# PIC MAGAZINE

CONNECTING THE PHOTONIC INTEGRATED CIRCUITS COMMUNITY

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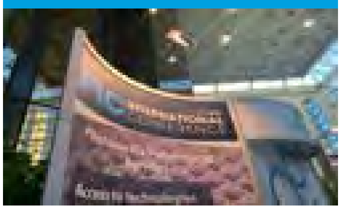
Advancing hybrid PICs

Silicon Nitride offers flexibility from R&D

PIC International Conference review



Paving the way beyond 400G Ethernet

Mode-locked lasers for spectroscopy

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# Viewpoint

By Mark Andrews, Technical Editor

## Photonics sales soar as supply chain worries linger

AS THIS FOURTH 2021 edition of PIC Magazine is finalized, sales numbers across photonics sectors remain strong, so 2022 should be great – right? Well, there is still the matter of ways that supply chain gaffs effect materials and finished product deliveries.

Worries aside, and as 2021 ticks away, researchers at the Dell'Oro Group note that network spending on broadband access began the year with a net 18 percent increase compared to 2020 figures that were themselves buoyed by the massive pandemic-driven shift to working and schooling from home. Analysts expect 2021 sales to be strong, but this is tempered by pull-backs in China and further delivery 'adjustments' that tie to ongoing supply chain disruptions. Put simply: we have done well selling photonics solutions and manufacturing them, but shipping and receiving can remain a Herculean task. Don't expect many changes until at least the second half of 2022, experts say. Meanwhile, analysts over at Lightcounting tout a five year photonics forecast that predicts the access optical market will grow to (USD) $7.6 billion by 2026 with most spending – 44 percent – going towards FTTx-PON expansions.

November marked the return to live programming for AngelTech 2021 in Brussels. The PIC International Conference, CS and Sensor Solutions International Conferences made up the full programme. PIC International Co-Chairmen Dr. Michael lebby and Dr. David Cheskis said the sixth edition of the only event focused entirely on photonic integrated circuits (PICs) again exceeded expectations. Dr. Lebby noted, "We again filled all of our seats, and believe it or not, we had standing only in many of the aural presentation sessions! There was (also) much cross pollination between parallel sessions from CS International and Sensor Solutions International."

In this edition of PIC Magazine we examine the leap in performance provided by Yokogawa's newest optical spectrum analyzer (OSA), the AQ6380. The new instrument's exceptional spectral resolution is ideal for PIC device development, R&D and related applications. We also look at emerging IEEE Ethernet standards that will create a framework for future PIC advances, and new Silicon Nitride (SiN) solutions from LIGENTEC that support the transition from pilot production to HVM.


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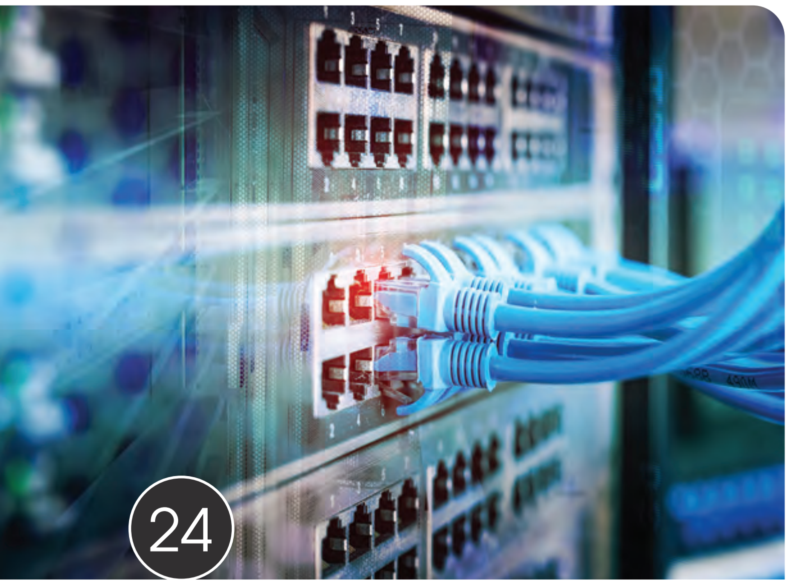


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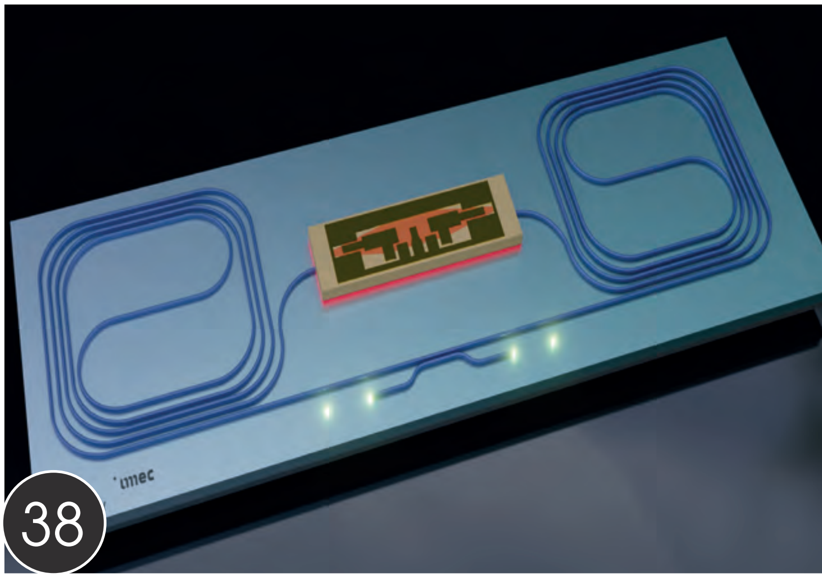
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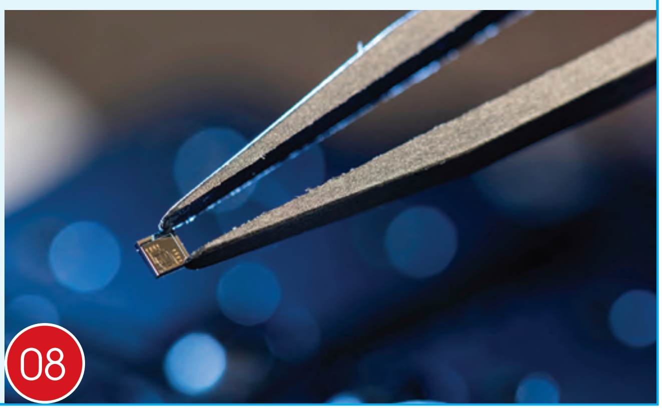
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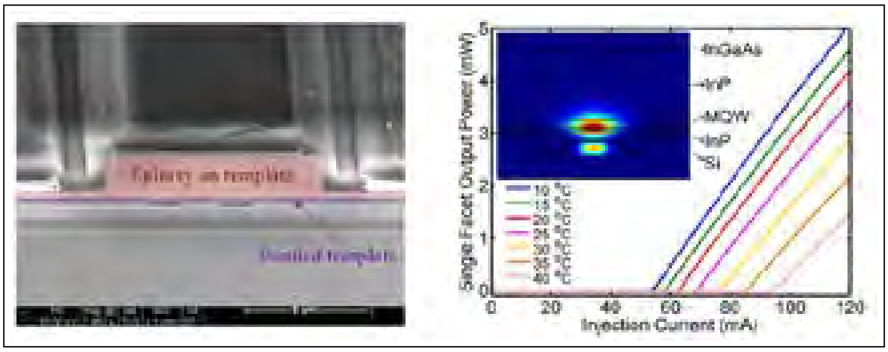
# Advanced III-V-on-silicon photonics

IN A NEW REVIEW ARTICLE publication from Opto-Electronic Advances, scientists from Hewlett Packard Labs in Milpitas discuss advanced III-V-on-silicon photonic integration.




Among various integration methods, heterogeneously integrating III-V material onto silicon substrate by using wafer bonding technology is the most popular one and is currently appearing in commercial products. Direct epitaxial growth of III-V layers on silicon, on the other hand, also has huge research interest due to its potential as a solution for very high density integration in the long term. In addition, a newly emerged III-V-on-silicon photonic integration method by epitaxial regrowth III-V material on a bonded substrate has attracted a lot of interest.

Research groups from Hewlett Packard Labs, III-V labs and Sophia University have invested in this advanced integration method and demonstrated their working lasers separately. By creating a native template on silicon substrate by using wafer bonding technology, lattice-matched epitaxy can be conducted accordingly on the template. This advanced integration method aims to providing high quality III-V-on-silicon photonic integration by benefit from both direct epitaxy and wafer bonding technologies.

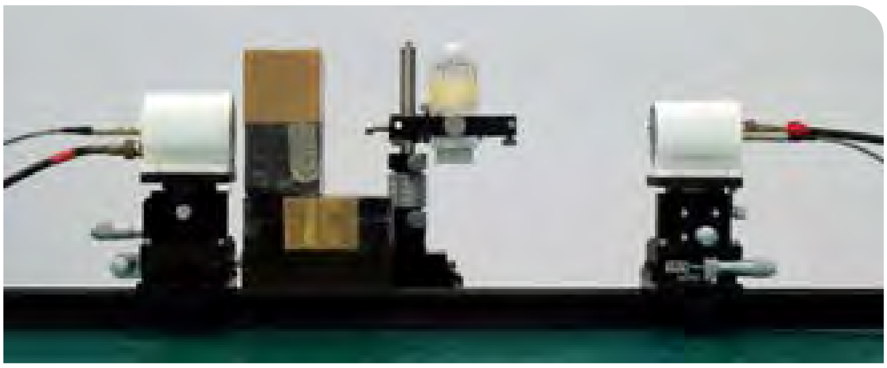
In this article, researchers from Hewlett Packard Labs review recent research work on this integration platform of regrowth on bonded template from various research groups. With the investigations of the similarities and differences of template developments, comparisons and analysis of the epitaxial regrowth and fabricated laser devices, growing interest and huge potential in this novel concept of regrowth on bonded template have been present.

Further discussions have indicated that this method has many potential advantages such as it provides high-quality laser material on Si substrate, and it is cost competitive over other existing III-V-on-silicon integration approaches. Particularly, except the great practicality for on-chip light source and other functional devices for Si photonics, researchers from Hewlett Packard Labs believes that this integration concept is a general approach for combining different materials onto various substrates.

'An advanced III-V-on-silicon photonic integration platform' by Hu YT, Liang D, Beausoleil RG; Opto-Electron Adv 4, 200094 (2021)

# Hamamatsu Photonics succeed in medical diagnostic imaging without image reconstruction

HAMAMATSU PHOTONICS has succeeded in being the first in the world to achieve high accuracy medical imaging without image reconstruction by utilizing a pair of detectors, and unique light detection and signal processing techniques.



Applying these successful research results are promising to achieve a completely innovative new type of radiation medical imaging system capable of making speedy diagnoses from a simple, compact setup yet with the same or higher accuracy than currently used radiation imaging systems including positron emission tomography (PET) and computed tomography (CT).

This will help boost inspection efficiency for detecting diseased tissues or organs, such as from cancer, and also reduce the radiation exposure dose, alleviating the load on the patient and medical staff. These research results were gained through a joint effort with a group led by Simon Cherry, a distinguished professor at UC Davis School of Medicine in the US, a group led by Professor Yoichi Tamagawa at University of Fukui in Japan, and with Professor Tomoyuki Hasegawa at Kitasato University in Japan.

The major results were published on Thursday, October 14, 2021 in the electronic edition of "Nature Photonics", a British scientific journal.

# Rockley Photonics unveils collaborative clinical research initiative

ROCKLEY PHOTONICS has formed a strategic relationship to incorporate Rockley's non-invasive biomarker sensing platform into potential clinical and healthcare research studies. Rockley will be working with the Icahn School of Medicine at Mount Sinai in New York, NY, part of the Mount Sinai Health System, for potential collaboration in future research studies.

The initiative aims to incorporate the next generation of non-invasive biomarker sensing in a series of studies to evaluate the use of wristbands and other wearables for a variety of potential applications, including remote monitoring and diagnosis. Rockley aims to create new opportunities for its photonics-based sensing platform in healthcare and medical applications and help expand the future use of real-time, non-invasive biomarker sensing for people around the globe.

"At Mount Sinai, we pride ourselves on our full-spectrum healthcare activities and relentless pursuit of leveraging the latest cutting-edge technologies in our research," said Zahi A. Fayad, director of the BioMedical Engineering and Imaging Institute, at the Icahn School of Medicine at Mount Sinai. "We are honored and delighted to incorporate our unique biomarker sensing technology in what could be many exciting and truly eye-opening research studies," said Dr. Andrew Rickman, chief executive officer and founder of Rockley Photonics.

"The learnings gained from these studies have the potential to accelerate the development of new algorithms and applications in remote healthcare, from real-time biomarker measurement to early disease state identification.

By enabling these new capabilities on a small wearable device, we expect to bring easier access to key health insights to larger and more diverse populations."

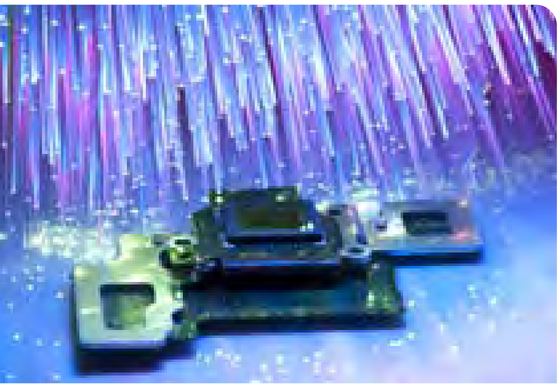
Rockley's sensing platform enables clinical and healthcare research practitioners to integrate more comprehensive non-invasive biomarker measurements in their remote monitoring studies. Rockley's patented silicon photonics-based laser technology significantly expands the range of biomarkers that can be detected and measured by current LED-based sensors.

This expanded range includes key biomarkers like core body temperature, blood pressure, body hydration, alcohol, lactate, and glucose trends, among others. These new measurement capabilities have the potential to transform digital healthcare by providing real-time insights into a variety of health conditions and by enabling early detection of multiple disease states.

# Tower Semiconductor and Anello Photonics Announce strategic partnership

TOWER SEMICONDUCTOR, a foundry of high value analog semiconductor solutions, and Anello Photonics, developer of the Silicon Photonic Optical Gyroscope (SiPhOGTM), has announced a strategic partnership for a new low-loss Silicon Optical Waveguide technology and manufacturing process.

The foundry version of the process will enable adoption in a wide range of markets such as including automotive LiDAR, bio-sensing, quantum computing, artificial intelligence, microwave photonics and optical communications requiring complex integration of high-performance optical devices.



The new low-loss Silicon Nitride waveguide process approaches 0.005dB/cm propagation loss at 1550nm wavelengths with less than 1mm bend radius. This novel process delivers one to two orders of magnitude lower loss than other commercial foundry processes at a compact bend radius for both 1550nm and 1310nm wavelengths.

The combination of low loss along with small bend radius enables fabrication of a new class of high performing devices, including long (>10m) delays lines and tiny on-chip resonators with high quality factors (high-Q) surpassing 100 million.

A range of optical applications such as automotive LiDAR, bio-sensing, quantum computing, artificial intelligence, microwave photonics and optical communications could all benefit from the breakthrough capabilities delivered by this new low-loss process.

"Silicon photonics is most strategic for Tower being a singular enabler in numerous fast-growing end-markets. Tower invests heavily in this area," said Russell Ellwanger, Tower Semiconductor CEO. "Working with Dr. Paniccia and his colleagues at Anello is an example of how Tower selectively partners with industry proven experts to develop and scale process technology with figures of merit otherwise unheard of, converting dreams into present realities."

Anello Photonics and Tower Semiconductor have developed this process over the last eighteen months, and Anello's SiPhOG gyroscope utilizes the process to directly replace the optical fiber found in a traditional Fiber Optic Gyroscope. A foundry version of this process is being offered by Tower to its customers beginning in Q1 2022.

"This announcement represents a breakthrough in low-loss optical transmission on silicon, enabling a variety of new silicon-based products previously not considered practical with integrated photonics fabrication technology", said Mario Paniccia, CEO and Co-Founder of Anello. "We are excited to work with Tower to industrialize this process for use in Anello's SiPhOG products and to meet other select Tower customer needs."

## Lumentum to acquire NeoPhotonics

LUMENTUM has announced that they have entered into a definitive agreement under which Lumentum will acquire NeoPhotonics for $16.00 per share in cash, which represents a total equity value of approximately $918 million. The transaction has been unanimously approved by the Boards of Directors of both companies.

The addition of NeoPhotonics expands Lumentum's opportunity in some of the fastest growing areas of the more than $10 billion market for optical components used in cloud and telecom network infrastructure. The integrated company will be better positioned to serve the needs of a global customer base who are increasingly using photonics to accelerate the shift to digital and virtual approaches to work and life, the proliferation of IoT, 5G, and next-generation mobile networks, and the transition to advanced cloud computing architectures. The combination creates a stronger partner for customers, with the ability and intent to invest strongly in innovation and manufacturing capacity.

"With NeoPhotonics, we're making another important investment in better serving our customers and expanding our photonics capabilities at a time when photonics are at the forefront of favorable long-term market trends," said Alan Lowe, Lumentum president and CEO. "At the centre of our strategy is a relentless focus on developing a differentiated portfolio with the most innovative products and technology in our industry so that we can help our customers compete and win in their respective markets. Adding NeoPhotonics' differentiated products and technology and innovative R&D team is consistent with this strategy and together, we will better meet the growing need for next generation optical networking solutions. We are confident this transaction will make us an even better partner to our customers, while enabling our team to deliver significant, long-term value to our stockholders. We look forward to welcoming NeoPhotonics' talented team of employees to Lumentum," concluded Lowe.

"Today's announcement is an exciting milestone for NeoPhotonics," said Tim Jenks, NeoPhotonics president, CEO, and chairman. "The increasing global demand for our ultra-pure light tunable lasers and photonics technologies for speed over distance applications is more apparent than ever, and Lumentum is the ideal partner to serve our customers on a larger scale.

# NTU Singapore launches Quantum Science and Engineering Centre

NANYANG TECHNOLOGICAL UNIVERSITY, Singapore (NTU Singapore) has launched the Quantum Science and Engineering Centre (QSec), which aims to develop devices and technologies powered by quantum science - the study of how particles behave at the atomic level.

The centre, the first of its kind in Singapore, will conduct research on developing and producing quantum chips using semiconductor fabrication technologies.

These chips form the backbone of quantum devices such as quantum chip processors, networks, and sensors. They hold important applications in many areas such as quantum computing, communication, cryptography, cybersecurity, and sensor technology.

The Centre aims to train skilled manpower for quantum engineering, the application of quantum science to real-world scenarios, and to promote and develop Singapore's quantum industry. It will collaborate with the Centre for Quantum Technologies (CQT), a Research Centre of Excellence established since 2007, on quantum technology research and engineering application, and look to establishing an international platform to collaborate with other overseas partners.

The opening ceremony for QSec was witnessed by Mr Chan Chun Sing, Minister for Education and NTU President Professor Subra Suresh.

Education Minister Mr Chan Chun Sing said: "Quantum science, technologies, and engineering have drawn huge investments worldwide. Singapore is a long-standing investor in its potential and remains at the forefront of this field. In 2018, the National Research Foundation started a quantum engineering programme with the goal of establishing a competitive quantum engineering research community and industry ecosystem to translate the technology into real-world applications. We look forward to the Quantum Science and Engineering Centre's (QSec) contributions to Singapore's efforts in advancing quantum technologies, especially in the development of quantum computing chips and quantum communications."

NTU President Professor Subra Suresh said: "The Quantum Science and Engineering Centre (QSec) aims to conduct ground-breaking research in several areas: quantum key distribution chips, quantum computation, quantum and classical neural network, cluster state computation and quantum sensing. NTU's focus in these areas is part of our strategy to be a key enabler in the development of quantum science technologies to support Singapore's efforts in quantum engineering for the benefit of industry and society."

# Luceda Photonics opens Chinese subsidiary

LUCEDA PHOTONICS has launched their subsidiary office Luceda (Shanghai) Software and Technology Co., Ltd, in Shanghai, China, after more than 4 years' experience in the Chinese market. The Chinese region is the second most important market within Luceda's portfolio (with revenue doubled between FY19 and FY20).

This local presence will enable Luceda to bring resources closer to customers and partners, such as CUMEC, IME-CAS, SITRI-CAS, AEMD Shanghai Jiaotong University, and provide products and services specifically targeted at the Chinese market. The team in Shanghai has a strong background in PIC and EDA (Electronics Design Automation) in addition to professional experience in the Belgian HQ.

The Integrated Photonics market in China is projected to grow 20% CAGR, more than other regions. Luceda has in-depth technical market knowledge, and the local venture responds to China's intention to replace IP in the fields of data- and telecom, IOT, 5G, Lidar, and sensing with international IP. The proximity to fabrication partners such as CUMEC, IME-CAS, and SITRI, will further enhance collaboration efficiency.

Luceda Photonics offers the IPKISS Photonics Design Platform, an integrated photonics design environment that enables researchers and companies to automate and integrate all aspects of their photonic design flow in one tool. Leveraging the benefits of its Python code-based approach, the platform enables IP management, and enhances teamwork and design flow efficiency.

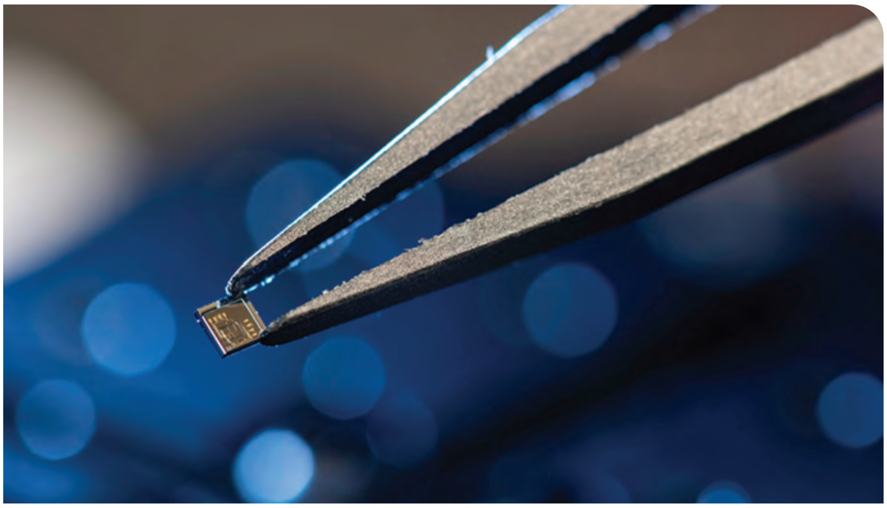
IPKISS covers the complete photonic integrated circuit (PIC) design flow, from initial idea to design, simulation and validation. It is equipped for niche solutions ranging from 5G, Internet of Things, fibre to the home, Lidar, Artificial Intelligence, (Bio)Sensing and Quantum Computing.

"Luceda's goal is to bring a 'human-centric' way of thinking to China and develop an attractive corporate culture with values such as empowerment, flexibility, expertise, and complement these with traditional Chinese values such as perseverance, (commercial) drive and commitment", says Dr. Ruping Cao, general manager of Luceda China.

"I am among the first users of Luceda's expert product in China. At CUMEC, we've set up an internal PDK development and knowledge consolidation workflow based on IPKISS, which helps us to quickly iterate the PDK development and release cycle.

We currently offer our CSiP180Al and CSiP130Cu PDKs in the Luceda software kit. This enables our foundry user to efficiently and confidently carry out Silicon Photonics design projects, and ship quality designs to us", says Dr. Guowei Cao, CUMEC PDK development team lead.

# Tiny chip provides a big boost in precision optics



RESEARCHERS at University of Rochester's Institute of Optics for first time distill novel interferometry into a photonic device.

By merging two or more sources of light, interferometers create interference patterns that can provide remarkably detailed information about everything they illuminate, from a tiny flaw on a mirror, to the dispersion of pollutants in the atmosphere, to gravitational patterns in far reaches of the Universe.

"If you want to measure something with very high precision, you almost always use an optical interferometer, because light makes for a very precise ruler," says Jaime Cardenas, assistant professor of optics at the University of Rochester.

Now, the Cardenas Lab has created a way to make these optical workhorses even more useful and sensitive. Meiting Song, a PhD student, has for the first time packaged an experimental way of amplifying interferometric signals – without a corresponding increase in extraneous, unwanted input, or "noise" – on a 2 mm by 2 mm integrated photonic chip. The breakthrough, described in Nature Communications, is based on a theory of weak value amplification with waveguides that was developed by Andrew Jordan, a professor of physics at Rochester, and students in his lab.

Jordan and his group have been studying weak value amplification for over a decade. They have applied mode analysis in a novel way on free space interferometer with weak value amplification, which bridged the gap between free space and waveguide weak value amplification. Therefore, they were able to prove the theoretical feasibility of integrating weak value amplification on a photonic chip.

"Basically, you can think of the weak value amplification technique as giving you amplification for free. It's not exactly free since you sacrifice power, but it's almost for free, because you can amplify the signal without adding noise – which is a very big deal," Cardenas says.
Weak value amplification is based on the quantum mechanics of light, and basically involves directing only certain photons that contain the information needed, to a detector. The concept has been demonstrated before, "but it's always with a large setup in a lab with a table, a bunch of mirrors and laser systems, all very painstakingly and carefully aligned," Cardenas says. "Meiting distilled all of this and put it into a photonic chip," Cardenas says. "And by having the interferometer on a chip, you can put it on a rocket, or a helicopter, in your phone – wherever you want – and it will never be misaligned."

The device Song created does not look like a traditional interferometer. Instead of using a set of tilted mirrors to bend light and create an interference pattern, Song's device includes a waveguide engineered to propagate the wavefront of an optical field through the chip.
"This is one of the novelties of the paper," Cardenas says. "No one has really talked about wavefront engineering on a photonic chip."

Traditional interferometry (left) requires an elaborate set up of mirrors and laser systems all very painstakingly and carefully aligned," Cardenas says. Song "distilled all of this and put it into a photonic chip." The chip (above) requires only a single microscope. (University of Rochester / J. Adam Fenster)

With traditional interferometers, the signal to noise ratio can be increased, resulting in more meaningful input, by simply cranking up the laser power. But there's actually a limitation, Cardenas says, because the traditional detectors used with interferometers can handle only so much laser power before becoming saturated, at which point the signal to noise ratio can't be increased.

Song's device removes that limitation by reaching the same interferometer signal with less light at the detectors, which leaves room to increase the signal to noise ratio by continuing to add laser power.

Bottom line: "If the same amount of power reaches the detector in Meiting's weak value device as in a traditional interferometer, Meiting's device will always have a better signal to noise ratio," Cardenas says. "This work is really cool, really subtle, with a lot of very nice physics and engineering going on in the background."

Next steps will include adapting the device for coherent communications and quantum applications using squeezed or entangled photons to enable devices such as quantum gyroscopes.
Other collaborators include Yi Zhang and Juniyali Nauriyal of the Cardenas lab, John Steinmetz of the Department of Physics and Astronomy, and Kevin Lyons of Hoplite AI.

The project was funded by A. N. Jordan Scientific, in partnership with Leonardo DRS, and in part by the Center for Emerging and Innovative Sciences (CEIS). Fabrication was performed at the Cornell NanoScale Facility, with support from the National Science Foundation.


# Yokogawa's AQ6380 OSA sets new performance standards

The optical spectrum analyzer (OSA) has been a mainstay instrument since photonics and optoelectronics first began transforming high speed digital communications. The experts at Yokogawa delve into highlights of their class-leading AQ6380 in a discussion with the company's European marketing manager.

**BY KELVIN HAGEBEUK, PRECISION MAKER, MARKETING MANAGER - TEST & MEASUREMENT, YOKOGAWA EUROPE B.V.**

**MA:** *Optical spectrum analyzers are essential to any advanced photonics R&D or product development work. Can you update us concerning Yokogawa's role in the industry and what led to the AQ6380?*

**YOKOGAWA:** For decades, the Optical Spectrum Analyzer (OSA) has been a workhorse in the R&D labs of telecommunications and networking equipment and component manufacturers. These companies use OSAs to characterize cables, components and systems for fiber optic communications applications.

With this field in mind, the Yokogawa AQ6380 offers the leading optical performance required by engineers and scientists as they develop and improve the speed, bandwidth and quality of the optical devices used in the next generation of telecommunication networks.

Yokogawa has been developing OSAs since 1980 and now offers eight models. These OSAs cover a wide range of wavelengths, from the visible light spectrum to the mid-wavelength infrared region.

This range of wavelengths is needed because as well as testing telecommunications components, they are also increasingly used for precision measurement in the fields of industrial production, bio-photonics and healthcare, LED lighting, quantum computing and environmental sensing. These trending application areas have all led to a demand for greater wavelength range. OSAs are key instruments for scientific researchers who appreciate the superior performance of Yokogawa's rotating grating technology compared to other measurement instruments such as spectrometers. In all these applications, our customers prize the precision and sensitivity of Yokogawa's spectrum analyzers.

**MA:** *The spectral resolution of the new analyzer appears to represent a real leap in performance. Can you describe the highlights of key factors that contribute to this achievement?*

**YOKOGAWA:** Our new monochromator, which forms the heart of the OSA, has been completely redesigned and has sharper spectral characteristics than ever before. It ensures the AQ6380 can offer an excellent optical wavelength resolution of up to 5 pico-meters. This means that optical signals in close-proximity, such as different DWDM-channels or different spectral components found in lasers, can be clearly separated.

This resolution is required because growing traffic leads to networks using more power, which also causes increased carbon emissions. One approach to cutting energy use is to utilize networks more efficiently, getting more data through the same cable. High capacity optical backhaul networks will be needed to serve this growing traffic density, so developers need to distinguish different frequencies more clearly. Another stand-out quality of the AQ6380 is the fact this new instrument offers 0.005 nm wavelength resolution, four times better than the AQ6370D-22's figure of 0.02nm. With the AQ6380, waveforms that were previously not even visible, such as modulation side peaks in the laser spectrum, can now be accurately visualized.

**MA:** *How does this new analyzer compare to competing solutions?*

**YOKOGAWA:** The AQ6380 offers the leading optical performance that engineers and scientists need to develop and improve the speed, bandwidth and quality of optical devices used in the next generation of telecommunication networks.

The AQ6380 is the world's best grating based OSA, so it is second to none. It outperforms other suppliers' OSAs by wavelength accuracy, resolution, dynamic range, and actual measurement speed. There isn't really another OSA on the market that offers this combination of competing specifications. The instrument that comes closest is Yokogawa's own high-performance AQ6370D-22.

**MA:** *What can the AQ6380 do for PICs that other analyzers can't do as well?*

**YOKOGAWA:** Future bandwidth requirements push the performance of DWDM systems. As a result, the telecommunication channels of optical transceivers become ever more closely spaced, making it a challenge for the OSA to separate the individual channels.

When testing PICs used in WDM transmission systems, high spectral measurement performance is required to test the system's internal circuit boards, including laser modules and optical transceivers.

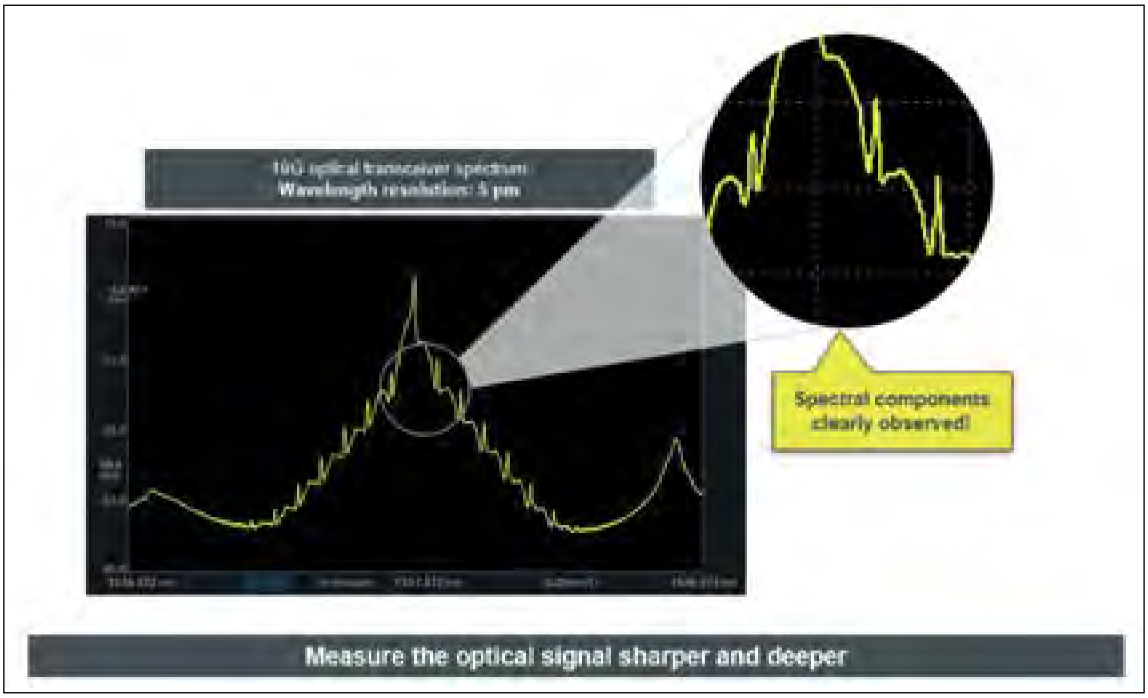
Testing these optical components requires high accuracy. Applications may include modulated signal measurement of optical transceivers and transponders and measurement of all WDM channels of optical transceivers beyond 100G.

The AQ6380's high resolution and wide close-in dynamic range allows accurate OSNR measurement, while the built-in WDM analysis function analyzes the measured waveform and shows peak wavelength, peak level, and OSNR up to 1024 channels simultaneously.

The AQ6380's SHARP spectral characteristics and high stray-light suppression performance enable developers to visualize and accurately measure spectral peaks that are very close together.

**MA:** *In comparing how the AQ6380 operates alongside other members of the Yokogawa lineup, or comparing it to competing analyzers, how easy is it to get started and use the AQ6380 on a daily basis?*

**YOKOGAWA:** The new AQ6380 is designed for ease and efficiency of use, ensuring the measurement scheme can be set up rapidly and data can be acquired easily.

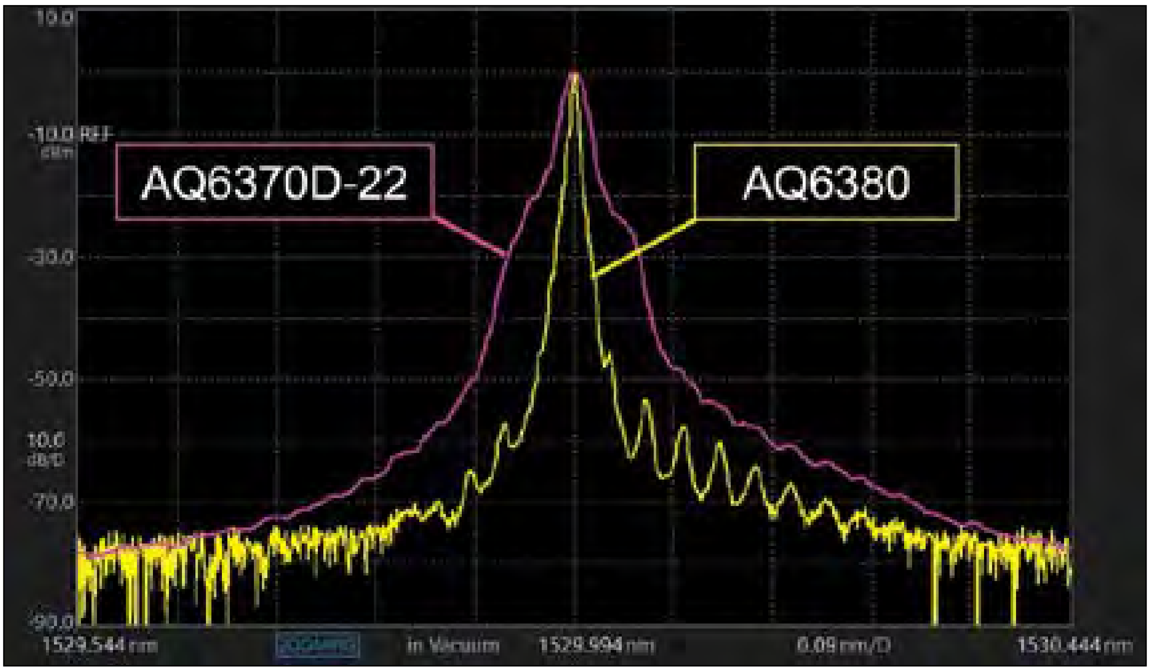



The AQ6380 achieves a wavelength resolution of 5 pm. It enables the separation of closely allocated DWDM channels and modulation side peaks of optical transceivers, which were not visible with previous models.

The high-resolution, responsive 10.4-inch touchscreen LCD makes the device as easy and intuitive to operate as a tablet. When it comes to analyzing results, the AQ6380 has built-in analysis functions to characterize optical spectrum from a variety of optical systems and devices, such as WDM system, DFB-LD, EDFA, and filters.

Analysis functions include: DFB-LD; FP-LD; LED; Spectral width (peak/notch); SMSR; Optical power; WDM (OSNR); EDFA (Gain and NF); Filter (peak/bottom) and WDM filter (peak/bottom). With a few button presses, all information is available on the display. The AQ6380 also features an application menu known as “APP mode”, which makes measurement set-up much easier. It is much like using a smart-phone or tablet. Pushing the APP button brings up an overview of the pre-installed testing apps – WDM, DFB-LD, FP-LD and LED testing. A guide through wizard leads the user through an easy set-up process for specific measurements and analysis.

New or additional testing applications will be made available to customers for download from the Yokogawa website and can be added to the AQ6380 by future firmware updates.




Modulated spectrum of 10G optical transceiver

**Yokogawa instruments are renowned for maintaining high levels of precision and for continuing to deliver value for far longer than the typical shelf-life of such equipment. Yokogawa believes that precise and effective measurement lies at the heart of successful innovation**

**MA:** *Yokogawa's analyzers are known for quality. How does the value proposition work when a researcher needs to convince her department to make a new investment?*

**YOKOGAWA:** The AQ6380 is not a basic analyzer - it's the world's best grating based OSA, so it is second to none. It's an extreme precision Optical Spectrum Analyzer that features improved precision for developing and producing the next generation of optical network backhaul components.

Moreover, Yokogawa instruments are renowned for maintaining high levels of precision and for continuing to deliver value for far longer than the typical shelf-life of such equipment. Yokogawa believes that precise and effective measurement lies at the heart of successful innovation. The company has focused its own R&D on providing the tools that researchers and engineers need to address challenges great and small.

One other benefit is the ability to emulate the OSA on a PC and control it remotely with the 'OSA Viewer' application software. OSA Viewer's user interface and analysis capabilities allow R&D and production users to easily view and analyze waveforms on their PC or laptop.

The AQ6380 can be controlled remotely via a direct connection or over a network. An automated measurement system can be readily built with a remote-control interface using either Ethernet or GP-IB. The remote command set conforms to the Standard Commands for Programmable Instruments (SCPI). Other Yokogawa OSAs use the same command set, which is compatible with AQ6370 series and AQ6319, as well as proprietary AQ6317-compatible commands.

These features are ideal when R&D users need to evaluate and analyze measurement data, optimize test conditions and troubleshoot on remote lines, and when production users need to collect and analyze measurement results from remote production lines.

**MA:** *What characteristics translate most readily into benefits the researcher will appreciate?*

**YOKOGAWA:** Excellent optical wavelength resolution of 5 pm allow optical signals in close proximity to be clearly separated. This is a key capability.

**MA:** *Yokogawa products are second to none. What else sets the company apart from competitors, especially in light of the challenges we face in recovering from a global pandemic?*

**YOKOGAWA:** At Yokogawa Test & Measurement, we provide more than simply products. We provide lasting value to customers. Our diverse and comprehensive range of solutions and services mean we are constantly working closely with our customers. Yokogawa believes that precise and effective measurement lies at the heart of successful innovation – and has focused its own R&D on providing the tools that researchers and engineers need to address challenges great and small.

One of the essential aspects of maintaining the accuracy of an OSA is regular calibration to known standards. The AQ6380 employs on-board calibration through a built-in light source. Calibration of the wavelength is performed automatically at set intervals by switching the optical path with an internal optical switch. Yokogawa instruments are renowned for maintaining high levels of precision and for continuing to deliver value for far longer than the typical shelf-life of such equipment. Purchasing an OSA from Yokogawa is a future proof investment. For current Yokogawa OSA users, the AQ6380 is also backward compatible, making it easy to upgrade existing measurement systems.

For further information about the AQ6380, please visit:

Cleanroom in a CMOS line. Image courtesy of X-FAB

# Silicon Nitride offers flexibility to move from R&D to volume production

Silicon nitride (SiN) now provides additional pathways to photonic integration including a new 200mm, high volume, automotive qualified CMOS production line. The material platform has gained maturity over the past years next to well-established silicon photonics and offers new opportunities in photonic integrated circuit (PIC) markets for applications that need very low propagation losses, visible wavelength or high laser power.

PHOTONIC INTEGRATED CIRCUITS (PICs) are ready to repeat the success story of electronic integrated circuits (ICs). PICs work with light instead of electrons and will play a key role in tomorrow's infrastructure in communication, sensing and transportation. Whereas silicon photonics has been around for more than 20 years, new material platforms have been introduced in the past decade that offer additional benefits.

The motivation for using silicon nitride (SiN) waveguides are manifold. Firstly, silicon nitride is a well-known material that is CMOS compatible and already used in the semiconductor industry. This enabled the development of fabrication techniques and process design kits (PDKs) with standard CMOS tools. This was one of the main requirements when scaling a process afterwards to volume or more importantly when using already existing infrastructure to run the process. Secondly, silicon nitride as a material offers new possibilities to the PIC market. If we look, for example, at the application wavelength as one major parameter we can see that in classical silicon photonics, where the optical wave is guided in silicon, transparency starts above one micron. This is perfect for many fiber optical applications, especially communications.

However, there are many more applications which require light propagation at lower wavelengths that cannot be served by silicon photonics. Silicon nitride with its transparency window spanning from the visible to the mid infrared opens the path for new applications. In addition to that, silicon nitride offers extremely low propagation losses compared to silicon or indium phosphide. Last but not least, high power propagation of several Watts of CW laser power is possible due to the large bandgap of silicon nitride. This is why silicon nitride offers superior performance to manage the light in the chip circuitry with unprecedented low propagation losses and high-power handling.

## Existing applications

Telecom and datacom industries are one of the largest PIC consumers as of today. Lowering optical losses is getting more important in those domains, since optical loss affects not only the energy consumption, but also the performance of the devices. The cross-talk performance of arrayed waveguide gratings for wavelength division as MUX and DEMUX for example is directly proportional to optical propagation loss. AWGs with high propagation losses are accumulating phase errors in their arms which results in increased cross talk between the channels. Another key parameter is to have low temperature dependence of the AWG to minimize the thermal effects on device performance.

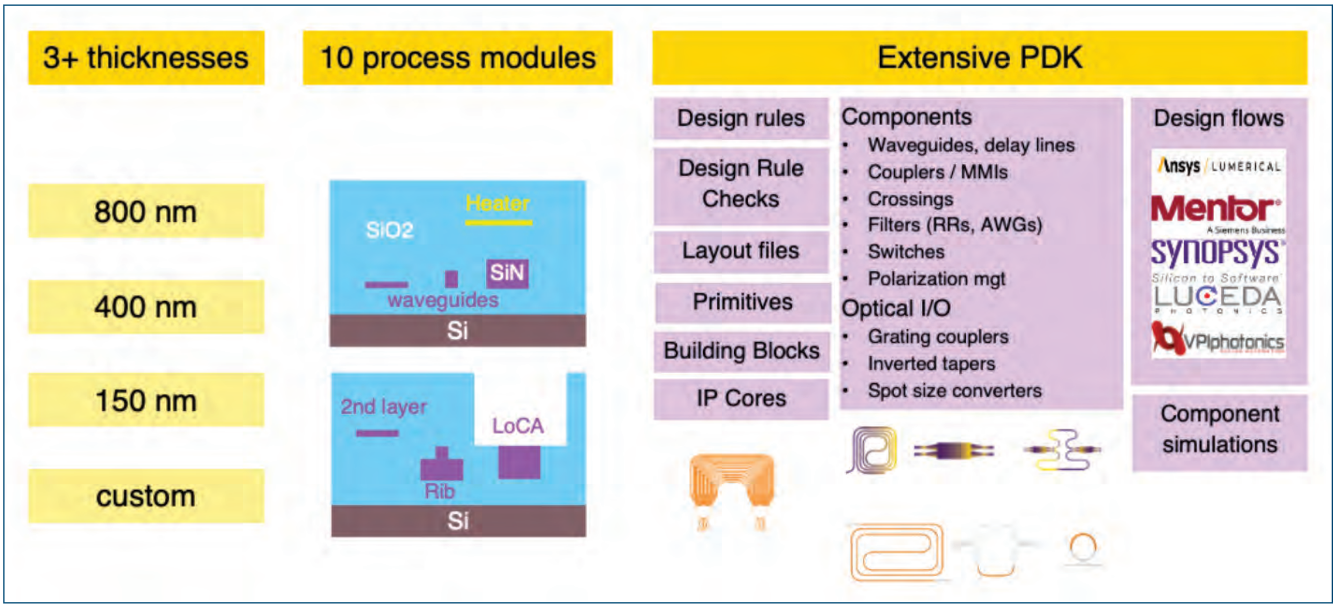
Here silicon nitride offers a 10 times lower temperature dependence than silicon. Additionally, a good process control is needed to ensure the right wavelength band selection. Statistical process control guarantees this with LIGENTEC's fabrication platform. Especially for AWGs LIGENTEC's proprietary technology provides a competitive advantage, as not only the loss of the waveguides are very low, but also the area size of the arrayed waveguide grating is small due to the small bending radius common to the platform. This is enabled by the high confinement of the optical mode in the waveguide. The LIGENTEC platform offers very low phase errors together with a small footprint.

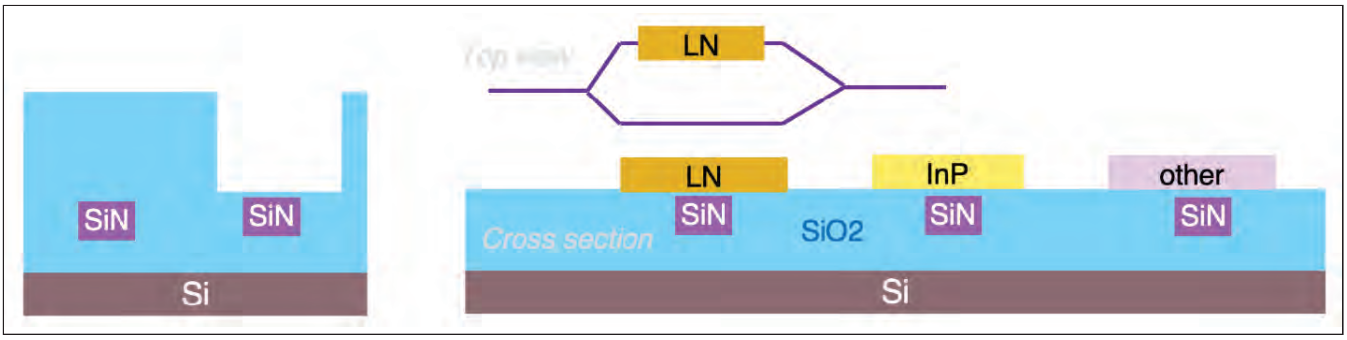
## New applications

The above-mentioned advantages are also of great importance to other new applications. To enable fully autonomous driving, for instance, it is expected that the next generation of LiDAR sensors for long distance sensing will be based on coherent detection. Here the reflected beam is mixed with a local oscillator, filtering out all light that is not coming back in reflection from the object. These coherent detection schemes are rather complex and benefit significantly from photonic integration.

Key requirements for such an FMCW LiDAR system are the ability to transmit high optical power, have low propagation loss and low phase errors and last but not least low cross talk between the transmit and receive channels. A key building block here is the delay line interferometer, used to control the modulation of the laser signal. The length of the delay line is a critical performance parameter since it relates directly to the precision of the range measurement. With the low propagation loss and short bend radius, delay lines of 1m on chip are possible. This in combination with low phase noise enables high resolution FMCW LiDAR solutions.

One of the most promising paths to realize quantum computers is with photons. The only way to achieve

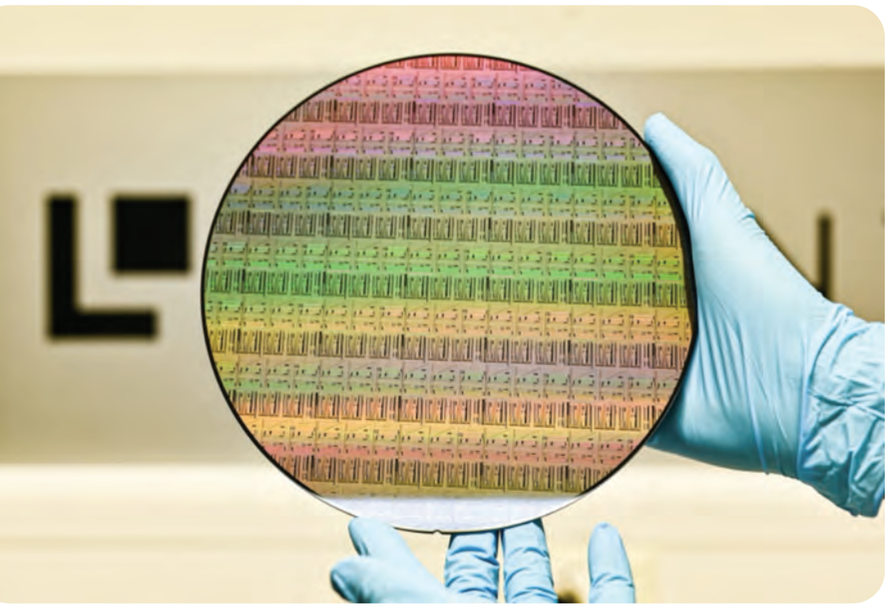





a scalable photonic quantum computer is via photonic integration where the quantum states are generated and processed optically. A high phase stability between the individual components is an absolute requirement to preserve the quantum states. The chip technology gives a phase stability which is not achievable with discrete optical components. Moreover, a quantum computer needs hundreds of nodes to be able to compete with classic computers, the components for each node need to be small and scalable at the same time. For all of the above-mentioned reasons, photonic integration is the only way to realize photonic quantum computers. In Quantum Photonics, every photon counts, the biggest challenge is to keep the photon losses at a minimum. A low loss PIC platform is therefore a key requirement for a successful photonic integration.

Xanadu, a leading quantum computation company has recently demonstrated first-time cloud-based quantum computing at room temperature using LIGENTEC silicon nitride chip technology.

To address existing and new applications LIGENTEC has developed a process fabrication offering that goes hand in hand with an extensive process design kit (PDK). The waveguide width is a design parameter and more than 10 process modules are available to create a variety of useful features, e.g. rib waveguides, dual layer waveguides, thermal tuning elements and local cladding openings for sensing applications or heterogeneous integration with other materials.



The PDK library also includes a large range of components and building blocks with known performance and statistical data to be used by designers as blocks to build the circuit. These building blocks range from various kinds of waveguides to splitters, crossings, and delay lines to filters, polarization rotators and polarization filters. Additional building blocks range from mirrors to components for optical in and out coupling. This is supported by design flows with commercial software and design houses with platform expertise.

As silicon nitride is an intrinsic passive material, LIGENTEC has developed special fabrication modules to integrate active materials. With heterogeneous integration, the material of choice can be placed on top of the SiN waveguide. For example, consider a Mach-Zehnder interferometer-based modulator where the optical phase is changed in one arm and the combined resulting output modulated to realize a fast switch or modulator reaching tens of GHz modulation speed. By placing a piece of Lithium Niobate directly on top of the SiN waveguide, part of the light will be travelling in the upper material and can then be manipulated.

The same principle can be applied to bond III-V components such as lasers or detectors.

In September 2021, LIGENTEC announced the implementation of its proprietary, low loss silicon nitride process technology within the X-FAB foundry ecosystem. With this partnership, all essential elements of the PIC ecosystem are now commercially available in volume within Europe, a key requisite to enable the secure and independent supply of the foreseen high volumes in sensors for self-driving cars, quantum computers, biosensors and other applications. Thanks to this strategic partnership with X-FAB, LIGENTEC now takes volume production requests for low loss SiN PICs based on 200mm wafers. In this way LIGENTEC is looking forward to expanding its offering of fast turnaround, high quality, low loss PICs to its existing base as well as new customers.

PIC INTERNATIONAL CONFERENCE

# A thrilling 6th Photonic Integrated Circuits International Conference in Brussels

Co-Conference Chairs, Dr Michael Lebby, Lightwave Logic and Dr David Cheskis, Lumentum, reflect on the 6th PIC International Conference that was not only well attended but became the core conference for PICs globally.

WE HAVE JUST FINISHED the 6th annual PIC International Conference, and again like in 2019 and 2020, it not only surpassed everybody's expectations, but thrilled us with live presentations, live audience, live panels, live Q&A and incredible technology updates and progress. The whole value chain was represented that ranged from wafers to epitaxial growth, devices, packaging, modules and systems, to social media that PIC International is the conference to attend if your interest is Photonic Integrated Circuits (PICs). We again filled all of our seats, and believe it or not, we had standing only in many of the aural presentation sessions! There was much cross pollination between parallel sessions from CS International and Sensor Solutions International.


This year, there were over 600 delegates attending three days of highly condensed sessions on photonic integrated circuits (PICs) that focused not only on innovative technology, but how PICs could alleviate major headaches that optical networks, datacentres, telecommunications systems, etc see today. Many talks focused on how PICs could be implemented into novel and innovative applications to move the industry forward, and keep the industry moving forward such as Automotive LIDAR, sensing, displays, healthcare, etc.

As in 2020, one of the biggest drivers for PICs are fiber optic communications for datacentre interconnects. A number of global giants conveyed huge opportunities for PIC innovative solutions for their businesses that addressed high speed, low power consumption, innovative packaging (via co-packaged solutions), reliability, and cost effectiveness.

There were 2 live panel sessions that were chaired by Dr. Bill Ring and Dr. Jose Pozo that addressed volume scaling and opportunities for PICs as well as the growing opportunities for PIC in Automotive LIDAR.

The panels were filled with technical experts that are internationally known PIC technologists. Both of these live panels generated lots of Q&A and live discussion. There were also talks that explored PIC based technologies outside of fiber optics, and those areas included healthcare, bio, sensing, and LIDAR for automotive applications. One of the most promising segments for PICs is the use of PICs in the automotive market, and this was forecasted to grow very quickly over the next decade.

The conference discussed in detail incumbent PIC technologies such as InP, Silicon Photonics, and GaAs, as well as exciting new and emerging technology platforms such as Polymer Photonics (PP) and Dielectric Photonics (DP). Hybrid PICs was used to denote the mixing of various technology platforms to improve the overall performance of PICs. Examples were the use of electro-optic polymers onto silicon photonics, and as well as dielectric materials for integrated Photonic solutions on silicon wafers.

The incredible growth of silicon photonics continues with an increase in popularity and acceptance as a new incumbent technology. Indium phosphide as one of the incumbents was demonstrated to show higher density PICs that are expected to impact the 5G markets, and there were exciting reports of PIC in novel 3D sensing and LIDAR applications.

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

There were a number of exciting sessions, where one session discussed improvements in PIC infrastructure for designing and manufacturing robust and reliable PICs using software tools for modelling, simulation, and production. This was supported by many PIC talks that addressed PDKs and other metrics needed to quickly grow PIC markets.

This year, new and innovative talks discussed how PICs based technologies can enable new products that are more miniature, low power, and high performance, which is becoming especially important for hand-held battery powered diagnosis and health monitoring products. The conference speakers showed that the result of designing PICs for the popular verticals of telecommunications and data communications and how these solutions could easily be applied to medical, measurement, automotive, and other industrial applications for PICs.
Networking was truly first class with a perfectly designed exhibit right next to the conference rooms

The conference discussed in detail incumbent PIC technologies such as InP, Silicon Photonics, and GaAs, as well as exciting new and emerging technology platforms such as Polymer Photonics (PP) and Dielectric Photonics (DP)

that gave the attendees incredible opportunities to meet other folks in the PIC infrastructure. The excitement of a live conference, and to some, the first live conference in 2years clearly showed amongst attendees. While virtual is great, and virtual allows work to get completed, and families to meet, live is better. Live is much better!

The good news is that some of these opportunities will be high volume such as GaAs VCSEL arrays for sensing (as used by mobile phones), as well as high density PICs for short distance optical interconnects. The opportunities that consumer markets will bring to PIC based technologies is only just beginning, and we will have to wait to see how the extreme high-volume ramps will play out over the next year.

All presentations showed a number of improvements in the technology over the past 24 months. PIC markets are growing strongly to many 10s of $B over the next decade, as well as the scalability of PIC technological platforms. The rise of the hybrid PIC, the co-packaged platform, and shared foundries showed that customers are now more open than ever to find the right PIC solution for their particular portfolio.

A focused, thrilling, and well attended conference, with a high level of technical content, PIC International surpassed itself again in 2021. PIC International is the conference to attend for the latest and greatest in photonic integrated circuits and has become a truly global and credible event. Have the event live really made the difference. You'll have to attend next year to immerse yourself in the excitement!

PIC INTERNATIONAL CONFERENCE

## PIC International 2022 dates announced!

We are delighted to announce that the dates for PIC International 2022 are confirmed for 28 - 29 June 2022.

# Standards pave the way to a future beyond 400G Ethernet

The ongoing development of advanced photonic data communications solutions is vital to future commercial and consumer applications that access, analyze and otherwise leverage data. IEEE standards are the framework around which future photonic integrated circuits (PICs) will be created. IEEE's Ethernet Task Force offers insights into how new standards are coalescing to ensure support for future requirements.

**BY JOHN D'AMBROSIA, IEEE 802.3 TASK FORCE CHAIR AND EPIC ADVISOR**

IN APRIL 2020, the IEEE 802.3 Ethernet Working Group released its 2020 Ethernet Bandwidth Assessment. The findings of this extensive 18-month effort indicated that by 2025, for a broad diversity of applications explored, traffic levels would grow from 2.3x to 55.4x the levels observed for 2017. Based on these findings, the IEEE 802.3 Ethernet Working Group launched its Beyond 400 Gigabit Ethernet Study Group in January of 2021.

This study group has recommended the formation of the IEEE P802.3df 200 Gb/s, 400 Gb/s, 800 Gb/s, and 1.6 Tb/s Ethernet project, which will be considered at the IEEE 802 November 2021 Plenary for approval.

The proposed project reflects the observed needs of the industry throughout this decade and well into the next.  Upon approval, it would be one of the largest projects in the recent history of the IEEE 802.3 Ethernet Working Group and reflects the desire to deliver new higher speed Ethernet solutions in a quicker manner to address the industry's never-ending need for more bandwidth, as well as to provide lower power, higher density solutions for existing Ethernet rates.

## The relationship between signaling rates and ethernet rates

Before diving into the IEEE P802.3df project, it would be useful to explore the relationship between the signaling rate of a "lane" and the Ethernet rate.  As illustrated in Figure 1, for a given Ethernet rate there are a number of solutions that are simply the product of the number of lanes of the given solution and the signaling rate per lane. For example, for 100 GbE, many of the initial solutions were four lanes of 25 Gb/s for an aggregate 100 Gb/s throughput.  As technology progressed, 100 GbE solutions based on 2 lanes of 50 Gb/s were introduced, and then finally 1 lane of 100 Gb/s.

The general rule of thumb was that Ethernet networking solutions would begin to ship in high volume when a four-lane variant was introduced, with the highest volume ultimately being achieved when moving to a one-lane serial variant.  A perfect example is the repeated use of the QSFP module, which has 4 electrical differential pair inputs and 4 electrical differential pair outputs to support four-lane variants of 40 GbE, 100 GbE, 200 GbE, and 400 GbE.  The race to higher densities ultimately led to the introduction of form factors that were based on eight-lane solutions, which allowed the faceplate density for four-lane Ethernet variants to approximately double. OSFP and QSFP-DD are examples of these form factors. Furthermore, the initial 400 GbE architecture and many of the physical layer specifications was based on 8 lanes of 50 Gb/s.  Market data forecasts highlighted growing market acceptance of eight-lane architectures, physical layer specifications, and module form factors.

Additionally, many ports today allow the user the flexibility to configure the port capacity. For example, a given eight-lane port could be configured to support one eight-lane implementation, two four-lane implementations, four two-lane implementations or even eight one-lane implementations. This provides both the system provider and end user the ability to use a single box in a variety of network topologies, which then enables leveraging economies of scale to drive costs down throughout the entire ecosystem.

## The IEEE P802.3df Physical Layer Objectives

As noted, the IEEE P802.3df project, when approved, will be one of the largest projects in recent IEEE 802.3 Ethernet history.  As highlighted in Table 1, the project will address specifications of at least 26 different interfaces and physical layer specifications.

**There are several observations that can be made from this list of objectives:**

- The project will address developing the higher speeds 800 GbE and 1.6 TbE.  It will leverage the specifications developed for these speeds to define lower-power, higher-density solutions for 200 GbE and 400 GbE.
- The overall size of the project has already been highlighted.  If one were to go back and visit the IEEE 802.3 Ethernet archives, these various objectives were addressed in several projects rather than a single effort.  The urgency to do this in a single project points to two things.  First, there is a need by the industry for all of the specifications

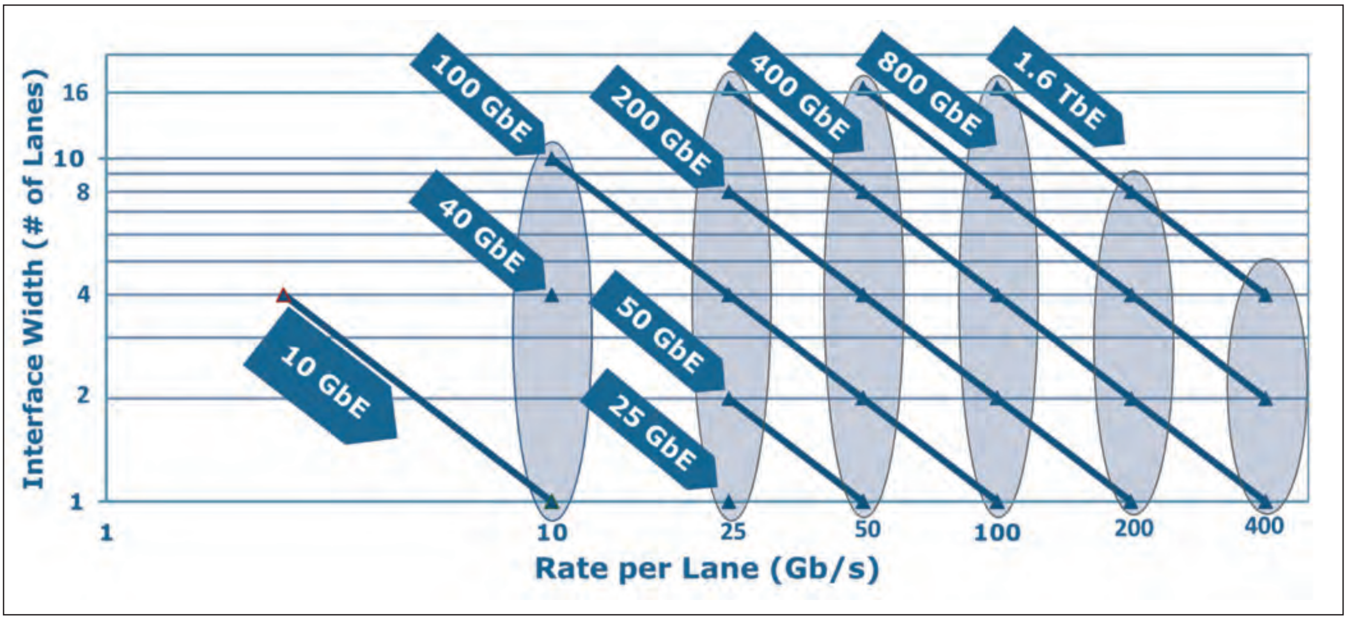



Figure 1: The relationship between ethernet rates & signaling rates

| Ethernet Rate | AUI | BP | Cu Cable | MMF 50m | MMF 100m | SMF 500m | SMF 2km | SMF 10km | SMF 40km |
|---|---|---|---|---|---|---|---|---|---|
| 200 Gb/s | Over 1 lane | | Over 1 pair | | | Over 1 Pair | Over 1 Pair | | |
| 400 Gb/s | Over 2 lanes | | Over 2 pairs | | | Over 2 Pair | | | |
| 800 Gb/s | Over 8 lanes | Over 8 lanes | Over 8 pairs | Over 8 pairs | Over 8 pairs | Over 8 pairs | Over 8 pairs | | |
| | Over 4 lanes | | Over 4 pairs | | | Over 4 pairs | 1) Over 4 pairs<br>2) Over 4 λ's | | |
| | | | | | | | | Over single SMF in each direction | Over single SMF in each direction |
| 1.6 Tb/s | Over 16 lanes | | | | | | | | |
| | Over 8 lanes | | Over 8 pairs | | | Over 8 pairs | Over 8 pairs | | |

Table 1 - Summary of IEEE P802.3df Objectives

that will be developed to support these various objectives. Second, there is a need to consider all these objectives simultaneously and employ a holistic approach to the development of an architecture that will enable development of equipment that can address all these various objectives and reduce the risk of future stranded ports on equipment that would be unable to support future interface specifications.

- As denoted by the coloring of cells within Table 1, there are several groupings of objectives that will leverage existing technology or specifications or will leverage new specifications defined in the P802.3df project.  For example, the fields highlighted in yellow will leverage existing standards or standards in development, specifically IEEE Std 802.3cuTM-2020, IEEE P802.3ck, and IEEE P802.3db.
- The fields highlighted in purple are anticipated to leverage development of 200 Gb/s per lane for electrical signaling for specifications defining AUI interfaces and copper twin axial cabling to address all speeds.  The fields highlighted in green are anticipated to leverage development of 200 Gb/s per lane optical signaling for specifications targeting single-mode fiber (SMF) with reaches of 500m and 2km.  The two objectives in grey, targeting SMF reaches of 10 km might leverage 200 Gb/s per wavelength or coherent optical solutions, and will be one of the key debates of the future P802.3df Task Force.

## Development of the IEEE 802.3df architecture

During the definition of the IEEE P802.3df project, it was recognized that a single project addressing the objectives noted in Table 1 would be advantageous to the Ethernet community. By considering all these objectives simultaneously, the future IEEE P802.3df Task Force will be able to address the architecture holistically when developing the standard. This will enable the development of equipment to support all of the noted physical layer specifications.

If the development of these specifications was accomplished via multiple standards, the risk that a port might not be able to support all of the noted specifications would increase. This could result in a port being "stranded" from supporting specifications defined by later standards. This happened during the course of 100 GbE, as the IEEE Std 802.3ba-2010 that initially defined 100 GbE did not define forward error correction (FEC) for 25 Gb/s per lane optics.

This became problematic for equipment defined to meet the initial 100 GbE standard when the later IEEE Std 802.3bmTM-2015 that defined RS (528, 514) KR4 FEC, which was introduced by IEEE Std 802.3bjTM-2014, necessary for 100GBASE-SR4 optics was ratified. These ports became stranded since they could not support these optical ports defined by 802.3bm, impacting the return on investment of this equipment for the component vendors, system vendors, and end-users.

Given the various physical layer specifications that the IEEE P802.3df project will define, there are several different forward error correction schemes that might be employed. Figure 2 illustrates a number of potential example FEC schemes that the IEEE P802.3df architecture may need to accommodate: 1) full end-to-end FEC; 2) full end-to-end FEC with a concatenated inner FEC; 3) partially segmented FEC; and 4) fully segmented FEC. The coding gain required by each FEC depends upon the characteristics of each link segment and the overall FEC scheme but must also be balanced with latency and power considerations.

It is quite plausible that the IEEE P802.3df architecture will enable at least two of these FEC schemes. For example, the end-to-end FEC scheme illustrated in Option #1 of Figure 2 might be the best approach for a backplane or copper cable solution.

Option #4 could provide the most flexibility and performance by allowing different FEC codes to be employed in the optical module to address different

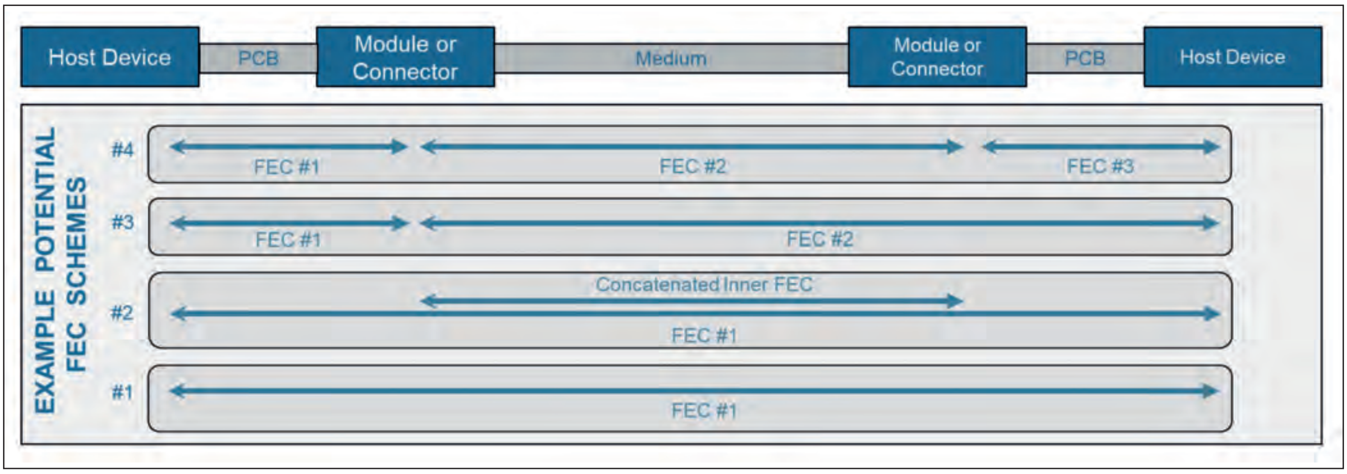



Figure 2- The Impact of forward error correction on the IEEE P802.3df architecture

optical physical layer specifications. Option #2 could provide a balance between performance, latency, and complexity. It is anticipated that the discussions, analysis, and technical decisions that will accompany this topic will be a key part of early task force discussions.

## The Promise of Ethernet Interoperability

As noted, the IEEE P802.3df project will address multiple Ethernet rates, signaling rates, and physical layer specifications, which will result in several interoperability challenges for the Task Force to consider.

At the time of writing this article the development of 100 Gb/s signaling to address electrical interfaces, backplanes, copper twin axial cabling, and multimode fiber physical layers is still underway within the IEEE 802.3 Ethernet Working Group.

It is anticipated that these development efforts will be leveraged, via 8 x 100 Gb/s solutions, to address electrical interfaces and physical layer specifications that support 800 GbE. However, project objectives were adopted which will lead to the development of electrical interfaces and physical layer specifications based on 4 lanes of 200 Gb/s.

The future IEEE P802.3df Task Force will need to consider the future scenario where system boxes based on 8 x 100 Gb/s electrical interfaces will need to coexist with future system boxes based on 4 x 200 Gb/s. This will need to be considered during the development of the IEEE P802.3df architecture, including situations where the fully segmented FEC approach shown in Option #4 of Figure 2 will need to be supported.

As noted in Table 1, it is expected that this project will also leverage the anticipated development of 200 Gb/s signaling to create lower-power, higher-density solutions for 200 GbE and 400 GbE. The IEEE P802.3df Task Force will need to review existing 200 GbE and 400 GbE solutions and consider any potential interoperability issues that may arise.

## Conclusions

Given the findings of the IEEE 802.3 2020 Bandwidth Assessment Report and the forecasted bandwidth growth by 2025, the effort to begin definition of 800 Gb/s and 1.6 Tb/s Ethernet to address the growing diverse bandwidth requirements throughout the industry needs to begin. Leveraging existing Ethernet standards and efforts to develop 100 Gb/s electrical and optical signaling will enable initial 800 GbE solutions.

The anticipated development of 200 Gb/s electrical and optical signaling, however, will enable 800 GbE and 1.6TbE solutions, assuming a x8 architecture. Additionally, while a building block for these higher speeds, the development of 200 Gb/s signaling will also enable the next generation of 200 GbE and 400 GbE solutions.

While the development of these multiple interfaces and physical layer specifications will be challenging, it is the development of the IEEE P802.3df architecture and the one or more FEC schemes it may need to support that will be critical. It is anticipated that this is where the future IEEE P802.3df Task Force will spend much of its initial time.

At this time further information about the work of the Beyond 400 Gigabit Ethernet Study Group can be found at https://www.ieee802.org/3/B400G/index.html.

## ENDNOTES

[1] IEEE 802.3TM Industry Connections Ethernet Bandwidth Assessment Part II, IEEE 802.3 Ethernet Working Group, https://www.ieee802.org/3/ad_hoc/bwa2/BWA2_Report.pdf, 03 April, 2020.

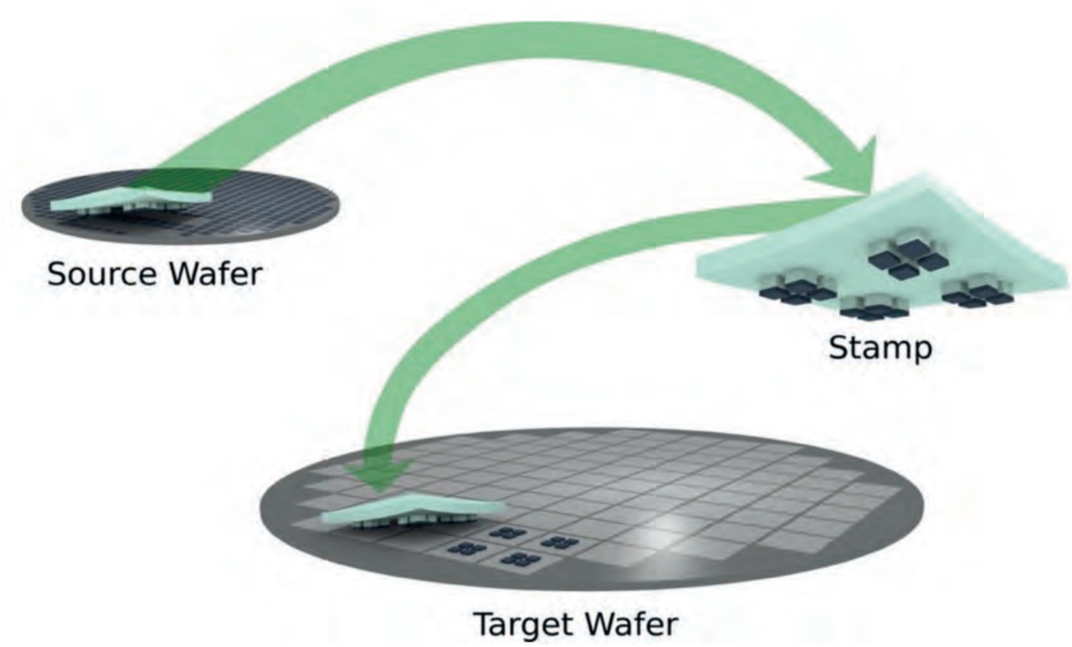
# INSPIRE project to lead a revolution in photonic integrated circuits

The H2020-funded INSPIRE project is leading a revolution in photonic integrated circuits with so-called micro-transfer printing technology and establishment of world-first fabrication platform.

OUR ACCESS to the internet is made possible by an ensemble of technologies such as photonic integrated circuits (PICs). There is also potential for PIC devices in healthcare or sensing, however their use in these applications is limited by issues with scalability and high-throughput manufacturing. The Eindhoven University of Technology (TU/e) coordinated H2020 funded project INSPIRE seeks to change how PIC devices are fabricated to make them suitable for applications beyond communications and speed up their large-scale production. INSPIRE has received close to €5 Million in funding.

The University of Cambridge is a consortium partner on the INSPIRE project. The activity at Cambridge primarily involves the Photonics Systems Research group. Dr Qixiang Cheng is PI for this project and Professor Richard Penty is the Co-I. The technological world is built on a foundation of electronic devices. In recent years though there has been an upsurge in the use of photonic devices, particularly for data transfer applications. These photonic devices are based on materials like silicon, silicon nitride (SiN) and indium phosphide (InP).

While these devices have the potential for wider impact in other fields like sensors used in aircraft or communication devices, their uptake is limited as different materials need to be effectively combined to meet performance requirements.




Source: INSPIRE project

For example, high-performance fiber sensors used in infrastructure monitoring and microwave signal processing in RADAR systems both require low-noise operation and ultra-low degradation of signals. This can only be achieved through a combination of materials in the manufacturing process. If this manufacturing process can be properly scaled to allow for large-scale production, it is expected that these photonic devices can have a major impact on sensing applications.

To facilitate the combination of these high-performance, so-called III-V opto-electronic materials in photonic devices, INSPIRE is developing wafer-scale micro-transfer printing technologies, and the project has received H2020 funding to the tune of €5 million euros to achieve its goals.

In micro-transfer printing, devices are first made on a source wafer, after which they are transferred to a target wafer (see image). This printing concept has been established and widely applied by project partner X-Celeprint to different wafers and materials. The INSPIRE project is focusing on the next step: parallel device printing with accurate placement where many integrated devices can be printed at the same time.

The INSPIRE micro-transfer printing technology will be validated for three specific cases: fiber sensors to measure stress, strain, and temperature for use in airplane safety measures, a microwave photonic radio-frequency (RF) pulse generator with application in RADAR and wireless communication, and optical switches for energy-efficient data centers. Compact versions of the III-V opto-electronic components will be developed, enabling designers to use this platform for a wide range of applications.

## Combining established fabrication technologies

INSPIRE aims to sustain Europe's industrial leadership in photonics by consolidating established fabrication approaches, such as those from the pioneering pure-play foundry and TU/e spinoff SMART Photonics and the silicon photonics pioneer imec, with the micro-transfer printing technology of X-Celeprint.

This will result in a world-first fabrication platform that combines the strengths of two of the most well-known PIC manufacturing platforms. Methods will chiefly be developed for the coupling of SiN and InP processes but could also be used for silicon-based photonics.

INSPIRE coordinator Professor Martijn Heck from Eindhoven University of Technology is excited by the possibilities that lie ahead: "By combining SMART and imec technologies, with only minor changes to the fabrication processes, we can leverage the major investments in the development of these platforms from the last decade. We can thus significantly reduce the time needed to transfer our technology out of the lab, and make a faster and telling impact in new application areas."

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## Onwards to application

And the potential of the INSPIRE approach is demonstrated by the participation of industrial partners such as Dr. Jerome Bourderionnet from THALES: "The INSPIRE platform enables high-performance building blocks, such as low-linewidth lasers, which are at the heart of THALES' applications for optical signal processing at large, or sensing integrated systems."

INSPIRE aims to create a full-function PIC platform, compatible with open-access pilot manufacturing, and with an order of magnitude lower cost for volume production.

INSPIRE's generic approach makes the technology widely applicable and ensures that European innovators can focus their research and development directly on manufacturing platforms. As a result, it should take a shorter time to bring these PIC technologies to market.

The INSPIRE project consortium is made up of TU/e, imec, Thales, University of Cambridge, X-Celeprint, SMART Photonics, and Amires. The project officially started on 1st January 2021. The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n°101017088, project INSPIRE.

*This article was written by Barry Fitzgerald, Science Information Officer at Eindhoven University of Technology and originally appeared on the Eindhoven University of Technology website.*

# Advancing hybrid PICs

## Innovations in InP laser design are destined to keep the energy consumed by the internet in check

BY RICHARD STEVENSON

JUDGED IN TERMS of its impact on our climate, the internet is both a friend and a foe. It has enabled teleworking and the remote attendance of international conferences, leading to a reduction in the number of journeys taken by car and plane; but it is having an impact on the climate that is roughly equivalent to the aviation industry, accounting for around 2 percent of the world's $CO_2$ emissions, according to the Boston Consulting Group.

With humanity's insatiable desire for data, there is the threat that the internet's contribution to the global carbon footprint will rocket. Fortunately, though, gains in the efficiency of infrastructure are offsetting exponential rises in the transmission and consumption of data.

To ensure that this equilibrium continues, much effort is being devoted to developing components that set a new benchmark for the energy required per bit. If they are to have a commercial impact, competitively pricing is also essential.

Addressing both of these key requirements is the hybrid photonic integrated circuit (PIC), combining the low cost, large wafer size and high level of maturity of silicon technology with the InP laser, the only realistic choice for a high-performance light source operating in the spectral domains employed for data transfer.

At the 27th International Semiconductor Laser Conference (ISLC), held in Postdam, Germany, from 10-14 October and organised by FBH Berlin, engineers showcased a variety of technologies for forming InP-based lasers on silicon substrates. Triumphs announced at that meeting included an 8-channel transmitter by Intel, featuring distributed feedback (DFB) lasers; a laser with a wide tuning range and a two-storied ridge structure, pioneered by a team led by Sumitomo Electric Industries; and a GaInAsP laser within a buried-ridge waveguide structure, trailblazed by researchers at Tokyo Institute of Technology.

### Turbo-charging optical engines

Intel is well-known for its development of optical transceivers for data centres. These products, which first hit the market in 2016, are produced with a 300 mm hybrid silicon photonics platform that features advanced lithography.

At ISLC, Intel's Duanni Huang outlined to delegates attending in-person and on-line how the deployment of these transceivers will evolve over time. Huang explained that the company's 100 Gbit/s to 400 Gbit/s transceivers are now being produced in high volume

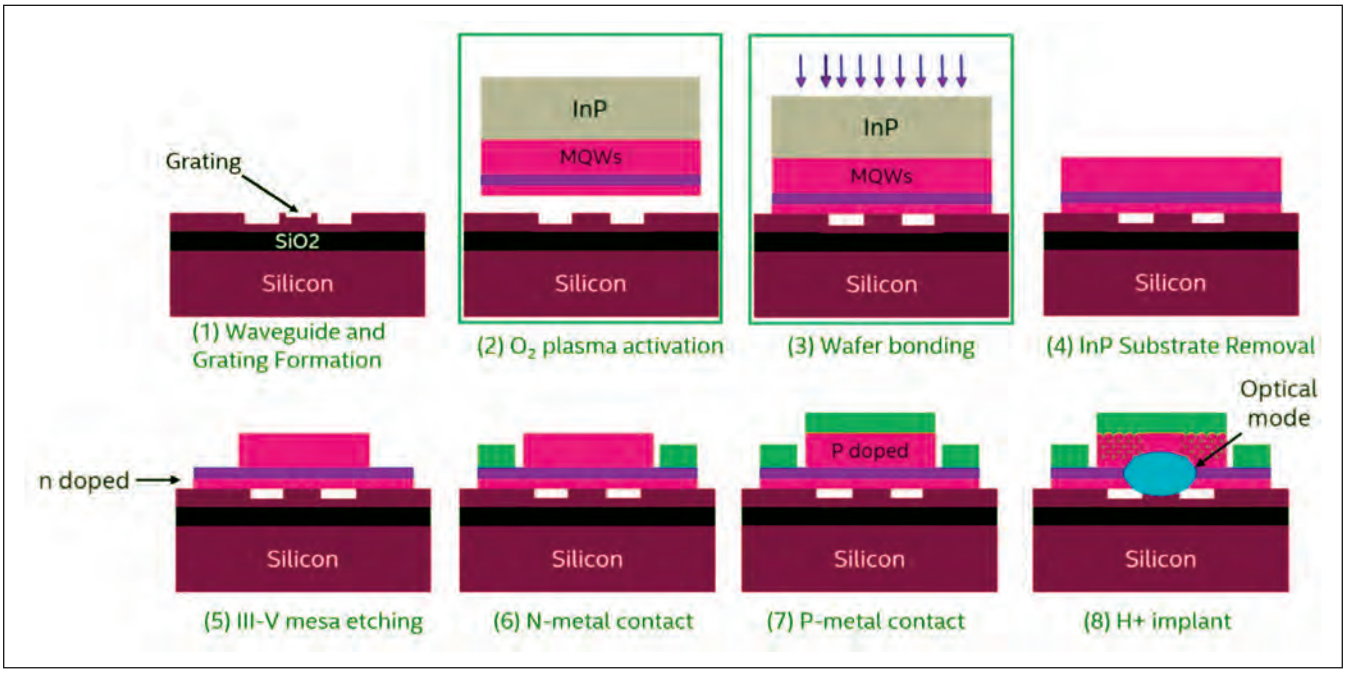



Figure 1. Intel's hybrid III-V/silicon laser process begins by taking a silicon wafer with a silicon-dioxide layer and defining a waveguide and a grating using deep-UV lithography. Oxygen plasma activation of the wafer follows, along with the bonding of InP chiplets to silicon. The bulk InP is removed to leave behind just the active region, before a III-V mesa is etched and the laser contacts added. The final step involves passivating regions of the mesa with hydrogen-ion implantation to leave a current channel in the centre that overlaps with the optical mode.

for ethernet-compliant products. These transceivers are based on front-plate pluggable optics and operate at an energy efficiency of 30 pJ/bit. "In these products, the optics is still very far away from the central Ethernet switch," remarked Huang.

"In 2020, we had a demonstration of so-called co-packaged optics, in which a photonic engine capable of 1.6 terabits-per second is co-packaged with the switch core," remarked Huang.

This is said to bring the optics much closer to the photonics. With this architecture, optical engines could run at a total data rate of up to 3.2 Tbit/s, while drawing less than 15 pJ/bit.

Looking further ahead, Intel anticipates a time when photonics will be united with the package where the processor sits, using an optimised optical interface. This architecture will operate at a total data rate that could be as high as 16 Tbit/s, and have an energy efficiency well below 5 pJ/bit.

"In order to reach the bandwidth density and energy efficiency needed to make this happen, we utilise wavelength-division multiplexing," revealed Huang. This approach, similar to that employed in long-haul links, exploits the resonance of silicon micro-ring modulators to select specific wavelengths. At the receiver, a similar approach can be employed to separate the various wavelengths transmitted down the fibre and extract encoded data. Intel produces its laser by forming a waveguide and a grating on a 300 mm silicon wafer with a silicon-dioxide layer, and then adding an InP chiplet that is subsequently processed (see Figure 1 for details).

To define the laser's emission wavelength, Intel adjusts the dimensions of the grating. For the 8 channels deployed in the latest generation of technology, there is a 200 GHz spacing, equating to a difference in the grating period between adjacent laser channels of just 0.2 nm. "This is difficult, but something that is achievable with our deep UV-lithography," remarked Huang.

He and his co-workers have provided a proof-of-concept transmitter. "Only a single indium-phosphide chiplet is used to fabricate all eight lasers, and each laser can be controlled individually," explained Huang.

An 8-channel transmitter is formed by combining the output from the eight lasers with three stages of multimode interferometer, formed in silicon. This is a relatively easy way to combine eight channels into four, then two, and finally just one. However, it does incur a power penalty of around 3 dB at each stage.

With this approach, the team have fabricated a transmitter with 8 wavelengths spaced apart by 200 GHz ± 13 GHz, centred at around 1305 nm. Driving each laser sequentially with 80 mA produces lasing peaks with a side-mode suppression ratio (SMSR) of 54 dB and an output power of around 1 mW. "When we turn on all eight laser together, we see a number of side peaks on either side of the eight main

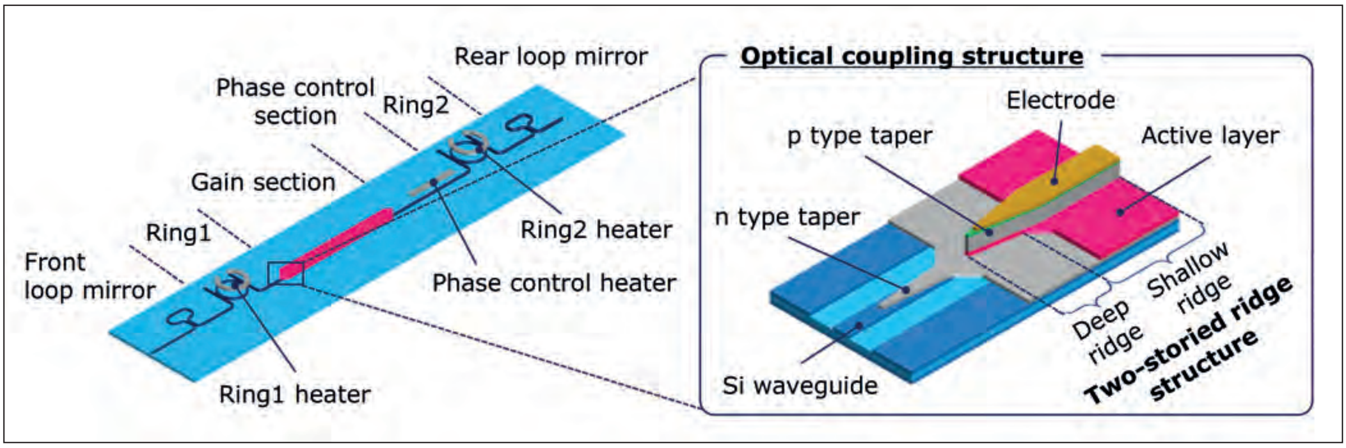



Figure 2. Sumitomo Electric Industries has developed a laser structure with a two-storied active region and *n*- and *p*-type tapers, introduced to minimise coupling losses. The laser's emission wavelength is tuned by heating the ring resonators. Reproduced from the paper MP2.1, 27th ISCL. © IEEE.

laser peaks," explained Huang. This is attributed to four-wave mixing in the silicon waveguide, which quashes the SMSR to 38 dB.

It is worth noting that changes in temperature do not have a devasting impact on the DFB lasers. While there is a red-shift with temperature, all channels move together, according to measurements at temperatures ranging from 22 °C to 62 °C.

Another encouraging result is that the power and channel uniformity are well within those defied in the CW-WDM-MSA standard. This standard stipulates values of ± 50 GHz and ± 1 dB power imbalance.

## Enhanced coupling

One of the downsides of hybrid PICs is that there are coupling losses when light transfers from one material system to another. To minimise these losses, a team led by Sumitomo Electric Industries, and including engineers from Tokyo Institute of Technology, has recently developed a novel hybrid-laser architecture. It features a two-storied ridge structure, employing *n*-type and *p*-type tapers to connect a III-V gain section to the silicon waveguide (see Figure 2).

Details relating to the fabrication of this laser, along with measurements demonstrating its wide tuning range, were provided in a presentation by Takuo Hiratani from Sumitomo Electric Industries. He and his co-workers are advocating the use of hybrid integration in data-centre optical interconnects, because they can combine the merits of InP-based lasers, photodetectors and modulators with silicon's strengths, which include passive waveguides with tight bends and the opportunity for large-scale integration.

The team from Sumitomo unite InP and silicon using wafer-bonding. "High density integration and high alignment tolerances are strong advantages," argued Hiratani, who compared this approach to butt-coupling and micro-transfer printing. Sumitomo's latest lasers, emitting at around 1.55 μm, are based on an architecture that realises gain within an InP-based section that is positioned in an external cavity laser featuring two silicon ring resonators, a phase-control section and rear-loop mirrors. With this design, controlling the heating of the rings, which have differing dimensions, allows a tuning of the lasing wavelength over 60 nm.

"In this [latest] work we introduced a new optical coupling structure, including a two-storied ridge structure," explained Hiratani. "This structure enables constriction of the current, plus, by a shallow-ridge-type gain section, a low optical coupling loss, with zero wavelength dependence." According to simulations, coupling loss at the interfaces is just 0.4 dB across the entire C-band.

To produce their novel laser, Hiratani and co-workers employ electron-beam lithography to prepare silicon waveguides on the silicon-on-insulator wafer. An InP epiwafer, containing the GaInAsP quantum wells, is directly bonded to this patterned surface, before the InP substrate is removed by chemical wet etching. Stepper lithography and dry etching form a shallow ridge structure and the two-step taper structures. To complete fabrication, cladding layers are deposited, electrodes formed by evaporation, and microheaters and anti-reflection coatings added.

By comparing the performance of Fabry-Pérot lasers with and without an optical coupling structure, the team estimated a loss per interface of less than 1 dB. "This low coupling loss is thanks to the two-storied ridge structure," remarked Huang.

Measurements on the team's novel laser, which has a 1.1 mm-long III-V gain section and a total device length of 2.5 mm, reveal a threshold current of 32 mA and a maximum output power of 1.3 mW. Kinks appear in the light-output power plot with increases in current,

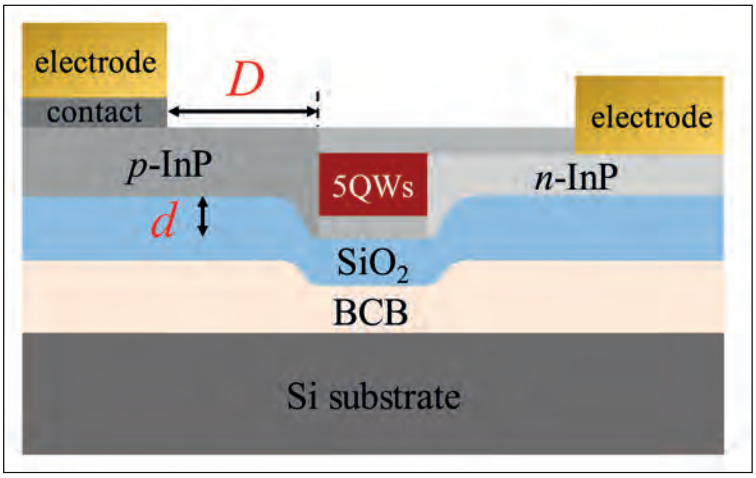



Figure 3. The performance of the GaInAsP membrane laser produced by the University of Tokyo is improved by introducing a ridge height, *d*, and reducing the distance *D*, which is the separation between the *p*-type electrode and the active region. Reproduced from the paper MP2.3, 27th ISCL. © IEEE.

due to mode-hopping associated with phase changes in the gain section. By exploiting the Vernier effect and applying up to 60 mW to the two rings, the laser's wavelength can be tuned over 56.2 nm. Over this range, the SMSR is at least 41 dB. "These results show that the III-V-silicon hybrid tuneable laser is very promising for next-generation PICs," concluded Hiratani.

## Masterful membranes

The massive microprocessor chips that are produced today suffer from Joule heating and a delay associated with wiring. A promising solution is to switch from electrical wiring to on-chip optical interconnects. But if this is to succeed, the associated light source must draw incredibly little power, be easily integrated with passive devices using an in-plane platform, and produce enough light for a corresponding detector.

"In order to meet these requirements, we propose a membrane laser light source," explained Naoki Takahashi from Tokyo Institute of Technology, during his talk to delegates at ISLC. He championed this novel form of laser, promoting its strong optical confinement and a high modal gain, realised by essentially replacing an InP cladding with $SiO_2$ or air. "This leads to a reduction in the threshold current, as well as a higher modulation efficiency."

To place the team's latest success in context, Takahashi began by sharing the results of previous work. In earlier development, he and his co-workers realised a membrane laser with a threshold current of 0.21 mA, a high differential quantum efficiency – it hit 32 percent – and a high differential resistance of 880 Ω. "This makes an energy cost of 93 femtojoules-per-bit when operating at 20 gigabits-per-second. However, it is estimated that an energy cost of 10 femtojoules-per-bit or less is required to realise on-chip optical wiring." Recently, efforts have been directed at reducing the energy-per-bit by increasing optical lateral confinement through modifications to *p*-type and *n*-type structures that surround the active region (see Figure 3). Calculations suggest that changes to the ridge height, *d*, in this buried-ridge waveguide architecture can lead to a substantial enhancement in lateral optical confinement.

Another approach to improving this key metric, which also trims differential resistance, is to move the *p*-type electrode closer to the active region. In a conventional structure, such a move would threaten to interfere with the optical mode; but by optimising the ridge height, this is avoided.

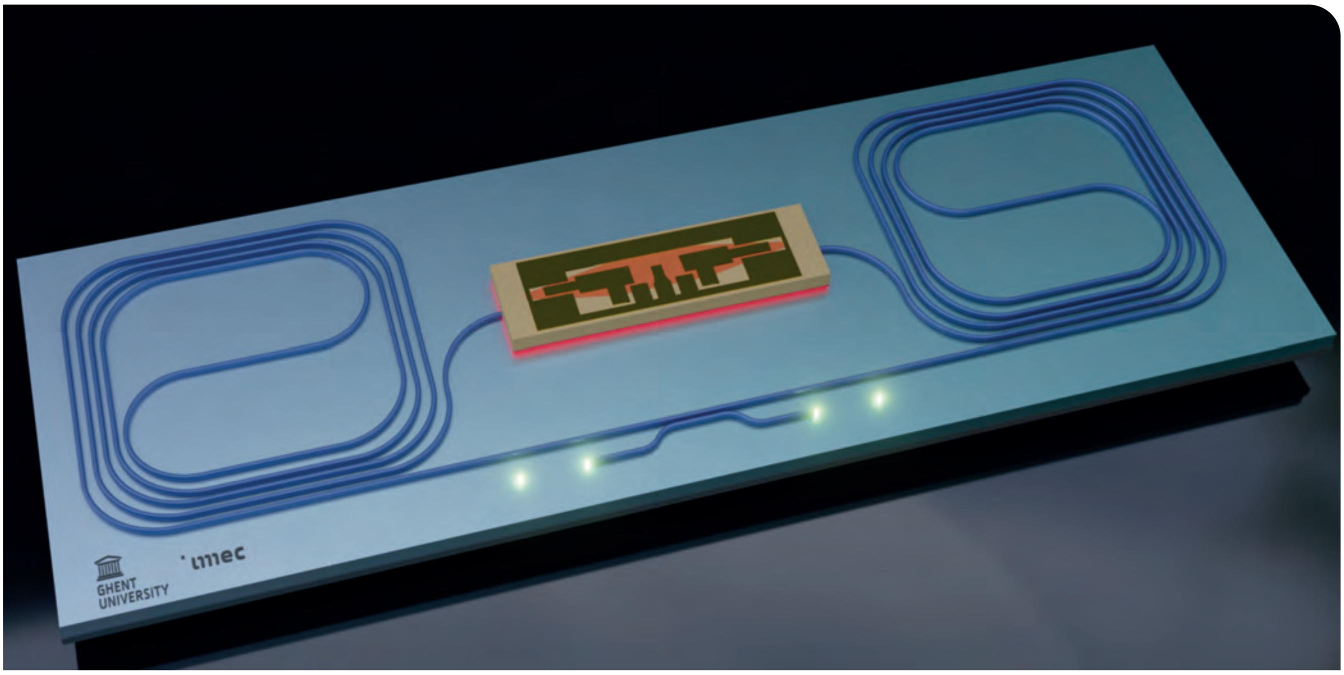
Calculations by the team have determined that a judicious choice for their laser's ridge height is 50 nm. This can lead to a 40 percent fall in device resistance. To produce their devices, Takahashi and co-workers begin by growing the *p*-type cladding, active region and an InP cap on an InP wafer.

Using a $SiO_2$ mask, photolithography and etching they define a ridge-shaped active region, before re-growing *p*-type and then *n*-type layers. A $SiO_2$ layer is grown on top, before this wafer is bonded to a silicon substrate coated with the polymer BCB, and the InP substrate removed and electrodes added.

The benefits of the buried waveguide architecture have been quantified by comparing this device with another that is identical, apart from having a flat structure. Measurements on these devices, which have a 560 μm-long cavity and a 1.8 μm ridge width, reveal that the introduction of the buried ridge reduces the threshold current from 12.5 mA to 9.8 mA and increases the output power. Investigations have also shown that reducing the distance between the electrode and active region from 1.3 μm to 0.8 μm drives down differential resistance by 20 percent.

Takahashi and colleagues have also fabricated a distributed-reflector laser with a buried waveguide that has a width of 1.3 μm. This 1558 nm laser has a threshold current of 0.24 mA and a differential resistance of 430 Ω. "The threshold current was almost the same as the previous work, and the differential resistance was reduced by about half from the previous work," enthused Takahashi, adding that the SMSR is 33 dB. "These results indicate that the introduction of the buried waveguide structure can effectively reduce the power consumption of membrane lasers."

With progress being made by academic and industrial developers on using InP lasers to reach higher data rates without paying a power penalty, there is hope that the internet will not become a major contributor to global warming. And that's clearly good news, given our increasing dependence on what is the virtual world.




# Mode-locked comb lasers for chip-scale spectroscopy

By integrating a semiconductor optical amplifier on a low-loss SiN photonic chip, an ultra-dense, low-noise laser comb is realized, delivering unprecedented precision for chip-scale spectroscopy

BY STIJN CUYVERS, BAHAWAL HAQ, GUNTHER ROELKENS, KASPER VAN GASSE AND BART KUYKEN FROM GHENT UNIVERSITY - IMEC

UNDERPINNING A REVOLUTION in precision frequency metrology and timekeeping is the optical frequency comb, an optical source that generates a large number of coherent equally spaced discrete laser lines. The impact of these combs has been widely recognized, most notably in 2005, when John Hall and Theodor Hänsch were awarded a Nobel prize in physics for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique.

Traditionally, comb spectra are generated using Ti:sapphire solid-state lasers and erbium- or ytterbium-doped fibre mode-locked lasers. As these laser sources are bulky, their use is restricted to experiments in a lab.

To unlock the full potential of comb spectra technologies, it is essential to develop a compact, mass-manufacturable device. In recent years, considerable effort has been directed towards this goal, with researchers focusing on the integration of optical comb generators on a photonic chip. Success on this front will extend the application range well beyond fundamental frequency metrology to areas such as laser ranging, telecommunications and on-chip spectroscopy.

There has been a great deal of interest in dual-comb spectroscopy, as it allows for a highly multiplexed interrogation of broadband absorption spectra using a single photodetector. This technique enables accurate characterization of rotational-vibrational transitions of numerous gases, liquids and solids. When using this spectroscopic tool, one comb is sent through the sample under study, while another, with a slightly different line spacing, acts as a 'local oscillator'. Interfering these two combs on a photodetector generates a frequency comb in the RF domain, composed of distinguishable beats between pairs of optical comb lines. With this approach, the sample's

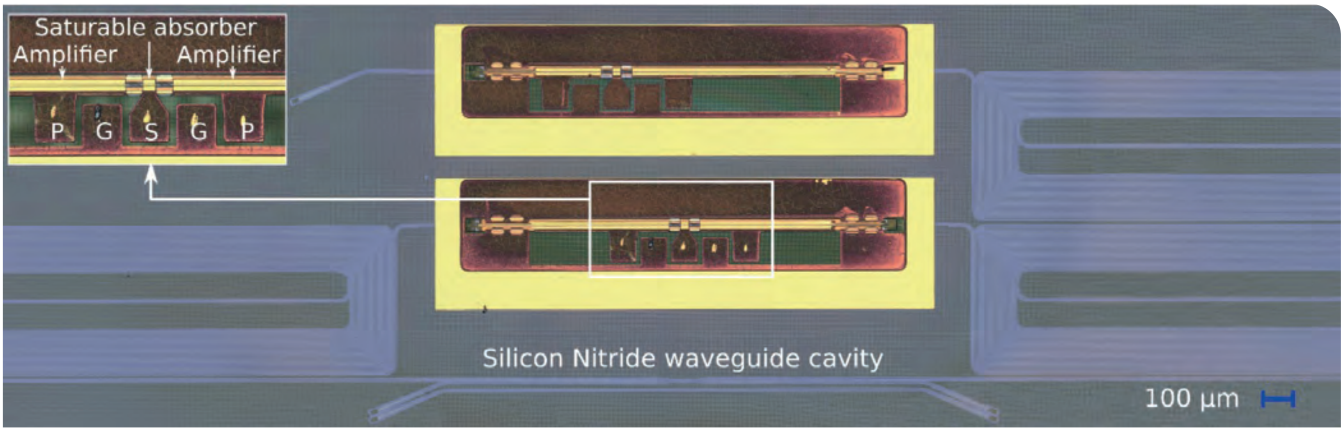



Figure 1. Microscope image of the III/V-semiconductor-on-SiN mode-locked laser chip, consisting of two 10 cm spirals and InP-based amplifiers and a saturable absorber.

spectral information is hence readily available in the RF domain and accessible for electronic processing. One of the merits of this method is that as all spectral components are simultaneously measured. Systematic errors, such as temporal variations in the sample, are effectively equalized. Another strength is that the frequency combs can be calibrated with an atomic clock to provide unrivalled precision.

A key requirement for this spectroscopic technique is the ability to generate a dense low-noise optical comb on-chip. As the resolution of the spectral measurement is directly related to the spacing between adjacent comb lines, a denser comb enables identification of otherwise undetectable features in the sample's spectral response. Efforts in developing the first chip-scale dual-comb spectrometers employed Kerr-effect combs, consisting of a high-quality optical ring resonator pumped with a continuous-wave laser. Due to the material's non-linearity, many new frequencies are generated in the resonator, leading to the creation of an optical comb with a line spacing determined by the size of the ring.

There have also been demonstrations involving quantum- and interband-cascade lasers, and so-called electro-optic frequency combs. The latter approach produces an optical comb by placing an electro-optic phase modulator in a resonator with a strong second-order nonlinearity, and pumping it with a continuous-wave laser. Modulation results in the growth of sidebands at the modulation frequency, which are subsequently modulated as well, resulting in a cascading effect.

Although these platforms have shown impressive results, their limited number of usable comb lines, integration challenges and their large comb line spacing (more than 10 GHz), inhibit their use in chip-scale high-resolution spectroscopic applications. In particular molecular spectroscopy in the gas-phase has proven challenging because gases typically have absorption features with linewidths on the order of 1 GHz. Optical combs with a narrow line spacing are crucial to accurately sample these spectra without the need for interleaving multiple spectra measured at different times.

Fortunately, there is a class of comb generators well-suited to the demands of on-chip gas-phase dual-comb spectroscopy. The breakthrough comes from translating the traditional optical frequency comb technique to a chip-scale device: the integrated mode-locked laser.

## Mode-locked lasers on a photonic chip

Mode-locked lasers are a special class of lasers that generate ultra-short optical pulses by phase-locking a large number of longitudinal modes within a cavity. In accordance with the Fourier theorem, such a series of short optical pulses creates an optical comb in the frequency domain.

Engineers can fabricate these devices on a chip using the same manufacturing techniques employed for making continuous-wave laser diodes. The primary difference is the addition of a saturable absorber, which favours the formation of pulses over continuous-wave lasing. Saturable absorbers are typically realized by electrically isolating a part of the gain waveguide and reverse biasing it.  Numerous material platforms have been used to develop integrated mode-locked lasers. They range from InP/InGaAsP

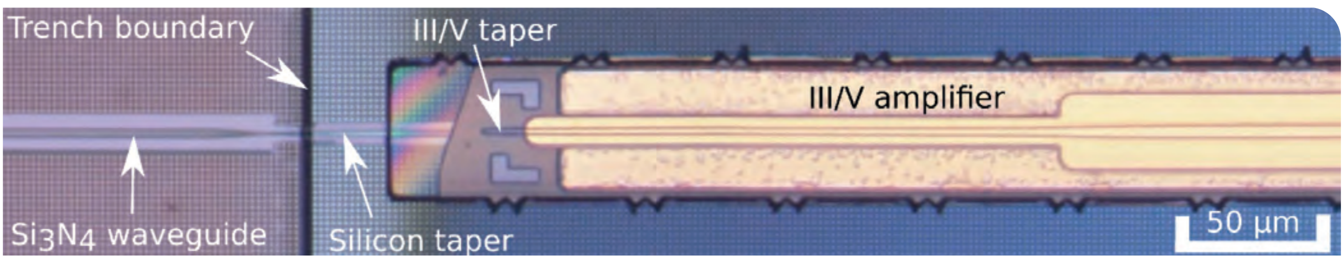



Figure 2. Microscope image of the micro-transfer printed coupon on top of the two-stage taper coupling structure.

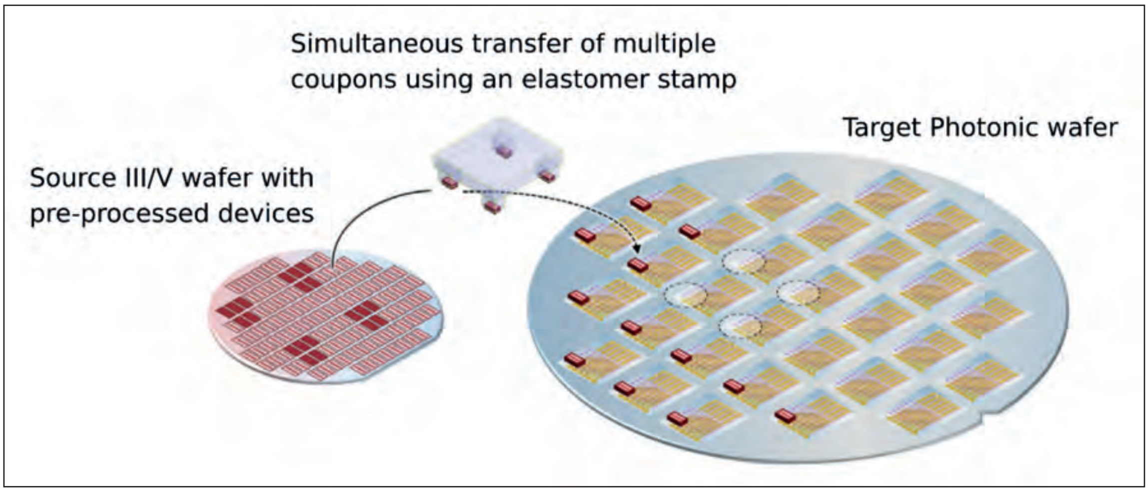



Figure 3. Concept of micro-transfer printing pre-processed III/V-semiconductor optical amplifiers on a target photonic integrated circuit using an elastomer stamp.

and InP/InAlGaAs quantum wells to InAs/InP, InAs/GaAs and InP/InAlGaAs quantum dots. As the noise performance and comb line spacing are proportional to the cavity length, there is a large incentive to extend the laser cavity. This has driven the development of InP and III/V-on-silicon lasers with long passive waveguide cavities.

In 2017, a collaboration between researchers at Ghent University – imec and the University of Eindhoven realised a milestone in integrated mode-locked laser performance. Back then, they unveiled a III/V-semiconductor-on-silicon mode-locked laser with a repetition rate – that is, a comb line spacing – of just 1 GHz. Success came from transferring an InP/InGaAsP gain material, epitaxially grown on its native substrate, on top of a silicon-on-insulator (SOI) passive photonic circuit through a die-to-wafer bonding technique. Combining a long, low-loss silicon waveguide cavity with a high-quality quantum well gain waveguide enabled a narrow linewidth and a small comb line spacing.

## SiN for ultra-low losses

A promising candidate for propelling performance to a new level is the use of a SiN platform for integrated laser sources. While typical silicon waveguides exhibit losses around 0.7 dB/cm, SiN waveguides can routinely realise losses that are far lower, close to 1 dB/m. Another advantage over their silicon cousins is that, thanks to the higher bandgap, they don't suffer from nonlinear two-photon and free-carrier absorption that fundamentally limit the attainable cavity size and lasing power.

Our team at the Photonics Research Group of Ghent University – imec has adopted this approach, developing the world's first on-chip mode-locked laser based on this novel III/V-semiconductor-on-SiN platform. By exploiting ultra-low losses of just 5 dB/m, we have realised the lowest noise reported for a chip-scale mode-locked laser to date and demonstrated a record comb line spacing of a mere 755 MHz, breaking the 1 GHz record.
Our laser has a ring cavity geometry, consisting of two 10 cm SiN spirals, deposited by means of low-pressure CVD on top of a patterned silicon-on-insulator wafer (see Figure 1 for a microscope image of this mode-locked laser). By defining the 330 nm-thick SiN waveguides using deep-UV lithography, we enabled low-cost, high-volume wafer-scale manufacturing.

To enable the heterogeneous integration of a III/V-semiconductor optical amplifier, we locally etch a trench in the 4.2 μm silicon oxide top cladding. This is accomplished with dry etching techniques, and results in a local exposure of the cavity waveguides. Furthermore, we employ a two-stage taper to efficiently couple the light from the SiN waveguide to the III/V gain waveguide. Light first couples from the SiN waveguide to a silicon waveguide underneath, and then into the III/V waveguide. This allows for an improved match in the refractive index and consequently an enhanced coupling efficiency (a microscope image of the coupling structure is shown in Figure 2).

## Micro-transfer printing

We use micro-transfer printing for the heterogeneous integration of the III/V amplifier. This process relies on the kinetically controlled adhesion of an elastomeric stamp to pick devices from a source wafer and print them on a target wafer, in this case the SiN photonic integrated circuit (PIC). An overview of the integration process is shown in Figure 3.

An important advantage of micro-transfer printing is its ability to integrate the III/V amplifier in a deep recess, an attribute that is essential for compatibility with low-loss top-cladded passive photonic platforms. Additional strengths of micro-transfer printing technology, which leverages the advantages of flip-chip integration and wafer bonding techniques, are efficient use of expensive III/V material and massively parallel integration, because many devices can be picked up and printed simultaneously. It's also worth noting that III/V devices can be pre-processed on their native substrate prior to transfer printing, permitting pretesting on the source wafer; and material stacks

can be co-integrated on the same target wafer to implement diverse functionalities, offering unmatched versatility. Fabrication of our devices begins by defining III/V semiconductor optical amplifiers, from here on denoted as 'coupons', on the native III/V InP-based substrate. The epilayer stack contains six InAlGaAs quantum wells and is grown on a 500 nm AlInAs release layer that can be selectively etched to release the active region from the substrate. After patterning the coupons, we deposit a photoresist encapsulation, before removing the AlInAs with a $FeCl_3$:$H_2O$ solution. This leaves the coupons solely supported by the resist encapsulation and ready for micro-transfer printing.

To ensure a high printing yield, we deposit a 50 nm-thick adhesive divinylsiloxane-bis-benzocyclobutene (BCB) layer on the patterned SiN target sample. The source and target are then loaded into the micro-transfer printing tool and carefully aligned. An elastomer stamp picks up a coupon from the source wafer by laminating the stamp against the coupon and then rapidly moving upwards. During this movement, adhesion between the coupon and stamp increases, and encapsulation tethers break at predetermined locations. After this, the coupon-loaded stamp is pressed against the target sample, before it is slowly retracted to leave the coupon behind on the target. Following the micro-transfer printing process, resist encapsulation is removed and the recess is planarized with BCB. The III/V amplifier is then post-processed, using a series of wet and dry etching steps to electrically isolate a saturable absorber, expose *n*-contacts and provide electrical contact pads for biasing.

## Record comb density

To evaluate our device's performance, we have biased the amplifiers and saturable absorber with contact probes and collected the light output with a single-mode fibre. Capturing the optical output with a photodetector allows us to translate the comb spectrum to the RF domain (see Figure 5(a)). This indicates a comb line spacing of 755 MHz, which is, to the best of our knowledge, the lowest reported comb line spacing for an on-chip passively mode-locked laser. Such a low spacing enables an unprecedented

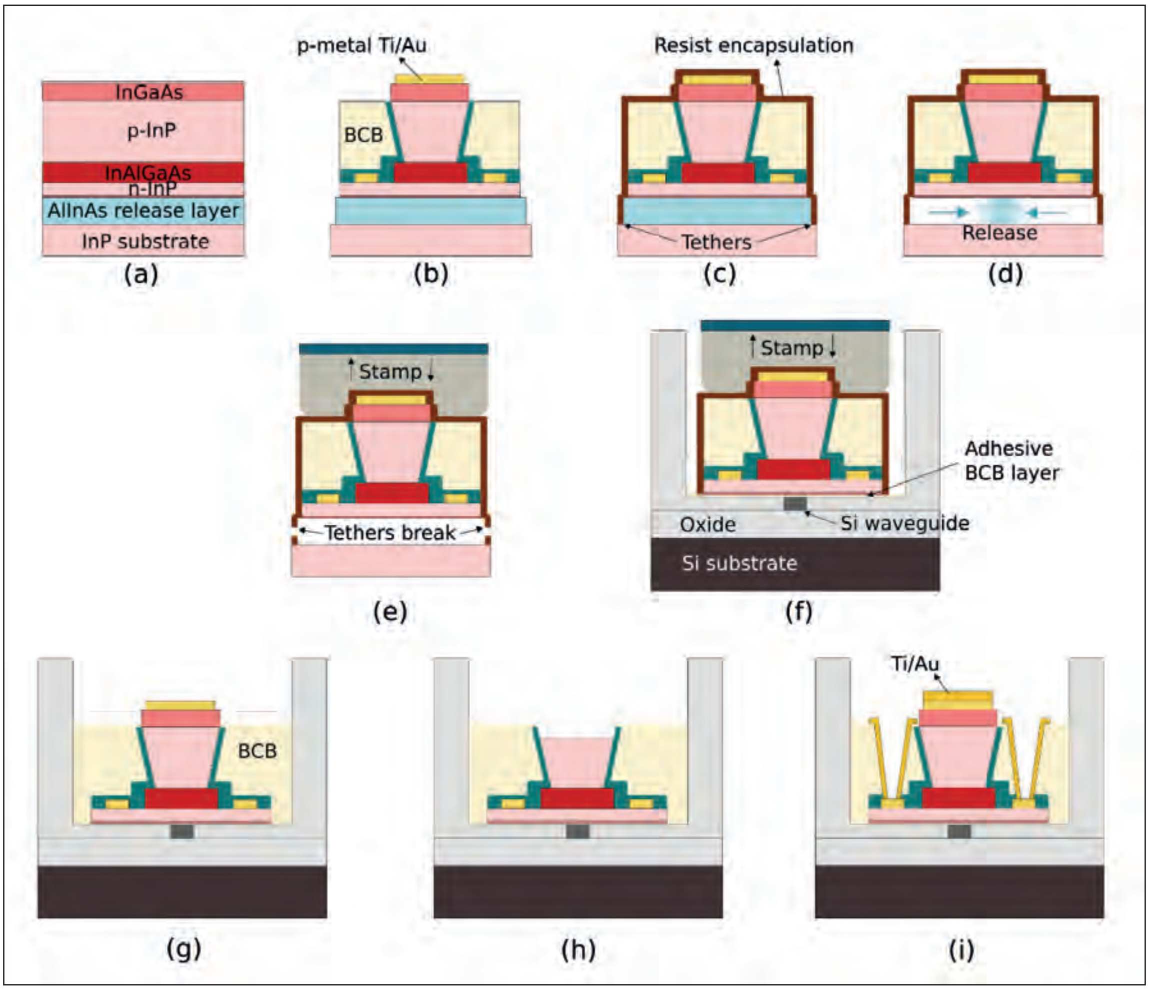



Figure 4. Fabrication process flow. (a)-(d) III/V-semiconductor optical amplifier fabrication, (e)-(f) micro-transfer printing process, (g)-(i) post-processing. (a) III/V-epilayer stack, (b) III/V coupon definition on the source substrate, (c) coupon encapsulation with photoresist, (d) release etch, (e) pick-up coupon from source, (f) print coupon on target in recess, (g) encapsulation removal and BCB planarization, (h) saturable absorber isolation, (i) final metallization.

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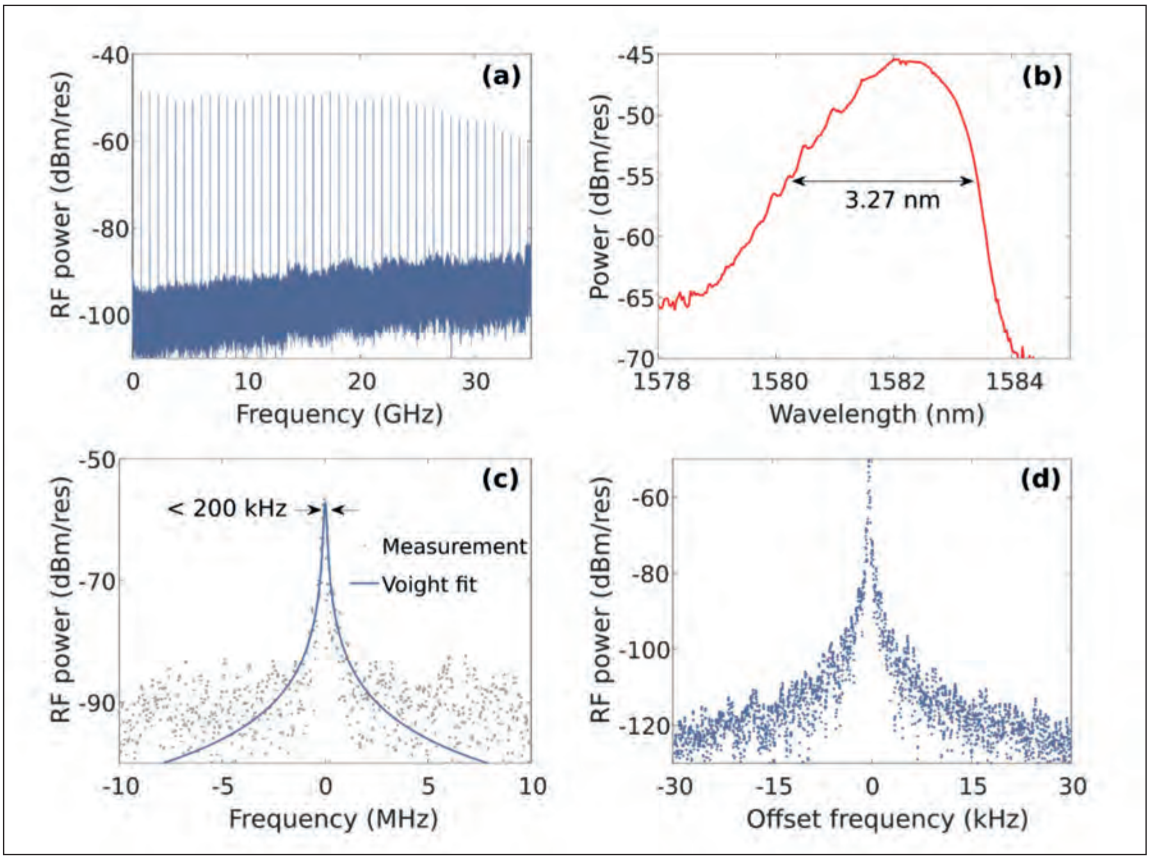


Figure 5. Experimental results. (a) RF spectrum of the generated pulse train with a comb line spacing of 755 MHz. (b) Optical spectrum with a 10-dB span of 3.27 nm, measured with a 30 pm resolution. (c) Optical linewidth, measured by heterodyning the mode-locked laser output with a tunable laser. (d) Repetition frequency signal at 755 MHz.

resolution for spectroscopic applications. Note that the comb roll-off at high frequencies is not related to the mode-locked laser, but rather a consequence of the 30 GHz bandwidth of the transimpedance amplifier of the photodetector. The optical comb spans over 3.27 nm (see Figure 5(b)), indicating that the laser generates over 500 densely and evenly spaced lines within a 10 dB bandwidth.

Characterisation of the noise properties has involved measuring the optical linewidth of the central lasing mode by heterodyning the output of the mode-locked laser with a tuneable continuous-wave laser on a photodetector (see Figure 5(c)). We fitted the heterodyne signal with a Voigt profile that has a full-width at half-maximum of just 146 kHz. To characterise the repetition frequency signal at 755 MHz, we measured the output of the mode-locked laser with a photodetector and an electrical spectrum analyser (see Figure 5 (d)). The narrow 300 Hz -10 dB RF linewidth indicates that all the optical modes are strongly phase-locked, and implies that the optical linewidth of the comb lines is similar to the linewidth of the central lasing mode. Single-sideband phase noise measurements reveal an amplified-spontaneous-emission-limited RF linewidth of 1 Hz, indicating that the RF linewidth is currently dominated by environmental and technical noise perturbations.

Our results showcase the potential of our on-chip mode-locked lasers for integrating high-resolution dual-comb spectrometers on a photonic chip. However, there are still a few challenges to overcome before commercial deployment follows. Firstly, it would be good to have an even larger number of usable comb lines, a goal that could be accomplished by further engineering of the laser cavity and spectral shaping of the gain. Secondly, there is a need to carefully package and stabilize these mode-locked lasers to minimize the impact of environmental perturbations. Another task is to explore other material platforms, such as GaSb, which could target spectral regions beyond 2 μm and enable us to uncover the full capabilities of on-chip spectroscopic sensing.

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