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PICs to play essential role in disaggregating network infrastructure

OPTICA

Editor's view

By Mark Andrews, Technical Editor

Strong 2021 photonic sales are expected to foster 2022 growth

SALES of optoelectronics, sensors/actuators and discrete semiconductors rose along with other IC sales in 2021, easily outpacing 2020's anemic 3 percent growth. Although the photonic segment of this market subset (collectively referred to as Optoelectronics, Sensors and Discrete semiconductors: OSD) did grow along with other device types; photonic sales simply grew more slowly.

Why did the 2021 photonic sales rebound fall behind the pace of other devices? Two major factors are noted in the January IC Insights report: 'Semiconductor Industry Flash Report'. First, the Opto market was hit harder than other segments by supply chain and delivery headaches. Second, sales of CMOS image sensors were held back by US/China trade disputes plus fluctuations in some key end-use applications, such as advanced automotive ADAS systems and IoT/IIoT (Industry 4.0).

But don't let a 'things-could-have-been-better' sentiment take the wind from your sails. The photonics sector grew 9 percent last year to a record high $47.9 billion. In Optoelectronics, a segment heavily dominated by image sensor sales, it is prudent to remember that these devices alone comprise a whopping 40 percent of sales. And in 2021, even though overall photonic sales tripled compared to 2020, image sensors grew at 6 percent, which pulled down overall numbers.

Prospects for 2022 look solid for optoelectronic/photonic/PIC growth. IC Insights predicts that OSD sales will increase about 11 percent this year to $115.5 billion; the photonic segment should rise 13 percent to $54.2 billion. Sensors and actuators are expected to grow a similar amount, with sales of discretes falling off compared to the last 18-24 months. This is not surprising since manufacturers of every stripe were scrambling for discretes in 2021; 2022 sales will shrink by comparison.

In this issue of PIC Magazine we take a look at ways that graphene continues to find greater application across photonic systems. A research, pilot line and state-of-the-market update comes courtesy of EPIC. Leading researchers from Fraunhofer HHI report on key PIC design advances made possible through its PolyBoard platform three years after its initial capabilities were first highlighted in PIC Magazine. Also on tap are T&M updates from EXFO and research from across industry.

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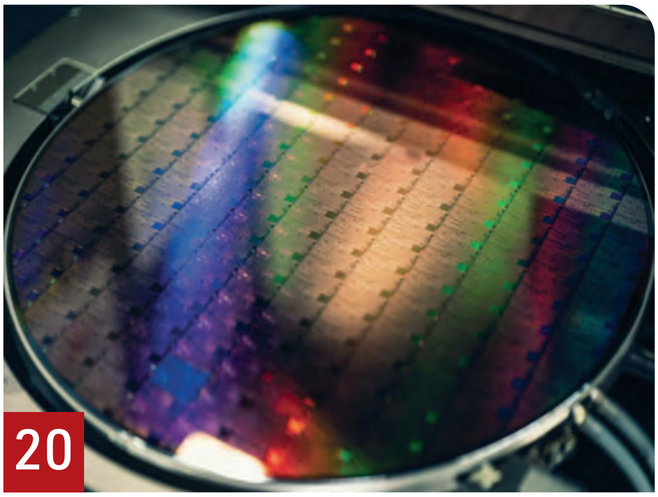
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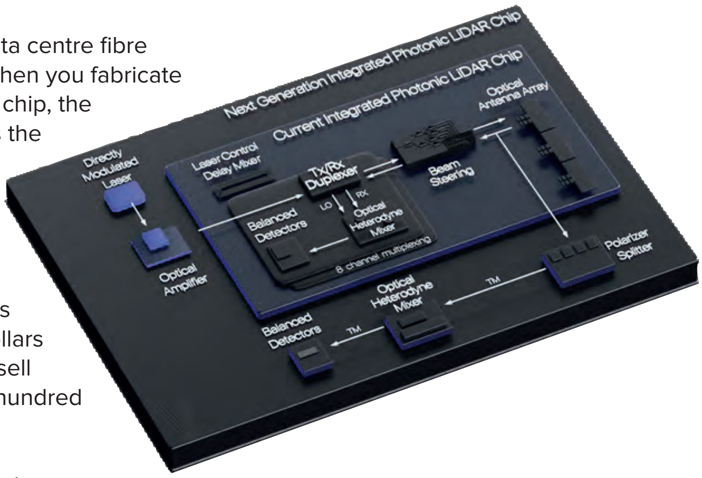
Voyant Photonics raises $15.4M for next gen LiDAR chip

COLUMBIA UNIVERSITY LiDAR spin-off Voyant Photonics has announced that it raised $15.4M in Series A led by UP.Partners with participation of earlier investors LDV Capital and Contour Ventures.

Voyant hopes that its silicon photonics LiDAR sensor chips, which contain an integrated InP/silicon laser, will pave the way for large-scale adoption of 3D sensing in the same way that CMOS image sensors enabled the accelerated growth of digital photography.

Co-founders Chris Phare and Steven Miller had been working on LiDAR chips for years at Columbia University's Lipson Nanophotonics Group when they decided to commercialise their technology and launched Voyant Photonics.

Miller and Phare's insight was to apply the silicon photonics technology used for optical data communications, the same technology that has made high-performance data centre fibre optics affordable. "When you fabricate a LiDAR system on a chip, the fabrication cost stays the same regardless of how many components you use," said Phare. "We will soon be selling LiDAR systems for a few hundred dollars and longer-term will sell them for less than a hundred dollars at scale."



Voyant Photonics' devices demonstrate a complete LiDAR system in a field-deployable package, using Voyant's patented techniques for on-chip digital beam steering, optical signal processing, and laser control.

"When we started on our mission to make LiDAR a ubiquitous technology for machine perception, a lot of people said silicon photonics was not ready to leave the lab," said Miller. "Our successful first milestones prove that we can build a complete LiDAR solution that meets industrial needs, using silicon photonics, and deploy it anywhere." "Now that we can make LiDAR systems on semiconductor chips, we can make them better and less expensive with every development cycle, similar to Moore's Law for computer chips," added Phare.

Nanoscribe partners with PHIX in photonic packaging market

NANOSCRIBE, a BICO company, and the Dutch photonics packaging foundry PHIX B.V. have announced a collaboration to provide on-fiber printing services to the photonic packaging industry. With Nanoscribe's new high-performance 3D microlens printing technology with nano-precision alignment capabilities, PHIX relies on this new technological approach in their manufacturing services of standard lensed fiber arrays (LFAs). The PHIX service portfolio will then contain the manufacturing of Free Space Microoptical Coupling (FSMOC) components printed directly on fiber arrays and photonic integrated circuits (PICs). This extends PHIX's portfolio for bringing hybrid integration into mass production.

Both partners take a multidisciplinary approach to the development of photonic packaging solutions: from simulation to design and assembly. Nanoscribe's Quantum X align automatically aligns and prints advanced optical lenses on fiber arrays, facilitating optimized optical coupling on PIC platforms.

In addition, this is a reliable solution for passive alignment of chip modules.

PHIX is thus adding a state-of-the-art manufacturing technology to provide solutions for hybrid integration of chip-to-chip and fiber-to-chip modules to its portfolio of assembly services for all major PIC platforms. "We are confident in Nanoscribe's new, aligned 3D printing technology for producing lensed fiber arrays and lensed chips with virtually limitless optical designs," stated Joost van Kerkhof, Chief Operations Officer (COO) of PHIX. "This will enable us to further advance integrated photonics packaging," Van Kerkhof added.

The PHIX service is designed as a gateway to standard LFA manufacturing, facilitating entry into such markets. It is also promising for low-volume applications and markets with industry-quality components. With Nanoscribe's technology, PHIX offers 3D-printed collimation, focusing and steering lenses on 4-32 channel fiber arrays. This is complimentary to PHIX's offering of spot size converters (SSCs) and can cover wavelengths from 450 to 1,550 nanometers and beyond. This marks an important milestone for the photonic packaging industry

Foundry-ready SiPho process integrates III-V lasers

TOWER SEMICONDUCTOR and Juniper Networks have announced the world's first silicon photonics (SiPho) foundry-ready process with integrated III-V lasers, amplifiers modulators and detectors. This integrated laser process addresses optical connectivity in datacentres and telecom networks, as well as new emerging applications in artificial intelligence (AI), LiDAR and other sensors.

According to the market research firm Yole, the silicon photonics transceiver market for datacenters is expected to grow rapidly at a CAGR of 40% to reach over $5B in 2025.

The new platform co-integrates III-V lasers, semiconductor optical amplifiers (SOA), electro-absorption modulators (EAM) and photodetectors with silicon photonics devices, all monolithically on a single chip. This enables smaller, higher-channel count and more power-efficient optical architectures and solutions.

Foundry availability will enable a broad array of product developers to create highly integrated photonic integrated circuits (PICs) for diverse markets.

Process design kits (PDK) are expected to be available by year end and the first open multi-project wafer (MPW) run are expected to be offered early next year. First samples of full 400Gb/s and 800Gb/s PICs reference designs with integrated laser are expected to be available in the second quarter of 2022.

"Our mutual development work with Tower has been extraordinarily successful in qualifying this innovative silicon photonics technology in a high-volume manufacturing facility," said Rami Rahim, CEO of Juniper Networks. "By offering this capability to the entire industry, Juniper offers the potential to radically reduce the cost of optics while lowering the barrier to entry for customers. Our partnership with Juniper on silicon photonics is bringing a paradigm shift for product development across our industry," said Russell Ellwanger, CEO of Tower Semiconductor. "It is now possible to mix the advantages of III-V semiconductors with high-volume silicon photonics manufacturing. Being the singular open market, integrated laser silicon photonics platform, and having a multi-year advantage over any potential foundry competitor, we are jointly creating breakthrough products with truly unique value for our industry and for society as a whole".

Vector Photonics boosts design team

VECTOR PHOTONICS is continuing to boost its design team. The latest appointment is design engineer Anna O'Dowd who will be responsible for developing simulation of the company's PCSEL devices.

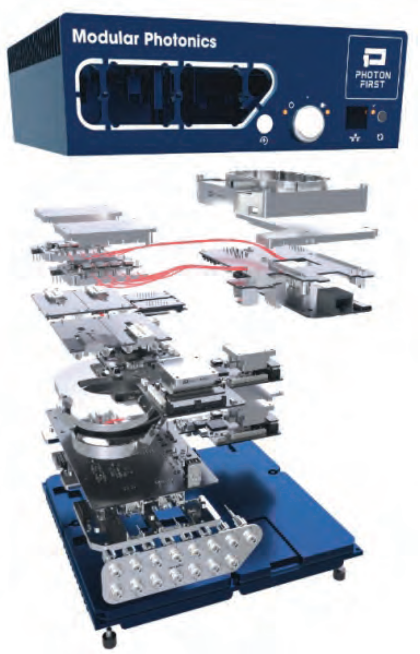
O'Dowd has a first class degree in physics with particle physics and cosmology, from Lancaster University and an MSc in Nanoscience and Nanotechnoloy from the University of Glasgow, where she worked with Vector Photonics on simulating the band structure of PCSELs.

Anna was previously Implementation Lead at Enable International, configuring and implementing DealTrack, rebate management software around the world. This included running the newly opened San Francisco office.

PhotonFirst launches modular photonics platform for advanced sensing

AT SPIE PHOTONICS WEST, conference and tradeshow on lasers, optics and optoelectronics, PhotonFirst launched Modular Photonics. With this new integrated photonics sensing platform, the application engineers of PhotonFirst are able to configure a dedicated sensing solution for each customer without developing the photonics system completely from scratch. With a targeted application time of only one week compared to the multiple months to a year it takes now, PhotonFirst reduces the lead-time greatly. This allows customers to start measuring and generating data almost instantly.

The technology can be used for a broad range of measurement applications: temperature, vibrations, strain, acceleration and shape. Since the modular building blocks are standardized, PhotonFirst has cracked the code and developed a solution where the traditional trade-off between performance, flexibility, scalability and cost no longer exists. The Modular Photonics platform is easily configured like using LEGO bricks. With a wide range of combinations, this covers the vast majority of customer requirements and lowers the threshold of using integrated photonics for measurement and data generation substantially.



This World Premiere also marks the expansion of PhotonFirst into North America. The fast-growing Dutch deeptech scale-up is planning for a foothold in the United States to support existing local customers as well as further expansion. This is crucial to execute on the company's growth ambitions and to further enlarge the sales volume.

'This Modular Photonics platform is the first PhotonFirst product line that embodies 15 years of experience and countless applications. Our team has found a unique architecture to use economies of scale at module level yet keep all technology options open.

This is a game-changer!', according to Daan Kersten, CEO of PhotonFirst. 'We took upon us the challenge to change our paradigm to democratize photonics sensing without compromising on quality. Our hardware and software teams have worked intimately with the application engineers and operations colleagues to make this reality with an ambitious deadline. What a great result of teamwork', Wessel van Haarlem, Team Lead for Development & Engineering added.

Ulrike Helfferich joins EPIC as Chief Operating Officer

EPIC, the European Photonics Industry Consortium, has strengthened its team by appointing Ulrike Helfferich as chief operating officer.

Helfferich has a Diploma in Engineering Physics and extensive sales and business development experience with wide knowledge in optics, photonics, semiconductor, and machine-building market, that is based on business relationships to large scale and medium-sized enterprises.

"With Ulrike joining me as COO, I feel confident we are building a sustainable organisation for EPIC" said Carlos Lee, director general of EPIC. "She has 30 years of industry experience. Ulrike will run the operations, and all 11 staff will report directly to her: 6 technology and market experts, and 5 events and marketing managers."

EPIC has become the world-largest photonics industry association, with more than 760 members within the last few years. To address the needs of the growing membership, Ulrike brings over 30 years of experience and deep knowledge of the photonic market, which will reinforce the robust systems and processes of the organisation. She will supervise daily business operations lead, key initiatives, and implement organisation-wide strategies.

"What I found most compelling about EPIC was its undisputed influence in the photonics sector," said Helfferich. "EPIC brings together the entire value chain to enable new business opportunities and creates collaborative bonds to facilitate technological innovation something that is truly mission-critical for the members and European industry. I'm looking forward to helping take the organisation to the next level in its leadership."

Helfferich worked among others with applications related to spectroscopy, distance sensors, optical measurement, and image sensors, and from 2006 to 2007, has been an Official Member of the DIN standardization committee on light engineering-photometry and LED and LED-systems. Her broad experience includes among others creating new business cooperation and especially in the past years a structured approach in different leadership roles. Ulrike Helfferich will provide management, leadership, and vision to further strengthen EPIC's structure as a sustainable organization committed to serving its more than 760 members.

POET Technologies to Supply Celestial AI

Photonics company POET Technologies has entered into an agreement with Celestial AI to provide multi-laser integrated external light source (ELS) modules using its advanced packaging platform based on the POET Optical Interposer. The agreement includes a contract for continued platform development, along with a purchase order for initial quantities of the advanced modules.

Celestial AI is an Artificial Intelligence accelerator company that has a proprietary technology platform which enables the next generation of high-performance computing solutions. Celestial AI's mission is to transform computing efficiency with their Photonic Fabric technology platform, that uses light for data movement both within chip and between chips.

"The customised Optical Interposer platform that we have co-developed with POET is among the most advanced of its kind in high-speed computing," said David Lazovsky, founder and CEO of Celestial AI. "POET's Light Engines provide us with precision optical power sources in a highly integrated form factor that meet the requirements for our Orion AI accelerator products." Celestial AI's Orion AI accelerator products serve the AI chipset market that is projected by Omdia to exceed $70 billion in 2025.

"We are truly excited to take the next step with Celestial AI, one of the leading technology companies in this burgeoning field, to create a highly differentiated means to co-package electronics and photonics and help overcome the fundamental challenges of speed and power faced in high performance computing," said Suresh Venkatesan, Chairman and CEO of POET Technologies.

"The challenges in this application are precisely those that the POET Optical Interposer was designed to overcome. They are the same as

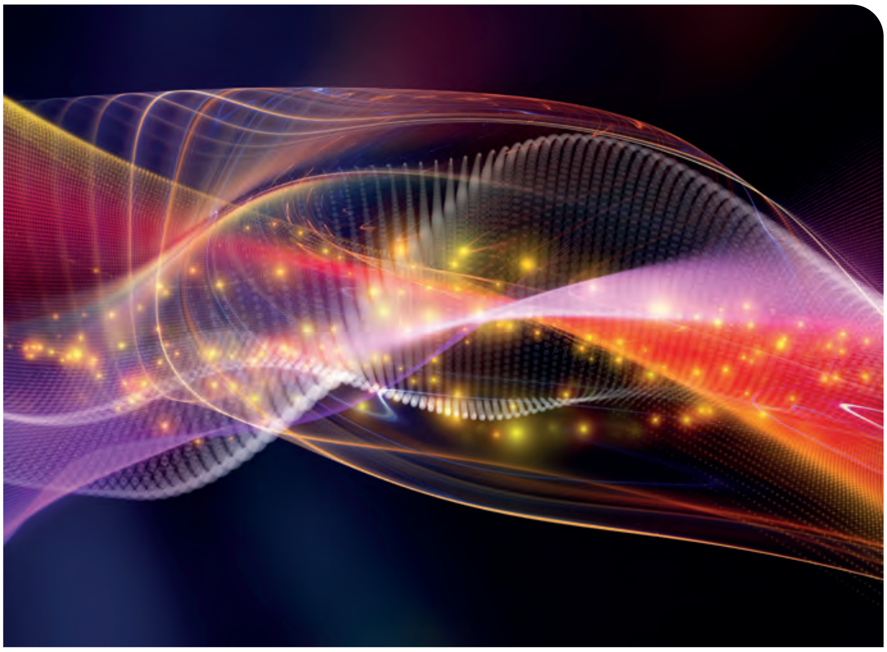
those faced by datacom and telecom companies as they seek to co-package electronics and optics and to achieve data transmission speeds of 3.2 and 6.4 Tbs across a number of channels with multiple wavelengths, with lower energy consumption and higher stability. The multi-laser integrated external light source developed for this application has direct applicability to other products in data communications and sensing."

Semiconductors 4 Photonics webinar

ORGANISED in partnership with Holland Semiconductors, High Tech NL, and supported by the Welsh Government the 'Semiconductor 4 Photonics' webinar on 8 March 2022 will explore the future potential of the Semiconductor enabled Photonics markets, and focus on building, and strengthening existing relationships, between the UK and Netherlands.

Compound semiconductor materials play an important part in driving today's and tomorrow's photonics applications. They have been at the forefront of the revolution in image sensing and will continue to support exciting innovations in photonics applications.

Two of the biggest future developments for photonics applications enabled by compound semiconductor materials are in healthcare wearable devices to monitor diseases and infections including glucose levels and coronaviruses and in remote sensing technology used for accurate dimensional measuring, object scanning for replication by 3D printing and the virtual placement of objects for augmented reality apps such as shopping and gaming.



According to a recent report analysis from the UK Photonics Leadership Group, companies manufacturing and delivering services based on photonics technology in the UK produced £14.5 billion in output in 2020 and contributed £6.5 billion of gross added value to the UK economy annually, employing 76,700 people in the UK at a productivity of £85,000 per employee. It is comparable to the pharmaceutical and fintech industries, making it one of the most important sectors for the UK economy.

More details are on the events page of the CSconnected website.

Vector Photonics appoints nano-fabrication expert

VECTOR PHOTONICS has appointed Joao Valente as process engineer, bringing extensive knowledge of the micro and nano-fabrication of optoelectronic devices to the company.

David Childs, director of product development at Vector Photonics, said, "Valente is both a material scientist and engineer, with outstanding experience and expertise in semiconductor device fabrication and characterisation.

This unique skill set has led to his involvement in the development of many innovative, epitaxial growth and silicon substrate nanofabrication concepts, at the cutting edge of semiconductor device manufacture. He will help Vector Photonics develop high-yield processes and high-performance devices, as we continue to commercialise our PCSEL technology during 2022. We welcome Joao to the team."

Valente most recently held research assistant roles at the University of Glasgow, James Watt Nanofabrication Centre; University College London, Electronic and Electric Department; and the University of Southampton, Optoelectronics Research Centre; advancing photonic nano-fabrication and characterisation performance.

His PhD, from the University of Southampton, entitled 'Controlling Light with Plasmonic Metasurfaces', led to several breakthroughs in the coherent control of light and demonstrated a new magneto-electro-optical effect in reconfigurable plasmonic metamaterials.

His European Masters in Material Science and Engineering, improved understanding of production techniques in high dielectric thin films and his degree from the Universidade Nova de Lisboa, focused on the optimisation of TCO films for microelectronic devices.

Hybrid photonic integration for sensing and communications

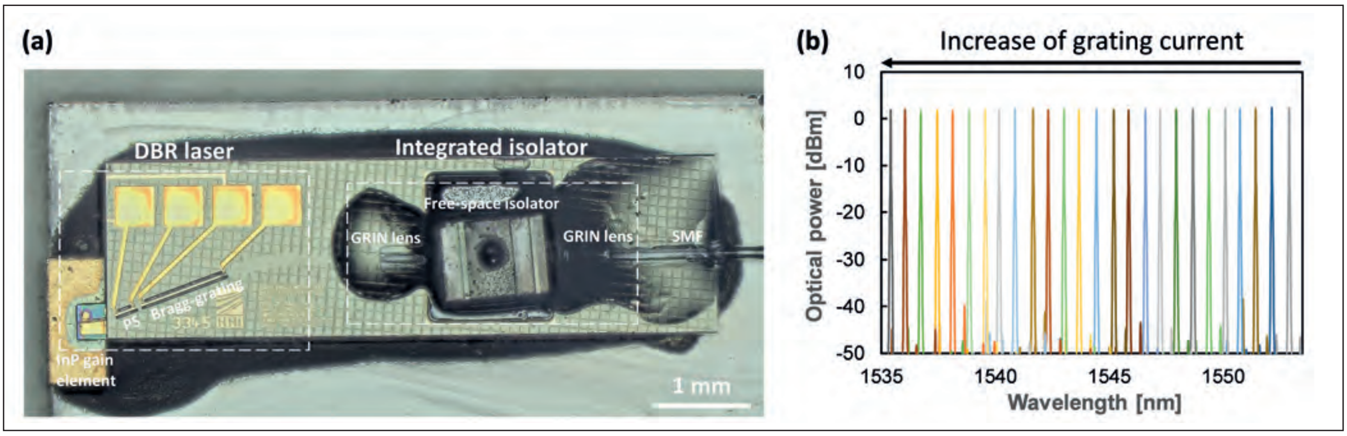
In 2018 Fraunhofer HHI first described PolyBoard in the pages of PIC Magazine. PolyBoard is the Institute's polymer-based, highly flexible hybrid photonic integration platform designed to support numerous applications. PolyBoard offers a straightforward integration approach through its micro-optical bench. In this article, Fraunhofer researchers describe key innovations since the platform's introduction and ways that continuing work is enabling photonic integration beyond telecom and datacom.

BY TIANWEN QIAN, HAUKE CONRADI AND MARTIN SCHELL, FRAUNHOFER HHI

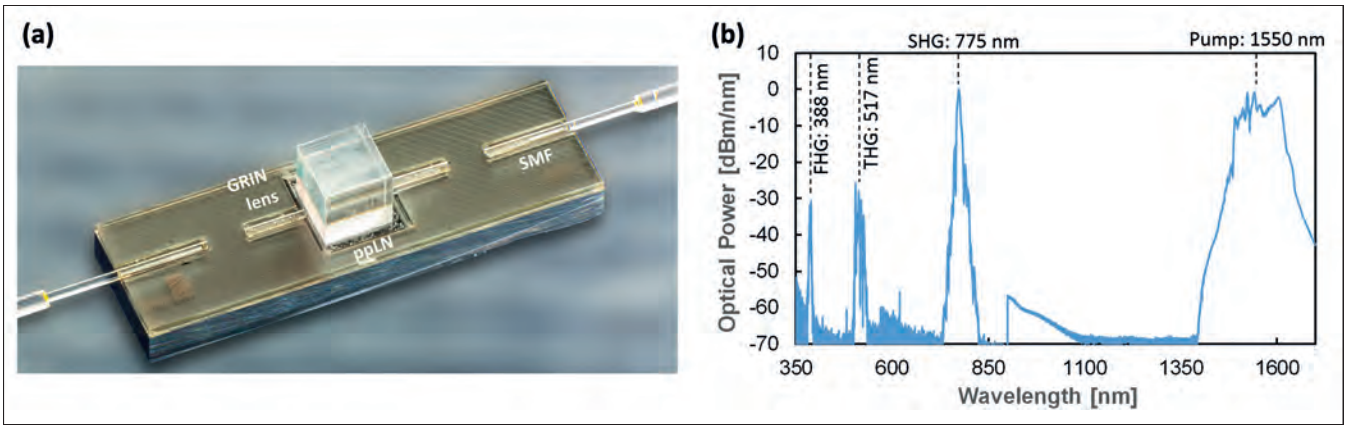
IN LATE 2018, the PIC magazine featured the PolyBoard, a polymer-based hybrid photonic integration platform developed at Fraunhofer HHI. This article described the first steps and concepts towards integrating optical isolators, circulators, and nonlinear crystals with the micro-optical bench. Moreover, ultra-widely tunable lasers and the possibilities of 3D photonic integration with vertical interconnects were introduced. Three years later, numerous advances within the further development of the PolyBoard were made.

This paper describes the progress made in the PolyBoard-implementation of integrated optical isolators and nonlinear crystals. Utilizing the wide transparency range of polymers, all functionalities of the PolyBoard can also be shifted towards lower wavelengths, even down into the visible. The second chapter of this article reviews tunable lasers at 1064 nm and 785 nm for applications beyond Telecom and Datacom.

Furthermore, complex photonic integrated circuits (PICs) for THz generation and detection highlight the versatility of hybrid photonic integration. As an essential step towards commercialization of these PICs, this article concludes with automated hybrid photonic assembly.



➤ Figure 1: (a) DBR laser with integrated isolator. The DBR laser consists of an indium phosphide (InP) gain element, phase shifter (PS) and Bragg-grating. The output of the micro-optical bench is coupled directly to a single-mode fiber (SMF). (b) Demonstrated tuning of the laser across a bandwidth of 17 nm. Different colors correspond to different tuning currents of the Bragg grating. The laser is operated under 10% back reflection.



➤ Figure 2: (a) Polyboard-integrated periodically poled lithium niobate (ppLN) crystal. (b) Spectrum of second-, third, and fourth-harmonic generation (SHG, THG, FHG), pumpt at 1550 nm.

The micro-optical bench

For optical isolators to work, they have to break the Lorentz reciprocity. In free-space optics, this is most often achieved with magneto-optic materials but the implementation of such materials in PICs is a challenging field of research. Especially when it comes to the integration with additional other optical components, for example lasers.

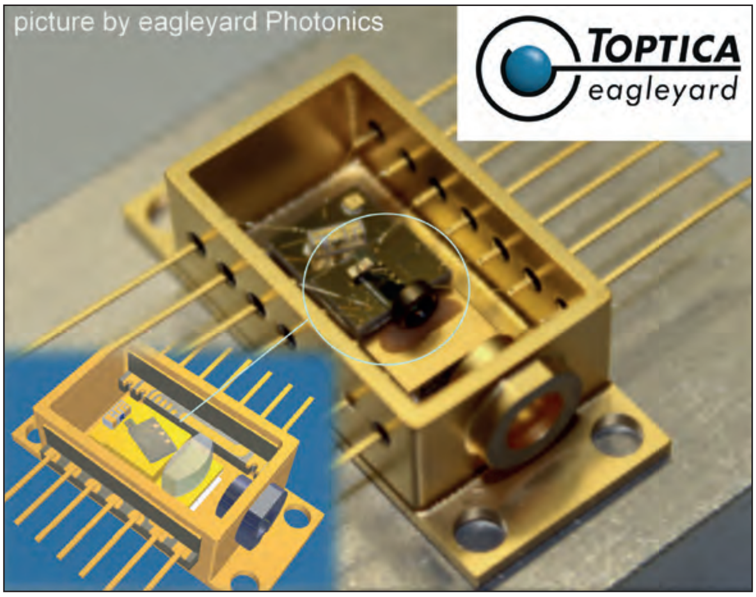
At OFC 2021, HHI presented the first tunable distributed bragg-reflector (DBR) laser with an integrated optical isolator based on the micro-optical bench [1]. The micro-optical bench is an on-chip free-space section consisting of two graded-index (GRIN) lenses coupled to polymer embedded waveguides with the help of precisely etched U-grooves. The first GRIN lens enlarges the beam diameter of the input waveguide and creates a collimated beam with low beam divergence. After the free-space section, the second GRIN lens couples the light back into the waveguide. This enables the low-loss integration of bulk elements, like free-space isolators, into the PolyBoard. The DBR laser protected by the isolator comprises an active indium phosphide gain section coupled to a polymer chip with a waveguide-inscribed tunable Bragg grating and a phase shifter. The fabricated device is depicted in Figure 1.

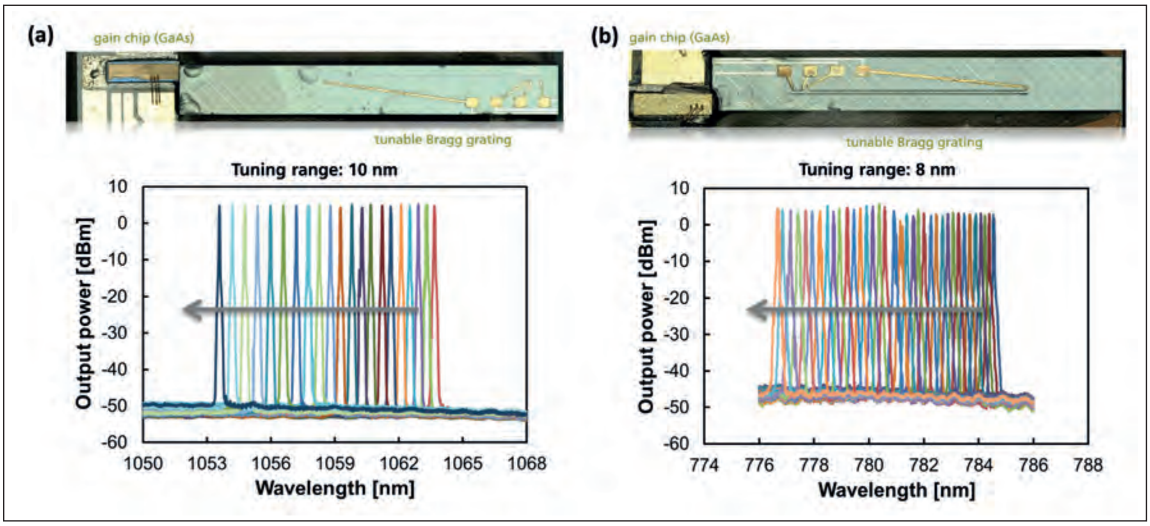
A maximum output power of 5.6 mW and a tunability of 17 nm was measured for this device. The excess loss added by the integrated isolator is only 1 dB, while it provides an optical isolation of 38 dB across the whole tuning range of the laser. The functionality of the PIC was tested during a 10 Gbit/s transmission across a 10 km fiber link with 10% of the laser power coupled back onto the chip as optical feedback. Even at these high levels of optical feedback, the isolator ensured a stable operation of the laser, while a coherence collapse appeared in a reference laser without optical isolator.

Besides optical isolators, the micro-optical bench enables the integration of any other materials. In [2], the integration of periodically poled nonlinear lithium niobate crystals for second-harmonic generation (SHG) was demonstrated by pumping it with a femtosecond pulse laser at 1550 nm, resulting in a conversion efficiency of 8 %. Figure 2 depicts the PIC used to create SHG together with the optical spectrum. Due to higher-order phase matching, not only the second but also the third and fourth harmonic at 517 nm and 388 nm are observable.

Besides SHG, nonlinear crystals are also useful to create photon pairs or entangled photons via spontaneous parametric down-conversion, targeting applications in quantum communications like quantum key distribution. Furthermore, the integration of nitrogen-vacancy-rich diamonds enables the development of sensitive magnetic field sensors. Both these applications are currently under investigation. Overall, the micro-optical bench is a key enabler for transferring quantum and non quantum lab experiments into photonic chips.

➤ Figure 3: The packaged laser diode in a butterfly housing with PolyBoard based hybrid tunable laser in the middle.



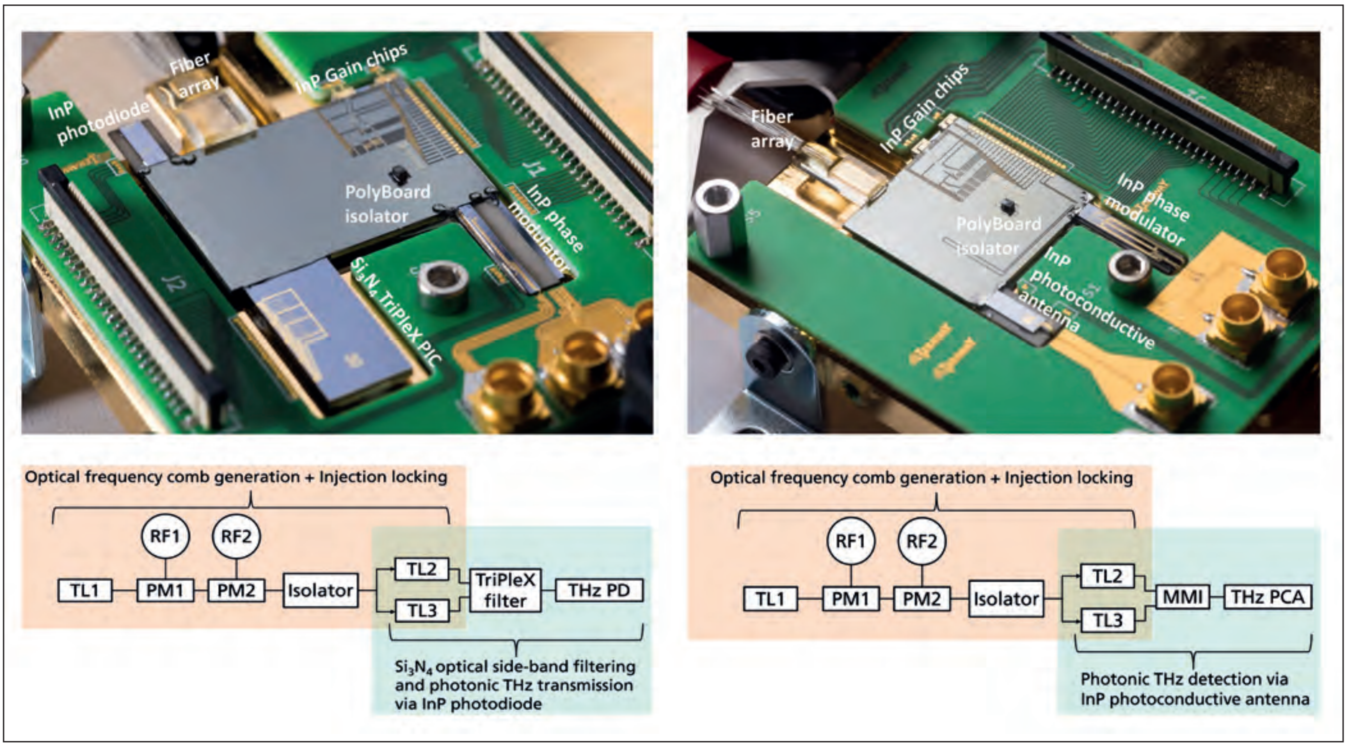


➤ Figure 4: Hybrid tunable laser lasing at (a) 1064 nm with 10 nm tuning range and (b) 785 nm with 8 nm tuning range.

Tunable lasers at 1064 nm and 785 nm

Many applications beyond telecommunication require wavelengths well below 1300 nm. This is why we extended our hybrid laser concept to shorter wavelengths. By replacing the indium phosphide (InP) with gallium arsenide (GaAs) gain material, combined with the efficient thermo-optically tunable gratings on the PolyBoard platform, tunable laser designs at shorter wavelengths are also possible [3].

Figure 3 shows an assembled laser with coupled GaAs gain element built up in a butterfly housing. The measured grating tuning spectra for wavelengths at 1064 nm and 785 nm are shown in Figure 4, 10 nm and 8 nm tuning range are achieved respectivly. The measured output power for both lasers is 2 mW and 1 mW respectively, with linewidths <200 kHz. The magneto-optic material used for the optical isolator described earlier also works at 1064 nm and 785 nm. Thus if required, the



➤ Figure 5: Packaged hybrid Polymer THz transmitter (left) and THz receiver (right) PICs comprise of indium phosphide (InP) SOA, phase modulator, photodiode, photoconductive antenna (PCA), Si_3N_4 TriPleX PIC and PolyBoard in the middle. The corresponding functional schematics are shown below. The concepts of on-chip optical frequency comb generation and injection locking, as well as the photonic THz transmission via InP photodiode or the photonic THz detection via photoconductive antenna are realized on these PICs.

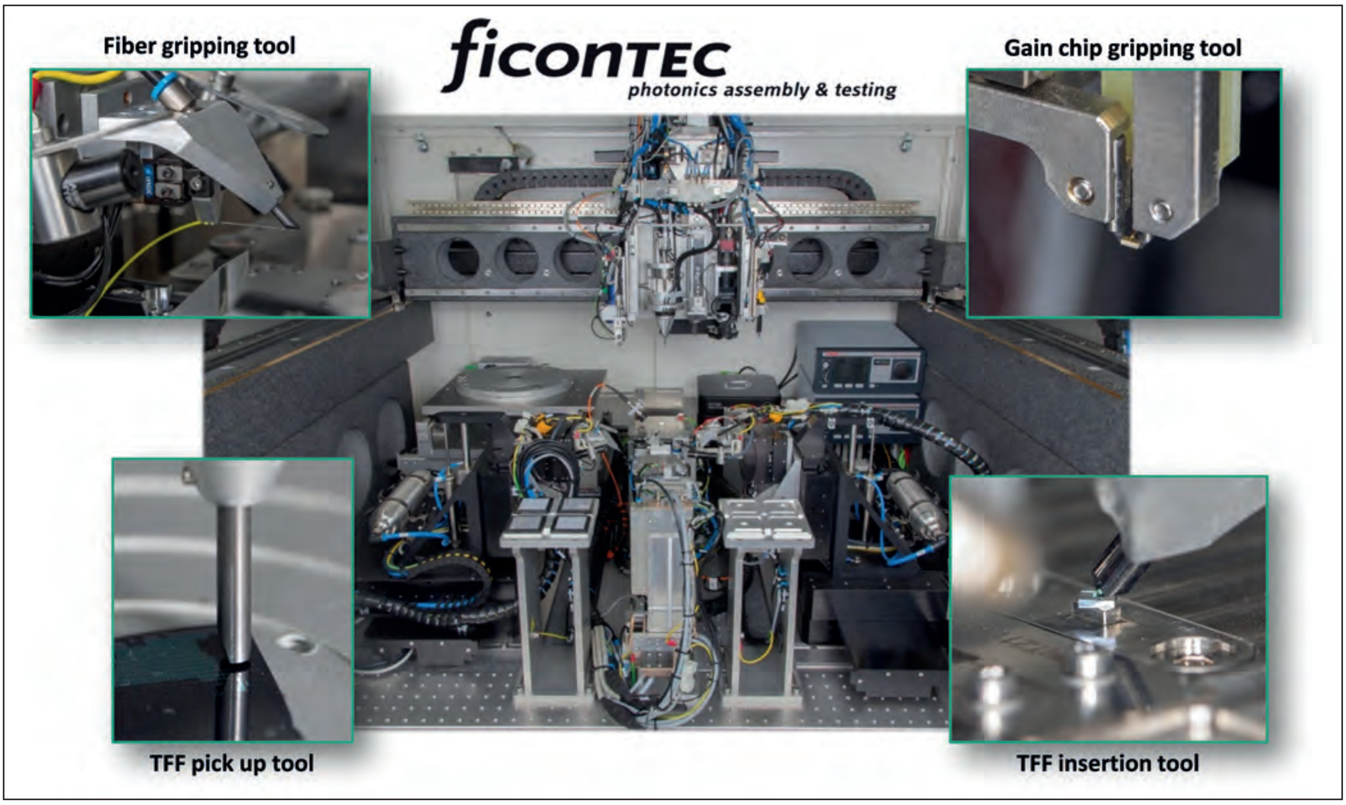


Figure 6: ficonTEC assembly machine with customized tools for fiber and gain chip gripping, TFF pick up and insertion.

co-integration with an optical isolator is also possible at shorter wavelengths.

Using the same concept, tunable lasers targeting visible light wavelengths are currently being developed in the framework of the PolyChrome project[1]. Together with other available building blocks like thin-film filters (TFFs) for polarization control and spectral filtering, this provides a photonic integration platform that can target numerous applications in quantum technologies, medical or life science and spectroscopy.

Complex hybrid photonic integration: THz transmitters and receivers

The versatile functionalities offered by PolyBoard also attract the integration with other material platforms, which makes complex hybrid PICs that combine numerous photonic chips possible. The concept of such complex hybrid integration using PolyBoard was recently demonstrated in the framework of EU Project TERAWAY [4].

Figure 5 depicts a hybrid THz transmitter and receiver comprising an InP semiconductor optical amplifier (SOA), phase modulator, photodiode, photoconductive antenna (PCA), Si_3N_4 TriPleX PIC and the PolyBoard in the middle. Taking the THz receiver as an example (Figure 5, right): a tunable laser followed by two cascaded phase modulators generates an optical frequency comb (OFC), which is used as a master signal for frequency-stabilization of two other tunable lasers by means of injection locking.

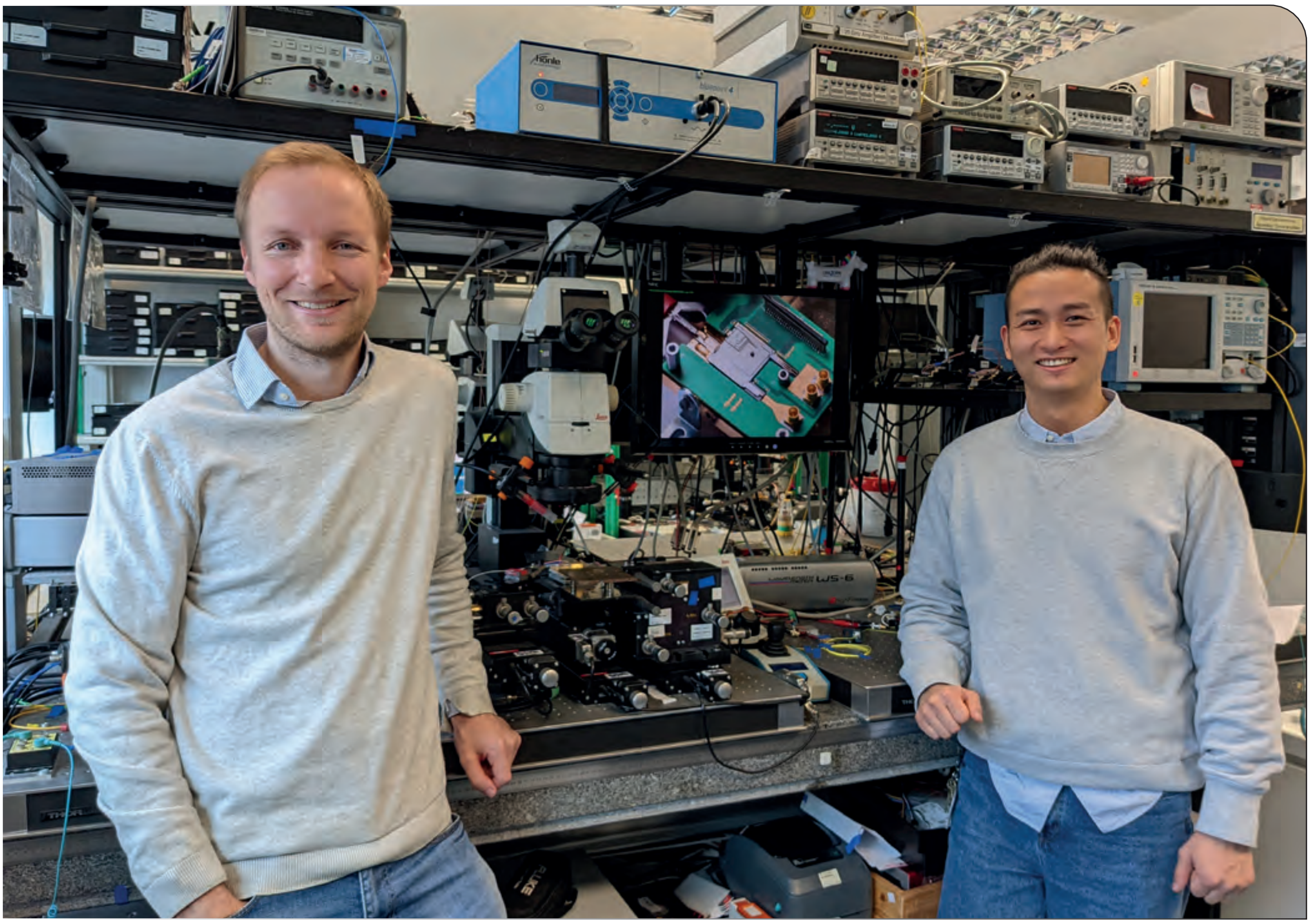
These two stabilized laser signals mix at the photoconductive antenna (PCA), enabling the photonic detection of the upcoming wireless THz signal covering 92 GHz to 322 GHz. The PolyBoard itself provides the functionalities such as tunable lasers, thermo-optically adjustable couplers and optical isolators [5, 6]. The hybrid approach enables using the adequate material for each function in order to maximize the performance of the whole PIC.

Towards automatic assembly

All PICs in this article require several assembly steps, ranging from lens- and crystal-alignment to coupling gain elements or even modulators. An essential step towards commercialization of these PICs is the automation of all assembly and alignment processes. In close collaboration with ficonTEC, a versatile ficonTEC assembly machine is in use to demonstrate these automatic processes.

As depicted in Figure 6, this machine has customized tools for holding fibers and GRIN lenses, gripping gain chips, picking up thin-film filters (TFFs) and inserting them into the PolyBoard. These pickup tools provide the handling of all components

1. https://polychrome-berlin.de/



The TERAWAY receiver during characterization. Hauke Conradi (left) and Tianwen Qian (right) are research associates at Fraunhofer HHI.

required in the assembly, while top- and bottom-view cameras together with dedicated image recognition algorithms, optical feedback loops and optical axes with submicrometer movement precision enable the fully automated chip-assembly.

Conclusion

In this paper, we gave a brief overview about our work on tunable lasers at different wavelengths, the possibility to integrate isolators or even nonlinear crystals and complex hybrid PICs for THz transmission. All these developments result in a highly versatile photonic integration platform that enables PICs that target not only classical communications, but also THz communications or quantum communications, e.g. entangled photon sources for quantum key distribution, and sensing applications.

FURTHER READING

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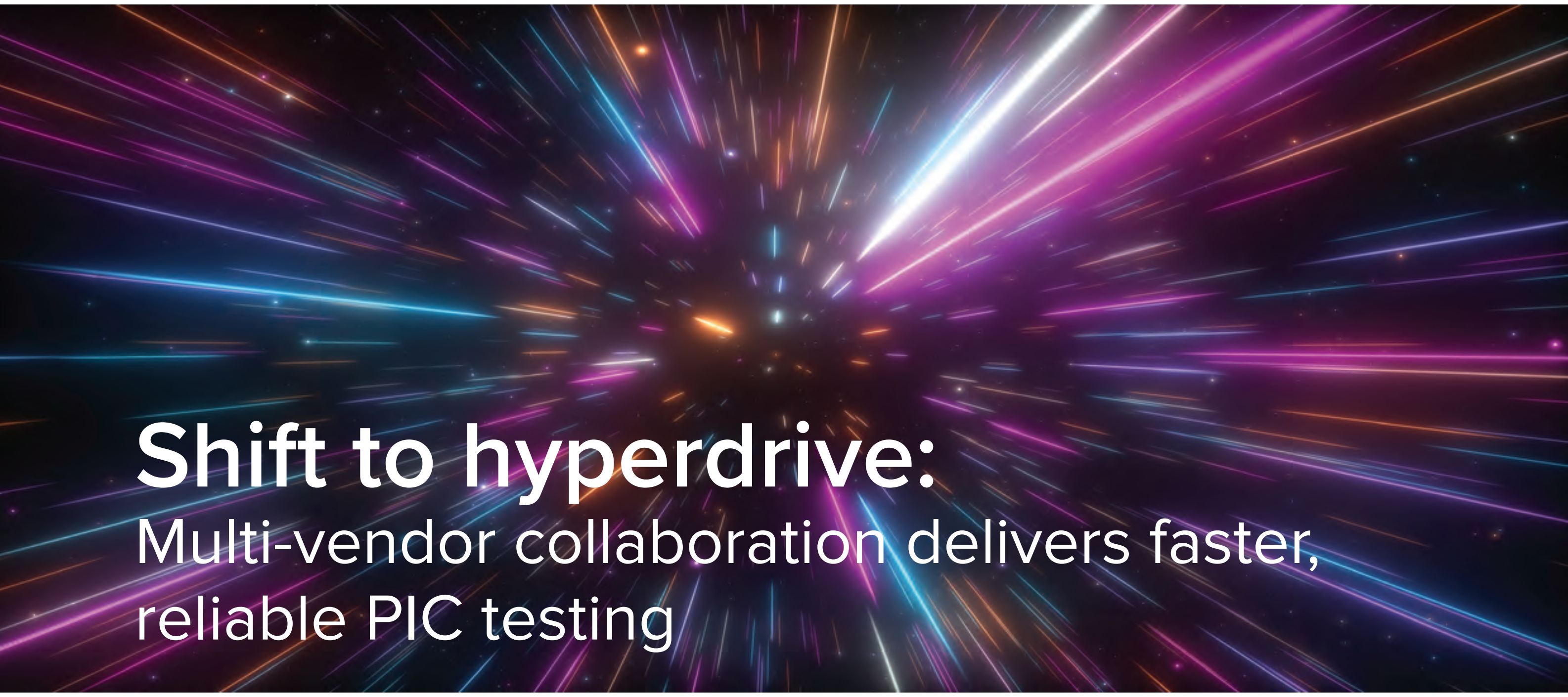


Shift to hyperdrive:
Multi-vendor collaboration delivers faster, reliable PIC testing

Testing the ever-expanding universe of PIC-based devices being designed and manufactured for next-generation photonic systems is complex. Industry leaders specializing in test and measurement including EXFO are increasingly pooling expertise and resources to create what might be described as a 'super-system' for addressing complex testing requirements. Collaborative system solutions, often called simply 'interop', are being highlighted at upcoming industry conferences such as Optica's OFC conference scheduled for March 2022 and at the PIC International Conference that is part of AngelTech 2022 scheduled for June.

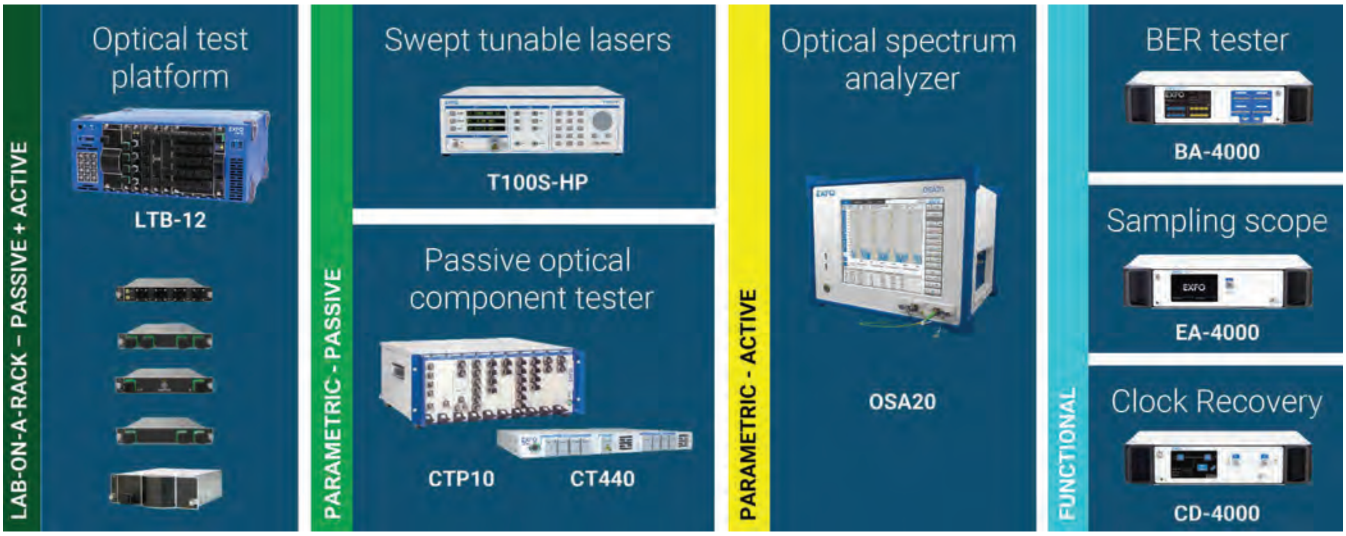
COMPONENT MANUFACTURERS globally need turn-key solutions to support end-to-end Photonic Integrated Circuits (PIC) testing in volume production settings. Fortunately, innovation in light coupling methods has made wafer-level testing possible for mass production, simplifying testing, reducing test time per unit, and avoiding bottlenecks.

But today's new PIC designs used in various types of applications bring with them added challenges for automated testing, requiring that diverse types of test and manufacturing instrumentation integrate and perform seamlessly. Multi-vendor collaborations can be key to successfully turning multi-faceted manufacturing and testing scenarios into automated, scalable setups. For example, EXFO has developed solutions that can interoperate with any third-party instrumentation such as wafer disc handling systems.

Interoperative solutions, also called 'interop' when describing the overall class of components and systems that can function in supplemental or complementary fashion, are enabling companies of all sizes to pool resources and develop testing or other manufacturing systems that combine components to create a higher order of system, most often with expanded capabilities. Typically, interop approaches rely on agreements by participating companies to use various standard components or systems in unison, all with established performance metrics, much the way today's microelectronic standards for process tools and test instrumentation enable silicon manufacturers to use the same toolsets across multiple applications, circuit types and technologies.

"We expect multi-vendor collaboration to be an ongoing trend given that interoperability brings together the best of disparate, specialized technologies to meet the exacting needs of component research & development and mass scale manufacturing globally," said Michael Scheppke, Vice President, Global Labs and Manufacturing at EXFO.

At OFC 2022 in San Diego, EXFO plans to demonstrate PIC and transceiver testing



➤ EXFO offers a number of test and measurement solutions that are designed for interoperability

collaborations in three automated set-ups with multiple partner companies, bringing together leading-edge PIC testing solutions, explained Scheppke.

Accelerating photonic testing

Two of the interop demos at OFC will feature partner solutions in combination with EXFO's CTP10 testing platform and T100S-HP continuous tunable laser. EXFO's solution enables swept laser testing of passive optical components at a picometer resolution and at high speed, even under the most stringent conditions. With the wafer disc auto-alignment capability of the CTP10, the lowest possible time is required to find the optimum position in and out of the PIC device under test, which is an essential requirement to keeping the overall testing time to a bare minimum.

The scheduled demos represent possibilities for PIC component manufacturers looking to scale operations cost-effectively. Demonstrations expected to be showcased at OFC include the following:

EXFO and MPI Corporation

At MPI's OFC booth, visitors will see EXFO's CTP10/T100S-HP integrated with MPI's PIC-specialized TS3000SE wafer probe stations that enable precision optical component alignment, and other dedicated functionality within their unique SENTIO® software. The collaboration delivers a fully integrated and automated PIC test solution at wafer level to deliver reliability, flexibility and scalability.

Aerotech, EHVA and EXFO

At the Aerotech booth, Aerotech, EHVA and EXFO will demo a fully automated integrated photonic PIC test solution that accelerates photonic testing. EHVA's process software suite seamlessly integrates EXFO's advanced swept continuous laser scanning technology with Aerotech's ultra-high precision photonics aligners, delivering exceptional reliability and efficiency.

Optiwave – Automated solutions for labs and manufacturing

An advancement with application for the lab through production settings will be demonstrated at the Optiwave booth.

EXFO and Optiwave

This joint demo will feature OptiInstrument, a software tool designed by Optiwave in collaboration with EXFO. OptiInstrument makes it easy to communicate with instruments and automate their operation using remote control scripts. The system is designed for use by researchers, scientists, photonic engineers, professors, and students. OptiInstrument provides a simple, efficient and user-friendly way to meet multiple application requirements.

Getting hands-on with PIC expertise

The 8th annual PIC Workshop will be held March 9 at OFC for those interested in discovering more about ways that photonic integration can benefit various applications requirements.

According to event organizers, the overarching goal of the PIC workshop is to bring together all relevant players, independent of material system, for the purpose of providing an in-depth overview that allows attendees to get to know key PIC service providers and better appreciate what can be accomplished in various test environments.

EXFO is a leader in the relatively new domain of PIC testing and will be participating in the workshop.

More information is available at https://www.exfo.com/en/corporate/news-events/events/ofc-2022/?utm_source=PIC&utm_medium=art_unpaid&utm_campaign=mdr_ALL_032022&utm_content=mdr_ALL&utm_id=8h0drj23l.v3

Graphene set to enable new generations of PICs

The possibilities of incorporating the unique electrical, physical and photonic properties of graphene into photonic integrated circuits has appealed to PIC developers since harvesting the 2D material was shown possible by two Russian physicists in 2004. Those physicists, Andre Geim and Kostya Novoselov, won the Nobel Prize in 2010 for their work with graphene. EPIC reports on advances being made to bring the potential of graphene into production across Europe and the UK.

BY IVAN NIKITSKIY, PHOTONICS TECHNOLOGY EXPERT, EUROPEAN PHOTONICS INDUSTRY CONSORTIUM (EPIC)

WITH its unique optical and electrical properties, strength, lightness, and thinness, graphene is seen as an ideal material to produce the next-generation of faster and more efficient electronic and photonic devices required to support the exponential growth in global data traffic for datacom and 5G industries.

In this article, we look at the development and commercialization of graphene optoelectronics in Europe and the challenges that need to be addressed to realize the large-scale integration of graphene into photonic integrated circuits.

Introduction

Graphene is the name given to a flat monolayer of carbon atoms or a two-dimensional (2D) form of graphite with a honeycomb lattice structure. Although the theoretical study of atomically thin carbon structures started almost 100 years ago, atomic monolayer materials have been known only as an integral part of larger 3D structures, usually grown epitaxially on top of monocrystals with matching crystal lattices. 2D materials were presumed not to exist in the free state, being described as purely academic models. However, in 2004, these academic models were suddenly turned into reality, when free-standing graphene was unexpectedly discovered by two Russian physicists, Andre Geim and Kostya Novoselov, who were the first to study its unique material properties experimentally, along with demonstrating the possibility to obtain a variety of other materials in their free-standing 2D form. In 2010 they were awarded the Nobel prize in physics, and the rise of graphene had begun[1].

Pure graphene is the thinnest, lightest, and strongest material yet discovered that is also flexible, almost transparent, and possesses ultra-high electrical and thermal conductivity. For this reason, graphene was heralded as a wonder material for applications in composites and coatings, transparent and flexible electronics, solar panels and batteries, drug delivery and DNA sequencing. But above all, the exceptional photonic properties of graphene make it ideal for ultrafast optical and data communication components, enabling ultrahigh spatial bandwidth density and low power consumption board connectivity and connectivity between data centres. Furthermore, the ultimate thinness of graphene facilitates its compatibility with modern silicon-based optoelectronics and suggests itself as the platform for the next generation of Photonic Integrated Circuits (PICs)[2].

EU initiatives

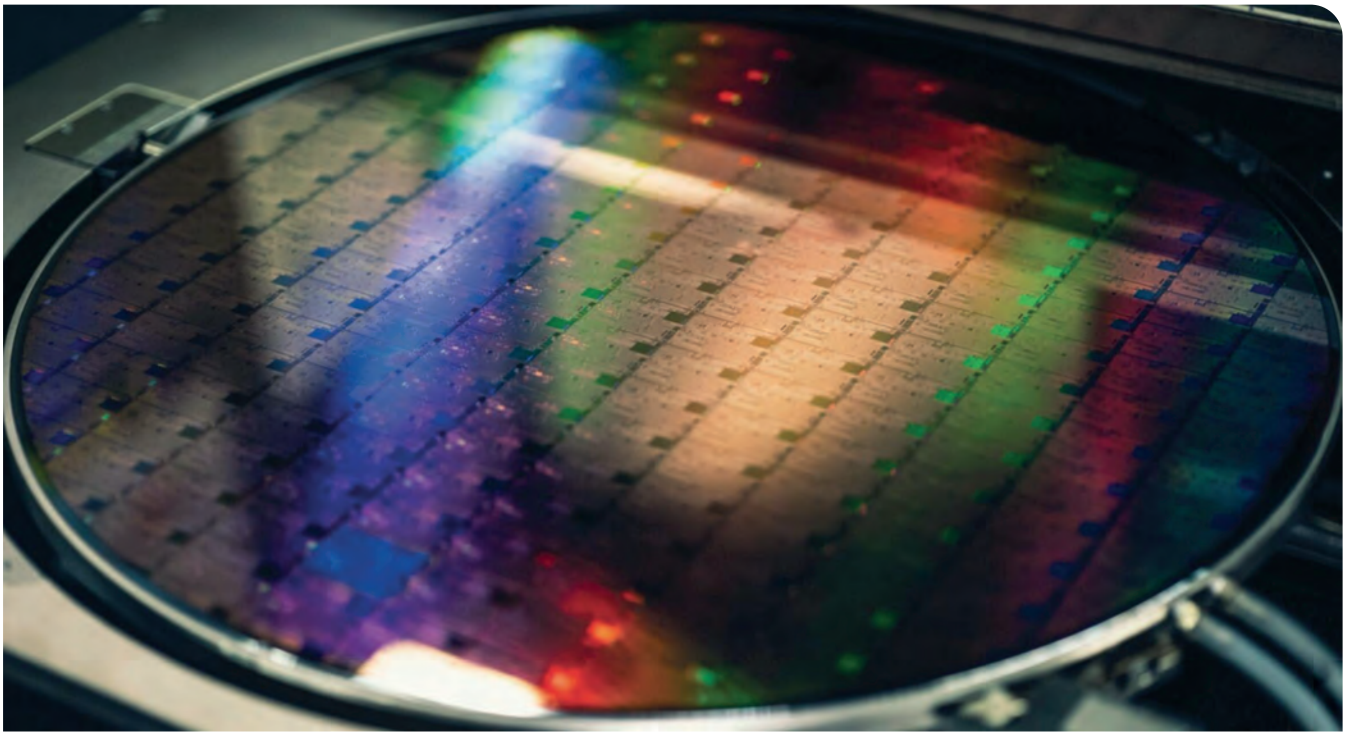
Discovered in Europe, graphene quickly became one of Europe's priorities in lab-to-fab technology transfer and recognizing the material's potential, in 2013, the European Commission set up the GRAPHENE FLAGSHIP project. With funding of €1 billion over 10 years, Flagship's mission was to take graphene and related layered materials, from the laboratory to industry with the aim of revolutionizing multiple industries and creating economic growth and new jobs in Europe.

2D-EPL: The Flagship's most recent initiative has been the launch of the Two-Dimensional materials Experimental Pilot Line (2D-EPL) to integrate graphene and Graphene Related Materials (GRM) in semiconductor platforms. Here, it needs to be pointed out that, in recent years, a large variety of other 2D materials were obtained using scalable synthesis methods with electronic properties ranging from semimetals, direct- and indirect-bandgap semiconductors, to superconductors.

Accordingly, 2D-EPL's mission is to bridge the gap between lab-scale manufacturing and large volume production of optoelectronic devices based on graphene and GRM. Starting in 2020, with funding of €20 million, the 4-year project aims to establish a European ecosystem for prototype production of 2D-based electronics, photonics, and sensors.

The project is built on two pillars: one, offering prototyping services in the form of Multi-Project Wafer runs as well as tailor-designed integrations for 150 mm and 200 mm wafers; and the other, the development of a fully automated process flow on 200 mm and 300 mm wafers, including the growth and transfer of high crystal quality graphene and GRM. With 11 partners, covering the whole value chain, including tool manufacturers, chemical and material providers, and research foundries, 2D-EPL is providing prototyping services not only to the core Graphene Flagship project but also to external partners.

➤ Figure 2 Wafer-scale graphene production (Courtesy of Graphenea)



➤ Figure 3 Wafer with integrated circuits comprising 2D materials (Courtesy IMEC)

METROGRAPH: As part of their Spearhead Projects. i.e., industry-led initiatives aimed to increase the Technology Readiness Level (TRL) of graphene-based technologies, in 2020, the Graphene Flagship launched METROGRAPH to develop a graphene-enabled optical transceiver. In view of the rapidly growing market for PICs and the associated need for integration in high bandwidth communications, the aim of the project is to develop a wavelength agnostic, coherent optical transmitter and receiver based on graphene photonic chips for low-cost, high bandwidth communications. The device will operate at 200 Gb/s in the conventional band and long-wavelength band, covering the 1530–1625 nm wavelength range. The graphene-based photonic circuits will be packaged and tested both in the lab and in a network line card with a TRL of 8, together with a state-of-the-art digital signal processor. Their functionality will be demonstrated in equipment for metro and metro-regional distances of 200 to 1000 kilometers.

R&D: The largest European research center working with the Graphene Flagship is the Belgium-based Interuniversity Microelectronics Centre (IMEC), an international research & development organization, active in the fields of nanoelectronics and digital technologies. Together with National Interuniversity Consortium for Telecommunications (CNIT) in Italy, IMEC develops the work package on wafer-scale integration. This work package targets the transition from laboratory to wafer-based fabrication technology. As Cedric Huyghebaert, program manager of exploratory materials and modules at IMEC and the 2D-EPL division leader, explains: “Many graphene-based concepts have been successfully demonstrated. But most of the demonstrations are limited to the lab and use graphene in the form of small, exfoliated flakes. The real challenge is to mature these concepts from flake-based devices towards real marketable products. And this requires the integration of the material at the wafer scale, in a real production environment”.

Another research organization participating in the Graphene Flagship is AMO GmbH, a non-profit research-oriented nanotechnology SME located in Aachen, Germany, that provides a range of services from consulting to prototype development. With a 400 sqm state-of-the-art cleanroom, AMO’s mission is to efficiently close the gap between university research and industrial application. In recent years, the company has become a global player in 2D materials research for electronics and photonics. In the framework of the 2D-EPL project, AMO will provide two multi-project wafer (MPW) runs where universities, research institutes, and companies can include their designs as dies on joint wafers.

Industry of graphene wafer-scale production

Headquartered in Germany, AIXTRON is one of the world’s leading suppliers of deposition equipment to the semiconductor industry and is a key partner of the 2D-EPL initiative. As one of the tool manufacturers, AIXTRON is responsible for developing the growth and transfer tools, as well as processes necessary for graphene and GRM production. AIXTRON has developed a Metal-Organic Chemical Vapor Deposition (MOCVD) reactor for the growth of graphene and GRM directly onto large substrates – up to 300mm – using its proprietary Close Coupled Showerhead® technology. Direct growth allows industrial-grade 2D materials and their associated heterostructures to be grown insitu for front-end applications. For effective back-end integration, AIXTRON is investigating novel processes as well as developing an automated transfer system of 2D material structures onto device wafers. These platforms will provide key capabilities for the pilot line in realizing large-scale integration of graphene and GRM into logic, memory, photonic, and sensor devices.

Spanish Graphenea is a graphene producer serving just over 800 customers in 55 countries. Its portfolio of products consists of graphene films produced by wafer-scale Chemical Vapor Deposition (CVD), graphene oxides, chips with graphene field-effect-transistors, and graphene foundry services. Around 65% of Graphenea's activities are related to medical biosensors, the other 35% to photonics devices such as photosensors and optical switches. Graphenea's most important products are foundry services that follow a pure-play model based on a vertical integration scheme. This enables the graphene to be grown, transferred, and processed under the same roof, which allows the manufacturing process to be continuously monitored and the delivery of high-quality, reliable graphene-based devices, tailored to the customer's needs.

Founded in 2012 in the Netherlands, Applied NanoLayers (ANL) is a high-volume foundry and producer of GRM sheets with a low defect density such as hexagonal boron nitride for BEOL silicon integration. As ANL points out, CVD growth of graphene is the only technique that can compete with exfoliation when it comes to the electronic properties of graphene, and their advanced CVD systems enable optimum film morphology for wafers from 50 to 200 mm in diameter. Additionally, CVD scales to industrial high-volume wafer-scale series production, where the quality of each graphene sheet can be continuously controlled. Their wafer-scale cold film transfer of 2D materials including graphene and hexagonal boron nitride enables integration with existing substrates such as Si, GaAs, and InP.

Industry of graphene integrated photonics

British Paragraf based near Cambridge, is currently producing commercial-quality, graphene-based electronic devices using contamination-free technology that is both scalable and compatible with existing electronic device manufacturing production processes. They have developed a novel production process whereby graphene can be produced directly onto semiconductor-compatible substrates such as silicon, silicon nitride, silicon carbide, and many dielectric materials, making the process suitable for commercially viable electronic devices. Using this technology, Paragraf has been able to integrate high purity graphene in sensors, also aiming to develop solid-state devices, such as transistors and optical modulators as their high electron mobility graphene offers a mass-manufacturable route to producing these devices at scale.

Also based in Cambridge, CamGraPhIC, is set to improve optical communications in data centers and 5G infrastructures. Their core product is a graphene photonic chip for data conversion that, with small variations dependent on applications, constitutes a single platform for datacom and telecom industries.

> The aim is to integrate graphene modulators and photodetectors into silicon chips, exploiting graphene's unique performance across multiple telecommunication bands (1280 – 1310nm, 1525 – 1565nm, and 1565 – 1610nm). Their Graphene Integrated Photonics (GIP) technology platform aims to enable next-generation high-performance up to 200 Gbps, low-cost, and low-power consumption optoelectronic devices

The aim is to integrate graphene modulators and photodetectors into silicon chips, exploiting graphene's unique performance across multiple telecommunication bands (1280 – 1310nm, 1525 – 1565nm, and 1565 – 1610nm). Their Graphene Integrated Photonics (GIP) technology platform aims to enable next-generation high-performance up to 200 Gbps, low-cost, and low-power consumption optoelectronic devices. CamGraPhIC is managing INPHOTEC, a high-tech R&D and prototyping center located in Pisa, Italy, which includes a 550 sqm cleanroom. The graphene is synthesized through a CVD process in a single crystal or continuous film format, and the facility makes available several technology platforms such as silicon photonics, graphene photonics, glass, SiN photonics, LNOI, and advanced photonic packaging.

Black Semiconductor based in Aachen, Germany, is developing a technology that allows mass production of high-performance photonics on any electronics enabling ultra-fast data transfer on-and-off chip or performing photonic signal processing, as used in AI systems. Their approach holds great promise for a radically new generation of energy-efficient and high-performance microchips that will enable ultra-fast CPUs, GPUs, and AI systems.

Additionally, Black Semiconductor is developing the first integrated super-chip, combining electronic and photonic circuits in a uniform mass production process without bonding. The approach is compatible with existing machines and technology in the established silicon foundries, which, together with integration into the back-end of chips, is a unique feature of their cost-efficient graphene photonics.

The future

While market reports vary, all predict a rapid growth in the global graphene electronics market over the next 5 years. As an example, Market Study Report forecasts a growth from USD 296.5 million in 2019 to USD 613.1 million by 2025, a CAGR of 19.9%[3]. Market drivers focus on graphene's unique properties that will be required for faster and more efficient electronic devices needed to support the rising adoption of IoT applications and the exponential growth in global data traffic. More importantly, existing technology platforms, including the emergent silicon photonics, will not be able to support current roadmaps due to intrinsic technological limitations.

But if these forecasts are to become a reality, several challenges need to be addressed. Firstly, since many of the promising graphene-based photonic and optoelectronic devices rely on single-layer graphene, manufactured using CVD, it is crucial to find solutions to the technological challenges that still exist. For example, how to optimize high-quality growth, transfer tools (which can guarantee high yield and integrity), and processes to fabricate devices at the wafer scale. There are also challenges resulting from the reluctance of the industry to accept new disruptive technology. In this sense, some of the target markets for graphene-based photonic devices can be classified as quasi-monopolistic, where new, disruptive technologies are seen as risks for suppliers. Finally, as with many other photonics technologies, there is a need for standardization, for example, terminology, characterization, processes, and quality control. Without this, it will be difficult to fabricate high-quality graphene-based devices and ensure reliable communication along the supply chains.

More specifically, for Alessio Pirastu, CTO of CamGraPhIC, what is needed is a clear prototyping path for performance validation; an early definition of the technology validation protocol; and early planning or desired qualification activities. Additionally, about scaling up in manufacturing, he sees a need to define what can be done in existing CMOS-compatible fabs, for example, via process design kits (PDKs) for monolithic integration of CMOS electronics with graphene-based photonics. Also important is the need to solve the technical problems that graphene photonics manufacturing might face in the mid-term, such as high-quality graphene, cross-contamination, scalability, and costs. Finally, several fabrication solutions should be implemented (e.g., continuous graphene film, single-crystal graphene) to enable the development and deployment of multiple technical solutions.

While these challenges should not be underestimated, the achievements to date are promising. Firstly, fostered by the Graphene Flagship, there is now an established ecosystem that coordinates nearly 170 academic and industrial partners in 22 countries and has more than 90 associated members in its various projects. With its industry-led initiatives aimed to increase the TRL of graphene-based technologies, this ecosystem is now well placed to resolve many of the technical challenges mentioned above. Secondly, several companies are already working their way towards commercialization in Europe, many of them already as members of EPIC - European Photonics Industry Consortium. These include several spin-offs created by Graphene Flagship, as well as those participating in the European 2D-EPL pilot line, which in February 2022, announced the first multi-project wafer production run with graphene. Finally, there are the companies reviewed in this article, particularly Black Semiconductors and CamGraPhIC, who are currently building the production platforms for graphene integrated photonics including next-generation photodetectors, modulators, and transceivers.

Taken together, these developments signal a bright future for graphene optoelectronics in Europe, and as affirmed by IMEC's research manager Cedric Huyghebaert, we are very likely to see the first graphene PICs appearing on the market in the next two to three years.

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Infrared laser spectroscopy at your fingertips

Sensing applications take a big step forward, thanks to a photonic chip spectrometer that delivers the performance of a table-top laboratory instrument

BY AUGUSTINAS VIZBARAS FROM BROLIS SENSOR TECHNOLOGY

DEVELOPED during the first half of the twentieth century, infrared spectroscopy has established itself as an effective, widely adopted laboratory technique for analysing organic and inorganic compounds. By measuring the interaction of matter with infrared radiation, this form of spectroscopy can identify compositions of substances, determine the presence and absence of chemical species, and offer quantitative and qualitative analysis. When radiation is directed at a substance, the photons that are absorbed have energies coinciding with vibrational frequencies that are molecule specific. Since every different molecule has a unique molecule-specific absorption spectrum, it is possible to identify species and measure their concentrations within a sample.

The tremendous insight garnered from infrared spectroscopy has led to the use of spectrometers in numerous applications. This technique is serving in the biomedical sphere, where it is used to analyse biological fluid, tissue and pharmaceuticals; it is deployed in industrial sectors, such as those involving chemicals, bioreactors, petrochemicals and polymer technology; it is valued in environmental settings, providing the likes of gas analysis and pollution monitoring; it is found in the food industry, where it provides trace element detection and unveils composition; and it also serves in agriculture and veterinary applications.

So common is infrared spectroscopy that it is found in every governmental, regulatory or industrial laboratory, providing a gold standard.

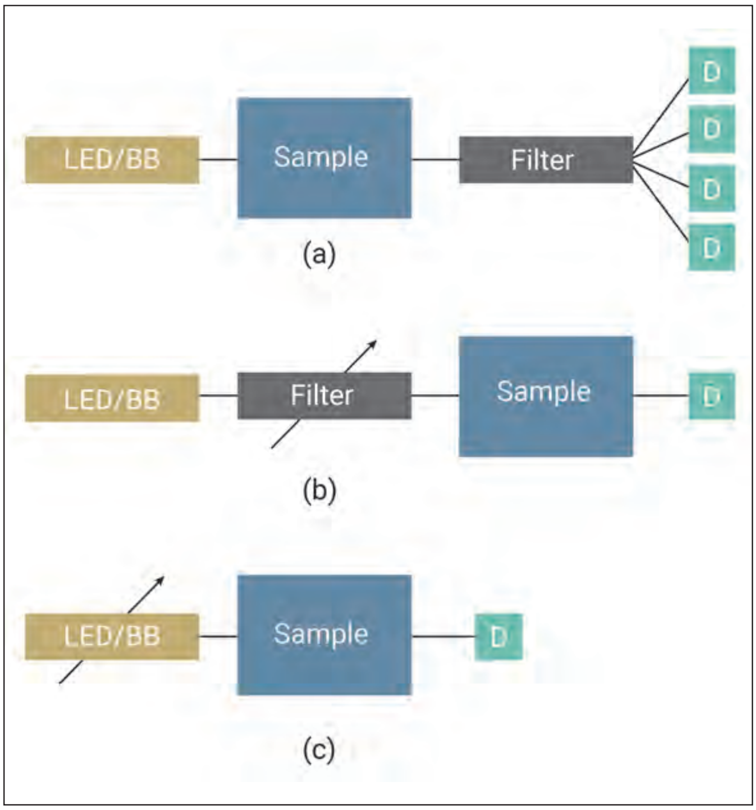
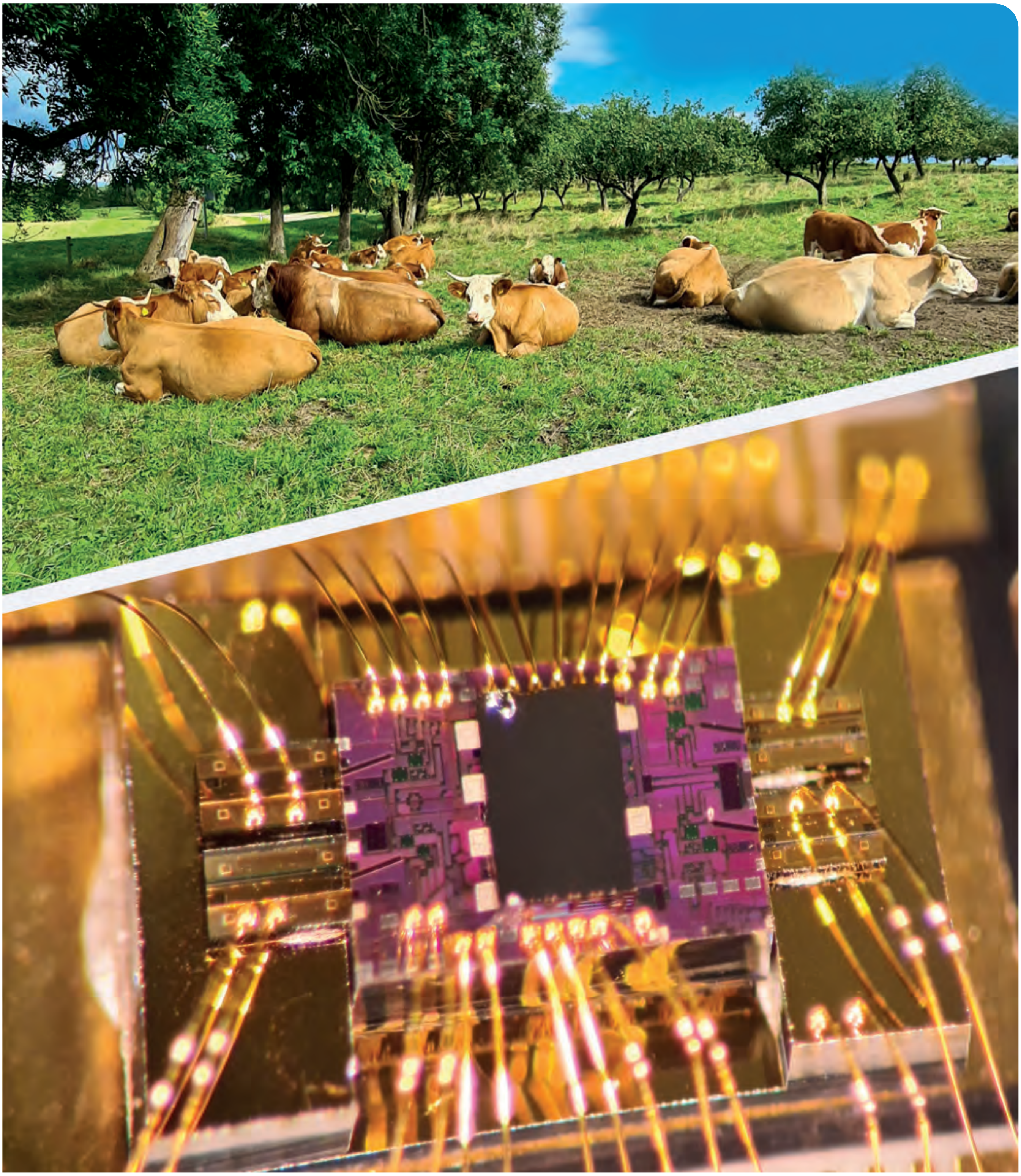


Figure 1. The basic principles of infrared spectroscopy, when measuring a sample in a transmission configuration. Orientations include: (a) a broadband light source and a static filter, (b) a broadband light source with a tuneable filter, and (c) a tuneable light source. BB short for the broadband light source, Sample is the object under investigation, Filter is the spectral filter/wavelength discriminator, and D is the detector of radiation.



Note that instrumentation takes many forms, from the universal table-top Fourier-transform infrared spectrometer (FTIR), to different designs of laser spectrometer and Raman spectrometer.

Unfortunately, all these high-end tools are bulky and expensive, restricting their use to the lab. It would be far better to deploy them directly at sites, providing in-line, *in-situ* monitoring. However, this is too expensive, preventing the opportunity to provide better control over processing and the identification of deviations from intended processes in real-time. Instead, when infrared spectroscopy is used today, it provides results that are offline – and often off-site.

Gathering results in real-time is hugely beneficial. As well as providing immediate feedback, it unveils dynamics – that is, trends over a given period of

	Light Source	Remarks
Type	GaSb/Si widely tunable laser	Hybrid external cavity laser, all electronic tuning. No moving parts
Wafer Size	3-inch, transition to 4-inch	Brolis is moving to 4-inch platform in the next 2 years
Growth Technology	MBE	Lattice-matched, mainly bulk layers
Spectral on **Bandwidth**	~120-140 nm/channel	Currently limitation the silicon side. GaSb chips provide over 400 nm of accessible bandwidth. Future developments should lead to extend the bandwidth on silicon
Wavelength Span* works	1850 – 2450 nm	GaSb can efficiently cover from 1700 nm to 3000+ nm. Standard silicon well up to 2500 nm
Threshold current	20-50 mA	–
Input threshold power	~50 mW	–
Operating power @ 0.2 mW output	~ 120 mW	Includes gain-chip, and thermal tuner power
Output power	1-5+ mW CW	Free-space, off-chip.
SMSR	50 dB+	Limited by test instrumentation noise floor
Tuning Speed	kHz range	–

*Current BROLIS design. Upon need, can be extended.

Table 1 (a). The light source, a laser, for a GaSb/silicon spectrometer-on-chip.

time. Rarely or never can a trend be deducted from a single data point.

Another attractive feature of spectroscopy is its generality. This technique is capable of identifying and quantifying many different molecules. While it's crucial to adapt data algorithms for every molecule, from a hardware perspective the technology is the same and thus generic.

Thanks to this, technology can be scaled, costs driven down and adoption increased. It is the choice of hardware that defines the cost, form-factor and performance. An additional decision facing the designers of spectrometers is the configuration that is used (several are shown in Figure 1).

One of the key differences between the various classes of infrared spectrometer is the technique employed for wavelength discrimination. This can be static, dynamic, or a combination of both. Which approach is taken has significant ramifications, impacting a number of system properties, including the spectral power density, the number of components, the power consumption and the footprint. The value for them may limit the level of miniaturization.

Typical state-of-the-art FTIR spectrometers command price tags between €20,000 and €70,000, have dimensions of around 1 m by 0.6 m by 0.2 m, and weigh about 30 kg. These table-top instruments feature one or more broadband light emitters, such as incandescent lamps or blackbody radiators. Such sources provide a broad emission spectrum, but this comes at the expense of a low total output power and thus a low power density. A moving-mirror interferometer ensures wavelength discrimination or filtering, while detection is performed by a single photodetector.

For static filtering, instrument designers may turn to prisms or arrayed waveguide gratings. These optical elements spatially separate different wavelengths, which are detected with a separate photodetector.

An alternative approach is to undertake wavelength discrimination on the laser side, using a wavelength tuneable laser. Merits of this methodology are minimising the number of components and employing the highest possible spectral power density, but there is complexity, associated with the tuneable laser. This can be in the form of an external cavity tuneable laser, which serves in the most advanced spectroscopic applications, such as cold atoms to gas sensing, and the detection of explosives and drugs. However, up until now the downsides of this approach have been the high cost and complexity of the laser, preventing this precision instrument from being deployed in many applications.

Spectrometers on a chip

At Brolis Sensors Technology of Vilnius, Lithuania, we are changing this state-of-affairs with our GaSb-based chips – they promise to revolutionize the sensing market. A year ago, in the first edition of this magazine, 2021, we detailed our path towards the realization of a spectrometer-on-a-chip with the potential to drive a paradigm shift in the sensing application domain. Twelve months on we are now in a position to share our latest advances that have propelled our technology to the doorstep of multiple markets.

Semiconductor technology is renowned for its capability to scale. This enables widespread adoption, driven by strengths that include a highly parallel technology, a low-cost potential, and an extremely small form factor. All these attributes hold for infrared spectroscopy – it has huge potential to be deployed in a wide range of applications, and drive a transformation from what is today an offsite laboratory test, directly in the field, to a real-time measurement capability.

To enable this to happen, all functional blocks of the spectrometer – including the light source, the wavelength discriminator or filter, and the detector – need to be semiconductor-based technologies that can be drawn together.

When it comes to the infrared, III-Vs are ideal for producing the light source and the photodetector technologies, with different materials better suited to different spectral regions. GaAs and InP are well established in markets from consumer to datacom, while GaSb is still either overlooked or largely unexplored when it comes to real market applications. However, GaSb has the largest potential for spectroscopy and sensing applications.

Our approach involves using a widely tuneable laser, realized by the hybrid integration of a GaSb-based gain-chip with a silicon photonic integrated circuit that houses all the wavelength tuning, filtering and locking blocks. Optical signals are sent to the object under test, prior to collection by either a discrete GaSb-based photodetector or an array of them. The response of these photodetectors is optimised for the spectrum of the laser spectrometer (see Table 1 for the main technical features of the technology platform, including the necessary semiconductor-based ingredients).

One of the features of our spectrometer-on-chip is the edge-coupling of GaSb gain-chips to mode-converters on the PIC side. Optimising this coupling is not easy, demanding alignment tolerances better than 0.5 μm. We meet this requirement with integration by glue or a solder, such as AuSn. A linear array of flip-chip integrated photodiodes monitors internal signals, such as the laser output and the degree of wavelength locking.

	Detector	**Remarks**
Type	GaSb based bulk type detector. *p-i-n*, *n*B*n*, or *p*B*p*	Very high quantum efficiency, lattice matched
Wafer Size	3-inch, transition to 4-inch	Brolis is moving to 4-inch platform in the next 2 years
Growth Technology	MBE	Lattice-matched, mainly bulk layers
Spectral Bandwidth	Broadband	Bulk absorber
Cut-off Wavelength	1500 – 4000 nm	By design
Responsivity	1 – 1.5 A/W	–
Detectivity	~10^{10} cm*$Hz^{0.5}$/W	For 2600 nm cut-off
Noise Equivalent Power	~10^{-12} W/$Hz^{0.5}$	For 2600 nm cut-off
On Wafer Yield	95%+	For single pixel

Table 1 (b). The detector technology for a GaSb/silicon spectrometer-on-chip.

	Photonic Integrated Circuit	**Remarks**
Type	Silicon-on-insulator*	Standard telecom platform
Wafer Size	8-inch (200 mm) and 300 mm	Available at least in several industrial PIC foundries
Spectral Bandwidth	Up to 2500 nm at least	For SOI, as tested at BROLIS
Node exact	160 nm	Depends on the platform used

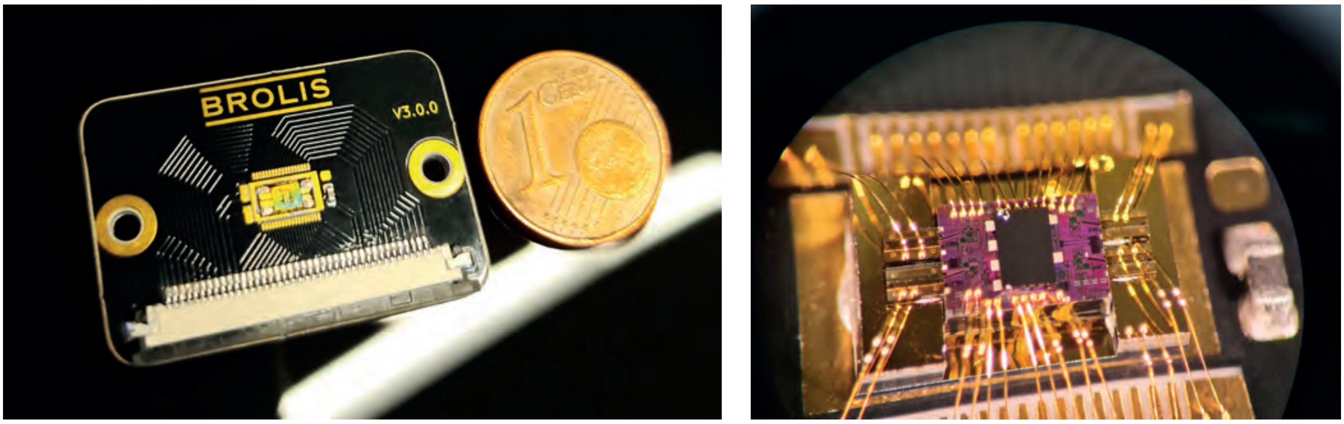
Table 1 (c). The photonic integrated circuit technology for a GaSb/silicon spectrometer-on-chip.

➤ Brolis runs all in-house hardware infrastructure in Vilnius, Lithuania and Ghent, Belgium.

For our initial prototype, we produced a 4-channel chip with a footprint of just 5.6 mm^2. This device provides spectral coverage greater than 400 nm (see Figure 2). It is easy to increase or reduce the number of channels so that they are suited to the final application.

We selected a 4-channel configuration to demonstrate the promise of our technology, because this provides a spectrometer that is suitable for many applications. For instance, applications involving the sensing of liquid-phase objects, such as fluids or tissue, require a large spectral bandwidth.

Typically, a bandwidth between 200 nm and 300 nm is sufficient for monitoring one or more molecules with absorption in the same spectral region. With our spectral region of choice, spanning 1850 nm to 2450 nm, we can cover various molecules, including glucose, lactate, urea, ethanol, lactose, albumin, cholesterol, milk fat and milk protein.



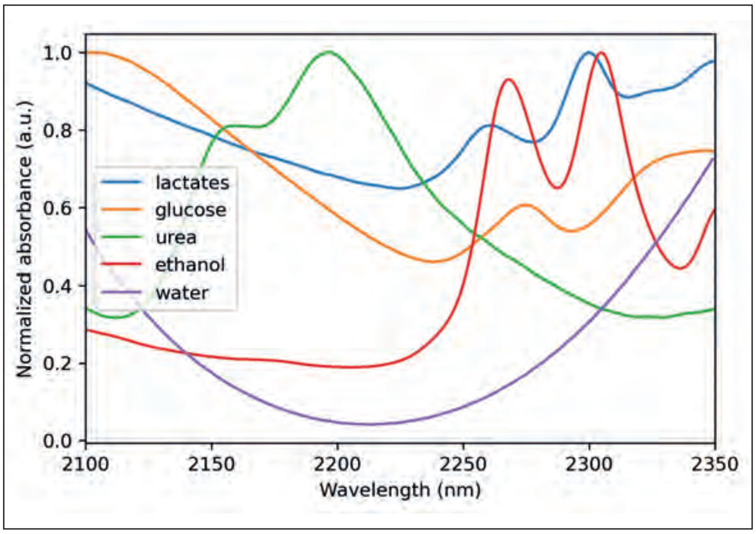
➤ Figure 2. (a) Brolis has all its in-house hardware infrastructure in Vilnius, Lithuania and Ghent, Belgium. (b) Brolis 4-channel laser spectrometer-on-chip on a PCB next to a 1 Euro cent coin (left), and a close-up of the system-on-a-chip (right). The optical output is surface-normal to the chip surface.

What's more, we can identify and monitor large-molecule compounds, as they have a specific spectral shape. This includes the likes of collagen and carotene (see Figure 3, which illustrates several different molecules falling within the spectral bandwidth of our chip). Note that by using two channels, we can sense molecules that are spectrally close together (see Figure 4).

For applications that involve spectroscopic sensing, there is a need to consider: mode purity, the scan speed or rate, how stable the wavelength is, and the power stability at a given wavelength. In addition, for handheld, wearable or battery-operated products, the output power and input power also matter.

Back at the beginning of last year we were unable to offer firm answers to questions related to these considerations, because what can be accomplished hinges on the optimisation and successful combination of all layers of our technology – from the chip to the photonic integrated circuit and integration. It is only in the last few months that we have finally been able to shed some light on what those answers might be.

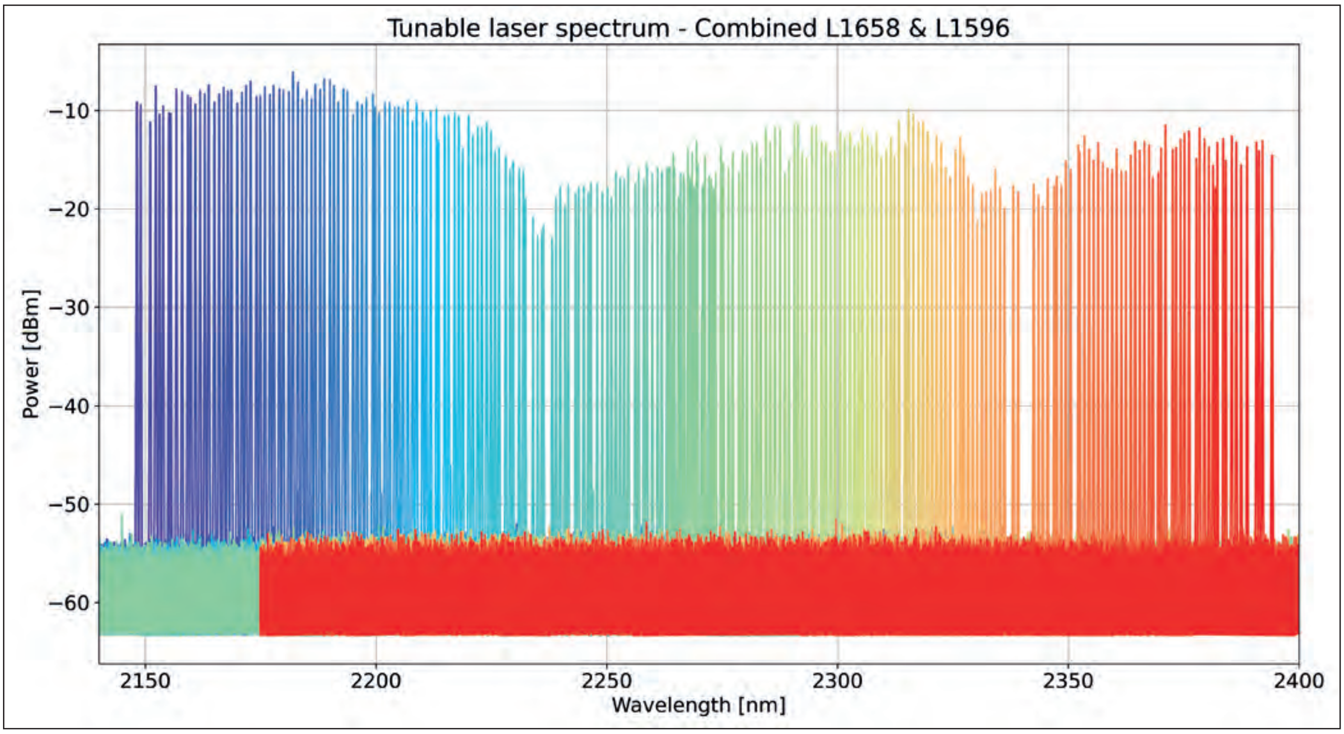
Our latest integrated spectrometer-on-a-chip provides pure single-mode operation at every wavelength. When providing fast sweeping, it takes around just 12 ms to record around 300 nm, realised with a resolution of at least 0.3 nm. By compromising speed, it is possible to provide fully continuous tuning with an additional phase control – this may be desirable for liquid or multi-gas sensing, or both.



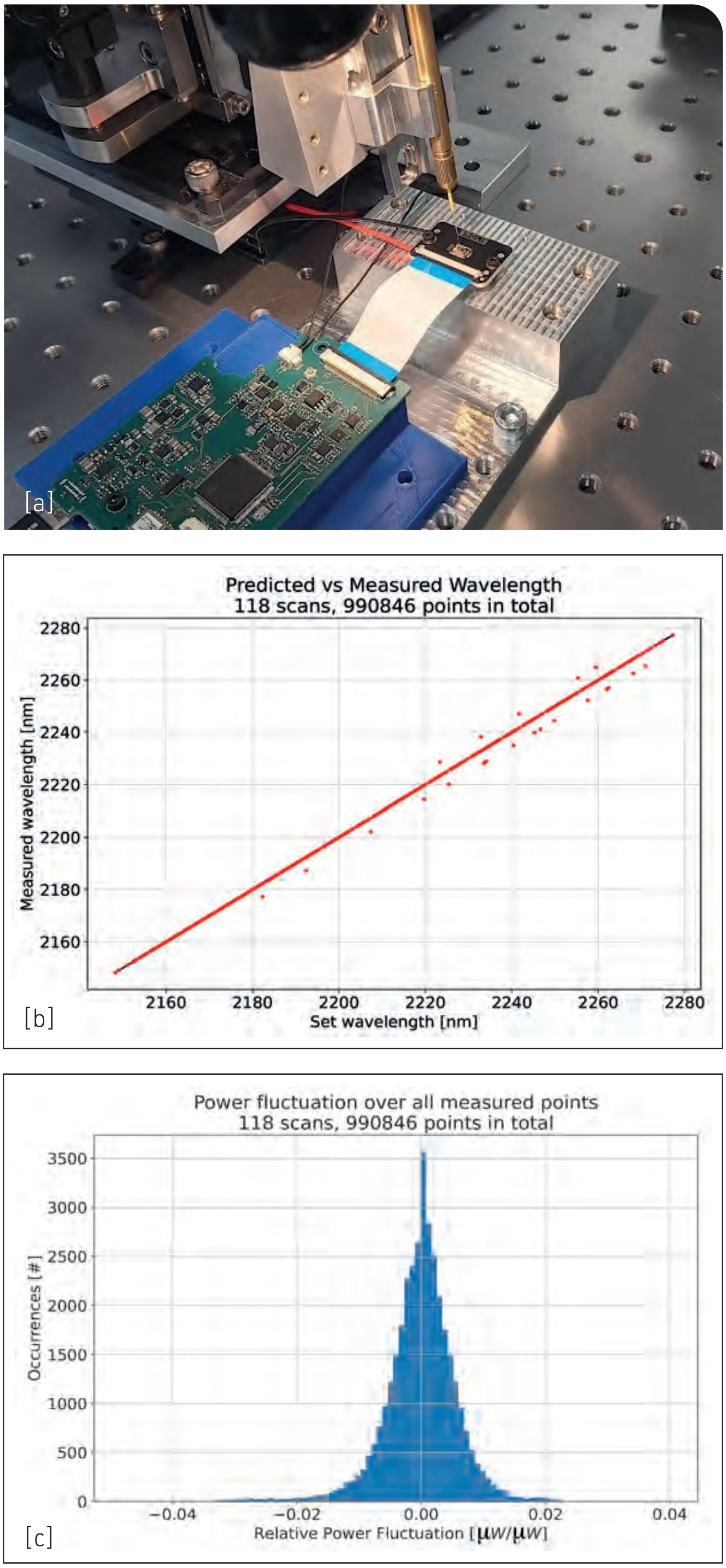
➤ Figure 3. Normalized absorbance for different molecules that fall into the Brolis spectrometer-on-chip bandwidth.

Two striking features of our spectrometer-on-chip are its stability and mode purity. The sidemode suppression ratio is maintained above 50 dB for the entire operation across a 265 nm bandwidth (see Figure 4). This is hard to beat by any table-top system or instrument.

Additional attributes of our patented technology are its excellent wavelength and power stability across an extended period of uninterrupted operation (see Figure 5). Without the aid of any outlier correcting software, we achieve a relative power stability of over 99 percent at a set wavelength. During an extended period of uninterrupted operation, wavelength stability – that is, the accuracy between



➤ Figure 4. The spectral output of a 2-channel laser spectrometer-on-chip with a resolution of 0.3 nm.



➤ Figure 5. (a) A Brolis spectrometer-on-chip under test. (b) Spectrometer-on-chip wavelength accuracy, determined during uninterrupted sweeps for nearly a million wavelengths and 14 hours of sweeping. Accuracy without any outlier correction is at least 97 percent. (c) The relative power of a spectrometer-on-chip at wavelength fluctuation during uninterrupted sweeps for nearly a million wavelengths and 14 hours of sweeping. Power stability is better than 99 percent.

set and actual wavelengths – is 97 percent. Again, such a high level of performance is hard-to reach with most table-top lab instruments. But in our case it comes from just a tiny chip. This highlights that we have a great technology with a real potential for advancing spectroscopy, through an expanded product range that will serve a vast number of applications.

Another strength of our technology is its power ratings – primarily the power output and the power consumption. It is important to point out that there is no universal output power level that separates what is and is not acceptable for all applications. Instead, criteria must be established on a case by case basis.

However, having said that, some numbers are possible to define. Based on our own internal work we have identified that most *in-vitro* applications need around 0.1-0.2 mW of CW laser power when using our GaSb detector. Note that this is the level for a single-mode laser, and does not correspond to the total power of a broadband emitter, but should rather be compared with a spectral power density, which is usually expressed in power/nm.

Governing the power consumption of our spectrometer-on-chip is its laser. To minimise what it draws, its threshold current should be as low as possible, as this ensures that the operational output power is realised at the lowest possible drive current. As we routinely achieve thresholds between 20 mA and 50 mA, we can operate at currents in the 100 mA to 150 mA range, and use input powers of around 100 mW. Such powers are very promising for a very broad range of applications – from implantable biosensors to wearables, handhelds and remote-operation sensors.

By combining a low power consumption with a small form factor and a monolithic design, our spectrometer offers stabilization and simple, reliable operation over an extended period of time.

The road ahead

We are pursuing parallel paths for the development of our products, and the applications that they will serve (see Table 2). Essentially, our products are ‘simple engines’ plus data. For every new application, every new molecule requires a dedicated application development experimental campaign. As this places a cost on resources, we must decide carefully what to pursue, based on considerations such as the demands of resource, the market opportunity and strategic interest.

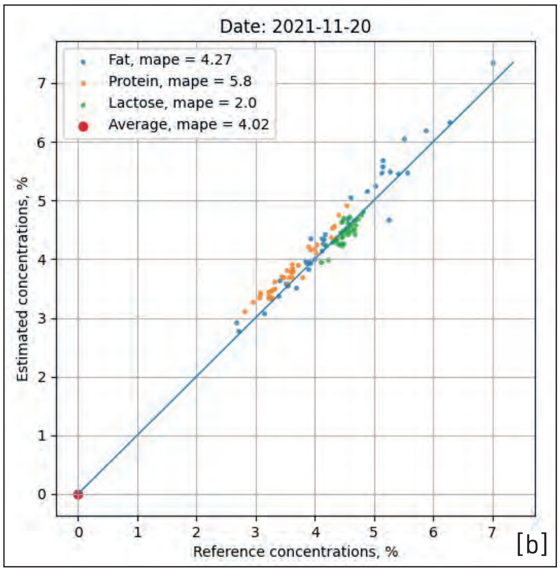
On dairy farms, spectroscopic sensing allows individual cow monitoring for critical molecular data. This can include the monitoring of lactose, fats, and proteins, and provide insight into productivity and herd health status. By drawing on accumulated data models, farmers can foresee the onset of health

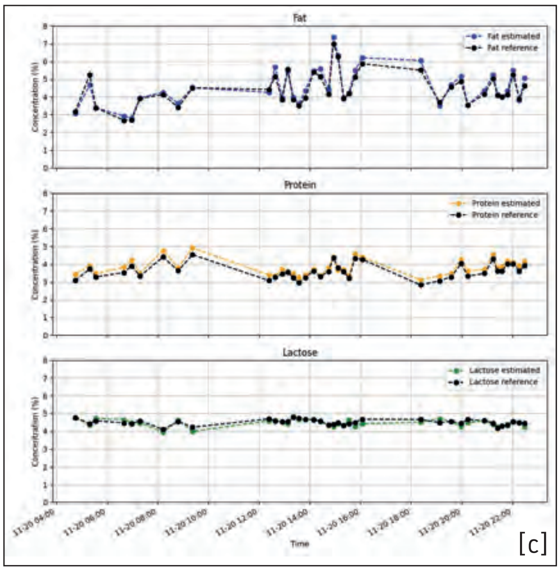
PRODUCT/APPLICATION	TYPE	SENSING OBJECT	MARKET READINESS
OEM spectrometer-on-chip	OEM	–	End of 2022
Dairy farm milk analyzer	Industrial hardware +data	Fat, protein, lactose, blood, milk volume, etc.	First sales 2022
***In-vitro* blood**	OEM biomedical / end-user	Glucose, lactate, urea, cholesterol, ethanol	End of 2023
***In-vivo* blood**	End-user	Ethanol, lactate, glucose, cholesterol	2025
In-line industrial (not disclosed)	Industrial hardware +data	Multiple molecules	2023

➤ Table 2. Brolis spectroscopic sensor product list and market readiness.

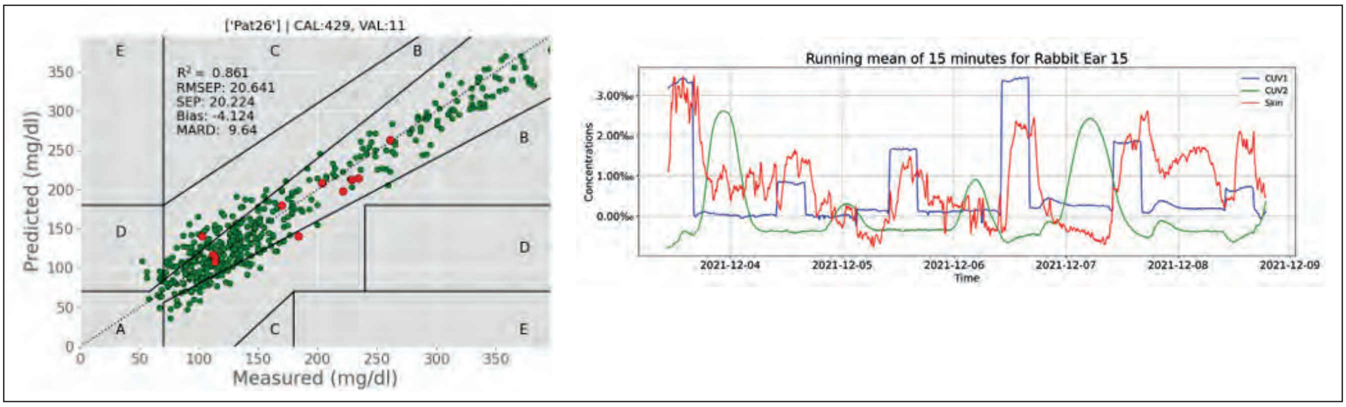
issues such as ketosis, mastitis and acidosis. This information may lead to antibiotic-free treatment and minimise off-line losses. Additional key metrics for those running dairy farms are the total volume of milk and how rich it is in proteins and fats. Individual animal data monitoring can capture all of this and enable efficient herd selection, and ultimately enhance the profitability of the business (see Figure 6 for performance data provided by our in-line dairy farm sensor).

There are also important, challenging, high-potential applications involving blood. We are targeting an *in-vitro* handheld blood spectrometer, by working towards a sensor for detecting multiple molecules, such as glucose, lactate, cholesterol and urea. This combination provides valuable insight into diet,





➤ Figure 6. (a) A Brolis in-line milk analyser. A spectrometer-on-chip measures the composition of milk during milking in-flow and real-time. (b) Accuracy of the in-line, in-flow, real-time milk analyser for milk fat, lactose and protein. (c) A one-day milk analyser trend data compared with a laboratory reference for milk fat, protein and lactose.



➤ Figure 7. (a) In-vitro prediction of blood glucose for a diabetic patient with an accuracy of slightly above 1 mmol/l or 20 mg/dl. (b) In-vivo trend for a 5-day transdermal blood ethanol detection in animal study. 1 permil blood ethanol is visible and detected through the skin.

kidney function, fatigue and metabolism in general. We are intending to have a pre-market prototype ready by the end of 2023 that will be suitable for at least several molecules.

Further ahead, we have plans for *in-vivo* or non-invasive sensing. Our first product will be a non-invasive blood alcohol (ethanol) sensor. We hope to follow this with devices that detect and monitor additional molecules (see Figure 7 for details of our *in-vitro* and *in-vivo* developments. The spectroscopic sensing of milk and blood provide just a couple of illustrations of the capability of our chip technology.

We have no doubt that many more products will follow – and in that light, we believe that over the next few years we will demonstrate some very exciting products, breaking new ground in functionality, form-factor and applicability.

PICs to play essential role in disaggregating network infrastructure

Today's metropolitan telecom networks employ photonic and microelectronic technologies to move data. Key infrastructure is manufactured by a small group of international companies that ensure interoperability through control of aggregated, system-level BOMs. Disaggregating infrastructure is an emerging 'ala carte' concept designed to enable a wider variety of services while lowering costs. Some believe it may also encourage network expansion into underserved markets. According to the **OPTICA** industry association and researchers from the EU's PASSION photonics project, future disaggregated networks will need PICs to realize their fullest potential.

MOVING ANALOG and digital data across the globe is complex and expensive. Today's network infrastructure evolved over decades, growing in speed, bandwidth, complexity and power consumption right along with the ever-expanding demand for faster, high-volume data throughput. But is today's infrastructure procurement methodology and network architecture the best ways to move data and serve customers? Some believe the answer is 'no.'

Achieving maximum uptime and quality of service (QoS) have become international broadband service benchmarks. One way to ensure this is the aggregated approach now used in sourcing components. Under aggregation, major infrastructure providers such as Ericsson, Huawei and Samsung essentially agree to ensure high reliability through a collectivized BOM, meaning in effect that achieving the highest QoS depends on essential network components being manufactured and sourced through the same company.

While aggregation helps ensure reliability, the process also locks an operator into a vendor relationship that is challenging to undue as was seen pointedly when concerns arose in recent years over whether Huawei was placing undetectable 'back doors' in new 5G network management software that might allow third party eavesdropping or even the ability by an outsider to take over network control. The company continues to deny such claims, yet concerns have led some regulators to require operators in their countries to choose different providers. Some argue disaggregation could have another less obvious benefit: it complicates efforts by bad actors to gain unauthorized network access.

Despite points against aggregation, the system has worked; infrastructure manufacturers are for the most part sensitive to customer needs and requirements. Nevertheless, the current system has also made upgrading and expanding a metropolitan area network (MAN) expensive and time consuming, especially if an operator wishes to offer a service not supported by their equipment vendor's system management software.

Expanding service into rural markets with lower population densities is also an issue since the countryside lacks the same profitability prospects as do high-density urban centers; if a means could be found to lower these costs it could encourage greater access. Today, operators in most countries typically offer rural customers fewer or more expensive services; most operators depend on governmental subsidies to expand into the farthest, most sparsely populated corners of their markets.

The Optica trade association (formerly the Optical Society of America, sponsor of the OFC conference event,) is actively addressing the prospects and challenges of network disaggregation. Optica recently worked with European Union researchers including those taking part in the EU's Horizon 2020 (EU-H2020) PASSION project. PASSION is designed to support the development of future MANs with high transmission capacity, low cost and reduced energy consumption. The project has focused on the network and its key elements, such as transceivers and network nodes, which were developed by different partners.

Josep Fabrega, of the Centre Tecnològic de Telecomunicacions de Catalunya (CTTC) in Spain, was a part of PASSION project team to develop a MAN disaggregation approach. Fabrega is scheduled to present the group's findings during the OFC Conference and Exhibition on 6th March. His presentation will in part discuss proposed network design architectures and ideas for making disaggregation achievable in future network development. PIC Magazine spoke with Fabrega prior to the event to discuss the roles that photonic integrated circuits can play in future network designs. As part of his group's work, the team demonstrated the feasibility of a disaggregated MAN by considering each relevant component.

They used sliceable bandwidth/bitrate variable transceivers, which are multi-flow programmable and enable point-to-multipoint connectivity.

"The challenge (with the transceivers) is to have a cost-effective solution," said Fabrega. "So, the PASSION project developed a photonic integrated solution that involves the use of specifically engineered photonic integrated circuits (PIC) and vertical-cavity surface-emitting lasers (VCSELs) for the transmitter part. The receiver part is relying on, again, specifically engineered PICs for coherent detection."

Although Fabrega's group does not speak for system operators, the group spoke with many telecom/datacom operators to ascertain the benefits and negatives of aggregation.

"Until a few years ago, equipment vendors and manufacturers were selling complete (closed) network solutions. This means that telcos were publishing RFQs and vendors were proposing solutions that would include equipment and the management software needed for guaranteeing the end-to-end connectivity in a given network. So, all the network elements were aggregated in the sense that telcos had to use the transceivers, nodes, and amplifiers (among other elements) from the same vendor. Of course, this paradigm has its benefits and drawbacks. The main benefit is that the vendor is guaranteeing the performance of the network," he remarked.

"Nevertheless, the (aggregated) network is less flexible in terms of resource assignment. This is quite critical when telcos are trying to slice their networks in order to provide differentiated services in a single infrastructure. For example, let's assume that they provide two different services that need to match different performance figures. This would need a highly flexible network solution that could be able to assign the right resources to each service.

Expanding service into rural markets with lower population densities is also an issue since the countryside lacks the same profitability prospects as do high-density urban centers; if a means could be found to lower these costs it could encourage greater access

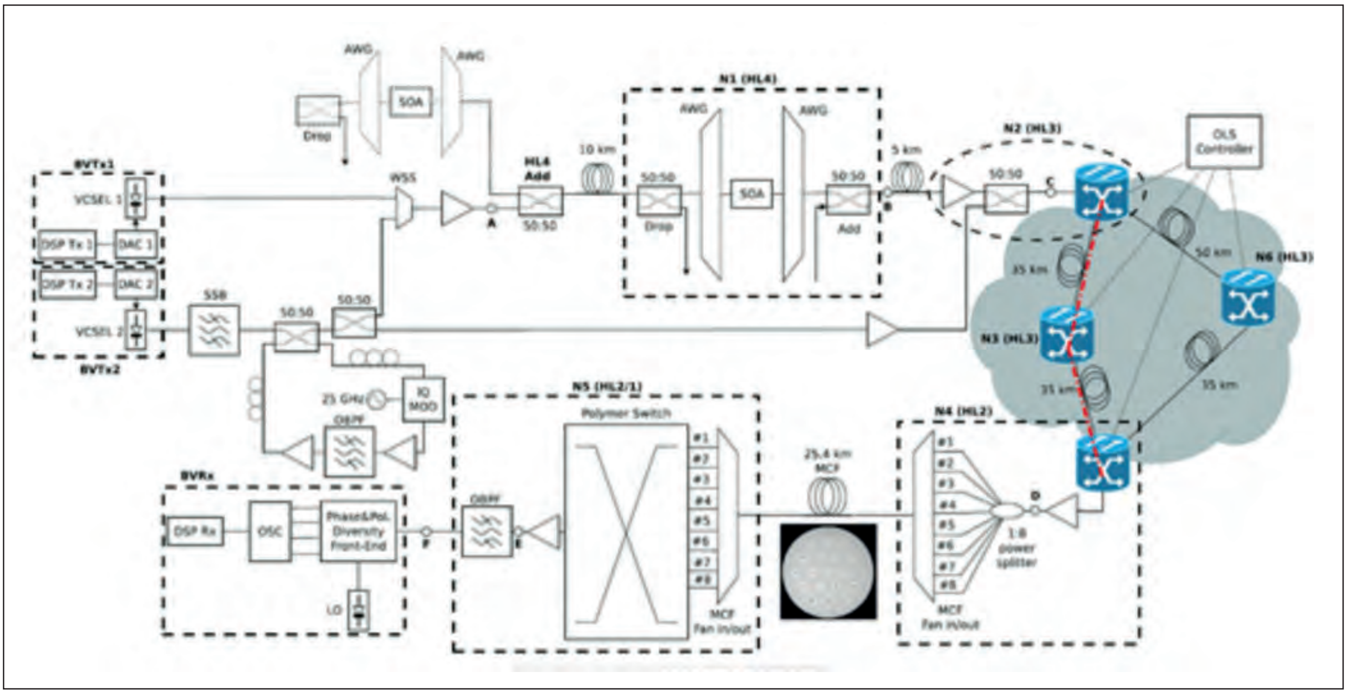


Figure 1: The experimental setup, including all components except the HL3 nodes, demonstrates the feasibility of the disaggregated metro area network.

Therefore, telcos are developing and deploying their own management software and would like to have open and standardized interfaces for the different network elements. That is why the disaggregated approach is an interesting paradigm that telcos are exploring," he said. Being free to source network equipment from a larger variety of providers enables an operator, for example, to offer types of services that most networks cannot accommodate today. It is about flexibility and innovation, he said.

"A main innovative network function could be network slicing. Let's assume that there are two services: One, critical infrastructure monitoring (e.g. in a railway network) and two, media content delivery (e.g. Amazon Prime Video, Netflix, or similar). These two services have different needs (and priorities) that should be matched. For example, the first service would be asking for limited capacity channels, but would need a consistent/limited latency/delay in order to communicate a plurality of sensors with an IT/cloud datacenter to process all the data and communicate with a command center that would be monitoring the infrastructure."

"On the other hand, our second example service would ask mainly for high-capacity connectivity between a content delivery datacenter and the corresponding subscribers. Of course, this service would also desire low latency, but this would be at a lower priority than what the first service needs. In order to match the different needs of those services, a telco can setup two different network slices, ensuring an exclusive use of resources (e.g. channels, network paths, transceivers, etc.,) is assigned to each service. In order to be able to perform this assignment at low level, the equipment should be able to be highly flexible and configurable. Of course, this could be achieved either by asking for an increased flexibility to the equipment vendor (increasing the cost of the solution) or by approaching the disaggregated paradigm," he explained.

Fabrega was quick to point out that the PASSION consortium of research groups dealt with the development of technologies, devices and systems that can support a disaggregated network. But network operators participated, and Fabrega pointed to the fact that Telefonica was a co-author of his group's report, 'In this sense, Telefonica was proposing the directions to follow and the requirements to be met in order to approach the disaggregation paradigm." According to Fabrega, designing a disaggregated network will need standardized components that meet internationally developed performance specifications as do components powering today's networks.

"Disaggregation is a paradigm that can be fully achievable with common state-of-the-art pluggable components, provided that they have an open interface and enough flexibility. In our case, we only focused on demonstrating the potential that PICs might offer, since they could cope with network disaggregation requirements while minimizing size, weight and power consumption. Even this last part is not a strong requirement for achieving network disaggregation, but it is of paramount importance in supporting environmental goals," he said.

Fabrega noted that PICs provide a compact/integrated version of what are today typically bulky devices. Saving space and reducing power consumption are essential PIC qualities. Concurrently, VCSELs offer the advantages of

> First, new components were developed/manufactured to this purpose: high-speed C-band VCSELs; a polymer optical switch, and an integrated coherent receiver (along with) others that were not used in the experiments

low cost and optical efficiency within a small footprint. VCSELs are lower cost due to a more straightforward manufacturing process than traditional commonly utilized semiconductor lasers. Since integrated photonic network components are still in their relative infancy compared to existing pluggable network counterparts, Fabrega said that anyone reading his group's report should appreciate that the idea was to demonstrate feasibility, which he believes was accomplished. But at no time did the group attempt to offer up a disaggregated network with fully qualified components ready for city-scale deployment.

"First, new components were developed/ manufactured to this purpose: high-speed C-band VCSELs; a polymer optical switch, and an integrated coherent receiver (along with) others that were not used in the experiments. Also, new systems were built based on these devices: network nodes and transceivers. Second, we had to integrate everything in a single place. In this case, it was at the CTTC premises in the Barcelona area of Spain. Since components were manufactured and tested in different areas of Europe (Germany, Netherlands, Italy, and Finland to name a few, and in South Korea,) they had to be appropriately packaged and shipped to the integration facilities," he explained. The actual integration phase started in mid-2020, which overlapped with the COVID-19 pandemic, a fact that slowed progress at a number of points and delayed completion by a number of months. Fabrega explained that for the network nodes, the researchers proposed an architecture depending on hierarchy level (HL). The HLs can be visualized as concentric rings, where traffic is aggregated from lower to upper levels. For example, traffic coming from HL4 is aggregated at HL3. In turn, HL3 traffic is aggregated at HL2, and so forth. Each transition means that more traffic must be supported.

"For HL4 nodes, PASSION proposes an architecture based on arrayed waveguide gratings in combination with semiconductor optical amplifiers," said Fabrega. "For higher hierarchy levels, a solution is proposed combining different types of wavelength selective switches together with innovative polymer switching stages."

The team tested their MAN with a transmission experiment and demonstrated a capacity of 1.6 terabytes per second, which is modest compared to the possible performance of the network, but demonstrates the feasibility of the concept. In the future, the researchers believe some of the constituent devices could be further improved to provide more flexibility. Although Fabrega said he believed the group demonstrated disaggregated network feasibility and its flexibility to enable new provisioning capabilities, he is not certain that disaggregation will automatically lead operators to see advantages to expanding their networks into underserved communities. But he noted that the disaggregation process, if taken to full implementation, could reduce equipment costs to the point that operators may have additional capital resources that could be used to serve new areas. At the same time, he expects that expanding service to some regions will likely still require governmental incentives.

"To my knowledge, it (would be) very difficult that disaggregation could enable (rural) expansion. The aim of disaggregation is to avoid vendor lock-in, and thus increase competitiveness and lower the cost of equipment. On the other hand, the main problem of rural areas is deploying optical fiber cables, rather than equipment. In those cases, a population is usually spread over a wide area. So, in order to cover rural areas, a high amount of work (and cost) is needed to lay down the cables; costs are high and potential revenues are low compared to an urban area where a high number of network subscribers can be expected in a smaller geographic area. This said, network disaggregation can decrease the cost of equipment. This could be beneficial in some specific cases, maybe some villages, in the sense that there might be a business case from the telco point of view. In other words, the decrease of cost in equipment could help to balance TCO in some cases," he concluded.

Whether disaggregation becomes a driving force in the development of future broadband networks remains to be seen. The concept does offer network operators the chance to remain 'unbound' to a single infrastructure equipment vendor, which could lead to reduced costs. By way of engaging more and different vendors in the equipment purchasing process, disaggregation could also support more flexible service provisioning. But opening up network equipment sourcing will not by itself provide more cost-effective means to serve rural areas. The build-out of rural broadband networks is likely to continue to require governmental supplements even if disaggregation moves to the center of creating new network architecture in the years to come.

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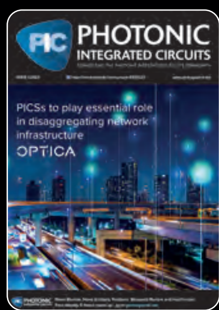

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