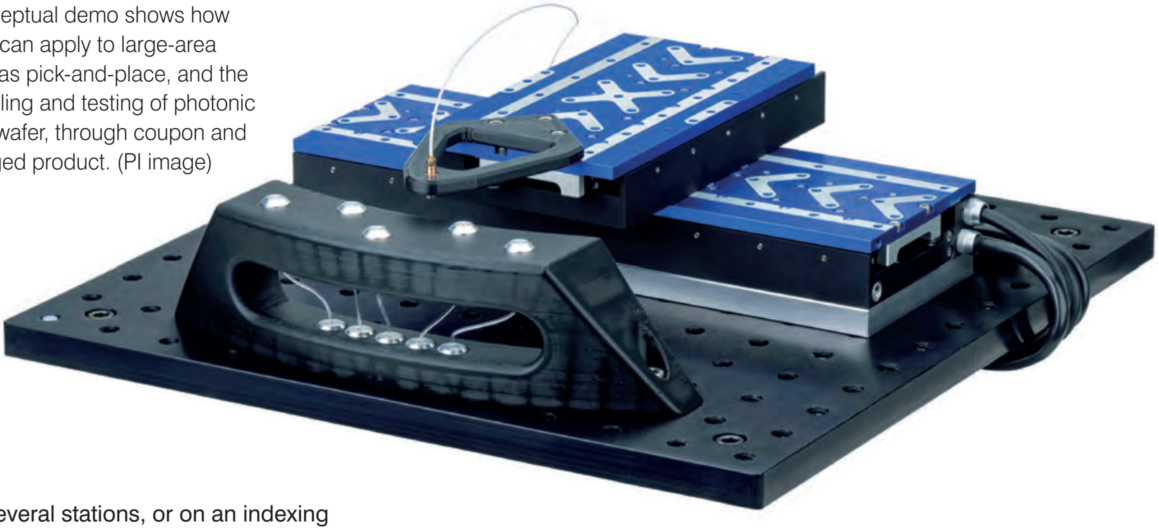


Image 6: This conceptual demo shows how PI's fast alignment can apply to large-area applications, such as pick-and-place, and the screening, assembling and testing of photonic devices. From the wafer, through coupon and chip, to the packaged product. (PI image)

trays, or across several stations, or on an indexing platform or conveyor.

ACS controls lead the industry in modularity and performance. Based on an EtherCAT open, distributed architecture, they support absolute encoders, minimizing system start up times, easing initialization approaches and reducing collision risks. ACS' yaw control (combined with PI's highly optimized joint construction) provides industry-leading orthogonality correction and minimizes risk of axis binding – a distressingly common issue for older architectures. True MIMO gantry control plus dynamic cross-axis control yields uniform performance over the gantry area, eliminating grid-based approximation methods and their consequent lowest.

common-denominator approach to tuning over large areas. Together, these mean higher performance and reproducibility in application.

These benefits come with PI's and ACS' rich offering of global support options, ranging from on-site Quick Start and training, to extended warranties and service plans, to consulting and co-engineering, to application and software consultation and quick-port approaches for key transiting from other architectures.

Summary

Photonics today is serious business, with a rapid rate of innovation and broad adoption by important semiconductor and networking players. Manufacturing and testing these devices demands flexibility and high performance from production systems and tooling.

Multiple studies have spotlighted alignment time as the highest cost contributor to photonic device fabrication, both from the lengthy process times formerly required and from the repeating requirement for alignment throughout the production process. PI's revolutionary fast alignment technology is unmatched for meeting these challenges, and now it is deployed in large-area mechanisms based on a modular, open-architecture approach ideal for systems integration and tooling platforms.

About the Author

Scott Jordan is head of the photonics market segment in the globally active PI Group, and a PI Fellow. He lives in Silicon Valley and has been with PI for over 20 years. Scott was active as Director of NanoAutomation Technologies and made a decisive contribution to continued technological development of the company. A physicist with an MBA in Finance/New Ventures, Scott is well known in the community for his passion and engagement.

PI

About Physik Instrumente L.P.

Physik Instrumente L.P. (PI) is a leading manufacturer of nanopositioning, linear actuators and precision motion-control equipment for photonics, nanotechnology, semiconductor and life science applications. PI has been developing and manufacturing standard and custom precision products with piezoelectric and electromagnetic drives for over 40 years.

By acquiring the majority shares in ACS Motion Control, a worldwide leading developer and manufacturer of modular motion controllers for multi-axis and high-precision drive systems, PI has made a major step forward in providing complete systems for industrial applications with the highest demand on precision and dynamics. In addition to four locations in Germany, the PI Group is represented internationally by fifteen sales and service subsidiaries. The company has been ISO 9001 certified since 1994.

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