OPTOELECTRONICS

Silicon Photonics Reaches Prime Time

By Sally Ward-Foxton

Intel's silicon photonics 100G CWDM4 QSFP28 optical transceiver supports extended-temperature-range operation. (Image: Intel)

Silicon photonics has always been an attractive idea. Because silicon is transparent to photons at the infrared wavelengths used in optical communications, why not integrate optical components onto a silicon chip? Silicon-on-insulator processes can be used to form waveguides, modulators, and other optical structures in silicon and take advantage of CMOS's low cost and scalability.

After decades of research and development, silicon photonics products have moved to market and into real-world applications in the past couple of years. The technology is particularly attractive in the data center, where intra-center links of hundreds of meters are required as hyperscale facilities come online. The best solution for these is optical fiber. Currently, pluggable transceiver modules are used, but there are cost-, space-, and power-saving advantages to integrating transceivers into the same package as the electronics.

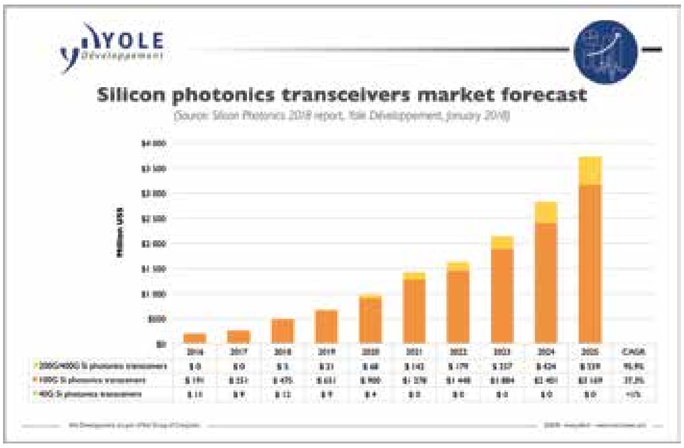
Traditional optical components often require hand assembly of hermetically sealed, discretely packaged components. Integrating some of these optical components onto silicon can leverage the cost benefits and ease of assembly of electronics packaging. Additionally, silicon photonics can enable the capacity increases that hyperscale data centers demand.

Many operators began installing optical fiber in mobile fronthaul (particularly in the links between the antenna on the mast and the baseband unit) during the 4G buildout to accelerate installations. The advent of 5G, and the speed and bandwidth increases it requires, creates another opportunity for silicon photonics.

Yole Développement estimates the 2018 global market for silicon photonics at US$500 million and predicts growth to US$3.5 billion by 2025. The numbers include potential applications, including data centers, 5G, LiDAR, and biosensors.

"It is still a very concentrated market," dominated by Intel and recent Cisco acquisition Luxtera, "though a lot of startups have been created," said Eric Mounier, fellow analyst in photonics, sensing, and display at Yole. "The total funding amount for silicon photonics is probably close to US$1 billion. This is because it holds big promise to solve the bandwidth bottleneck in data centers, and it is also a great technological platform for sensor applications."

Big companies are investing heavily in this area. Some, like Intel, have been developing their silicon photonics technology in-house over a couple of decades. Others are entering the market through acquisition. Cisco completed its purchase of Luxtera in February for US$660 million. And in a surprise move last month, Nvidia announced plans to acquire optical interconnect leader Mellanox for US$6.9 billion. The transaction will give Nvidia a silicon photonics portfolio based on technology that Mellanox acquired when it bought Kotura in 2013. Nvidia already has a strong presence in the data center space via its graphics processor products — the data center market accounts for about 25% of its business. The combined Nvidia-Mellanox lineup will enable data processing plus interconnection as part of the same solution.



The market for silicon photonics, 2016–2025
(Image: Yole Développement)

"Mellanox's main competitor is Intel, which is pushing silicon photonics to replace silicon technologies in data center interconnection," said Yole President and CEO Jean-Christophe Eloy. "Intel wants to add interconnection to the data processing it is already selling to the data center manufacturers. With the potential acquisition of Mellanox, Nvidia is following the same strategy ... This is a smart move for Nvidia — and bad news for Intel, as they will have an innovative and fast moving competitor in front of them."

Intel announced volume production of its first silicon photonic device in 2016 and has since added two more products. The three devices are 100G and 400G transceivers for data center applications and a 100G transceiver with extended temperature range targeting 5G fronthaul. The 5G device is a CWDM4 QSFP28 coarse wavelength-division multiplexing, quad small-form-factor pluggable transceiver supporting 10-km links over single-mode fiber at operating temperatures of –40°C to 85°C.

The GAFAM and BAT companies — Google, Apple, Facebook, Amazon, Microsoft, and, in China, Baidu, Alibaba, and Tencent — are pushing silicon photonics hard because of the technology's inherent advantages over legacy optics, said Yole's Mounier. Meanwhile, foundries are aiming to offer a generic process to fabless silicon photonics customers.

"It is true that more and more foundries are interested in silicon photonics, whether that's large foundries such as STM, GlobalFoundries, and TSMC or MEMS [microelectromechanical system] foundries that diversify, such as Silex Microsystems, APM, and VTT," Mounier said. "GlobalFoundries already has many partnerships with silicon photonics fabless companies ... silicon photonics will add more business by leveraging GlobalFoundries' existing semiconductor manufacturing platforms."

LASER ALIGNMENT

Communications giant MACOM is one company working with GlobalFoundries to scale its silicon photonics technology. The partners signed an agreement last month that lets MACOM use its self-aligning etched facet technology (SAEFT) in GlobalFoundries' fabs.

Because lasers can't be made of silicon (a direct-bandgap material such as indium phosphide is required), a separate laser die is typically flip-chip–assembled onto the silicon photonic chip with precise alignment. MACOM's proprietary SAEFT process allows the alignment of a laser die to a silicon photonic IC (PIC) to make an L-PIC. This technology is based on the EFT it gained with the acquisition of laser supplier BinOptics in 2014.

"This automated self-aligning process eliminates active alignment of lasers and the traditional epoxy fix-and-cure steps of discrete optical designs," said Arlen Martin, product marketing director for silicon

photonics at MACOM. "The agreement with GlobalFoundries is an extension of the parties' existing relationship and enables a multi-source supply chain leveraging GlobalFoundries' manufacturing in both Singapore and New York. MACOM will leverage GlobalFoundries' 300-mm (12-inch) silicon manufacturing process to achieve much-needed scale and cost."

According to Martin, MACOM is working on new products for data center and telecom customers based on its L-PIC platform, including products for enabling the transition to 100 Gb/s, 400 Gb/s, and beyond with its solutions for 100G CWDM4, 100G DR1/FR1, 200G FR4, 400G FR4, and 400G DR4.

Silicon photonics is ideally suited to high-volume applications such as 5G telecom infrastructure, he said. "The first phase of 5G fronthaul deployment will be a mix of 10G SFP+ and 25G SFP28 modules. For the midhaul, the optics will transition to Nx56G PAM-4 [pulse-amplitude modulation] QSFP modules. And as we transition from 10 and 25 Gb/s to 50 and 100 Gb/s, we expect to see silicon photonics beginning to play a major role."

SILICON GERMANIUM

Sicoya, a spinout of Technischen Universität Berlin, entered the market in 2017 with a 100G silicon photonics transceiver that uses a silicon-germanium (SiGe) BiCMOS process for the optical components. Most silicon photonics companies build their components on a silicon-on-insulator (SOI) process, but Sicoya CEO Sven Otte called it "a natural fit to start with the BiCMOS electronics and add the photonics."

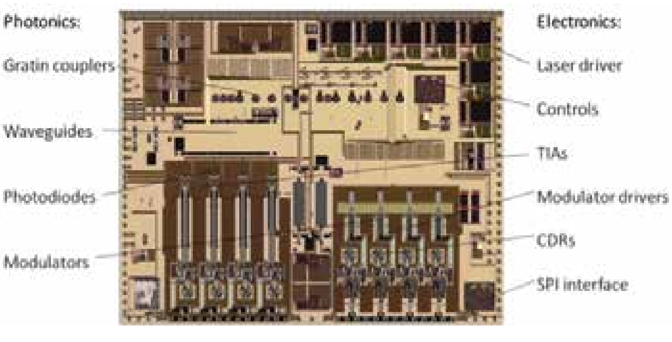
"It makes sense because the electronics part of most optical interconnects uses BiCMOS anyway," Otte said. "The transimpedance amplifiers, the clock and data recovery, and the laser drivers [are in SiGe BiCMOS] ... CMOS is used only where you need signal processing."

Today, said Otte, "Sicoya's electronics and photonics are on one chip, and our transistors are faster than CMOS transistors. SiGe is a super-efficient technology that not only gives us advantages from the performance perspective [but lets us] eliminate some of the assembly processes."

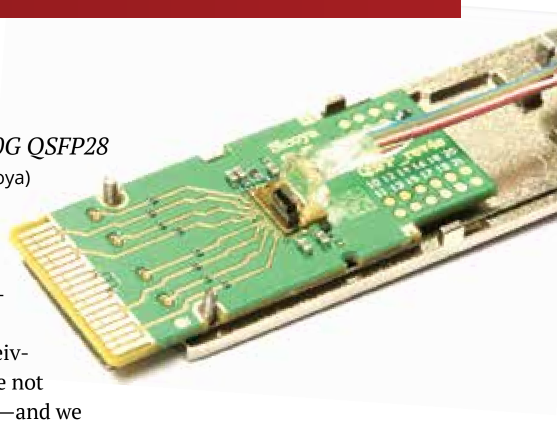
It's very difficult, if not impossible, to build optical components such as laser diodes and photodetectors (PIN diodes) effectively in silicon, so most silicon photonic solutions put those on a separate die. Sicoya integrates a SiGe photodetector on the same die as the electronics on the receive side. Will the company try to build a SiGe laser for a more integrated transmit side?

"We could, but it probably wouldn't be good enough for the particular wavelength that we need," said Otte. "More likely, we could grow indium phosphide as a layer onto one of our chips to generate a laser. But this is still at the research stage. Prototypes and qualification would take a bit more time."

Sicoya has a mixed business model, selling both chips and engines to strategic high-volume customers. "We are also selling transceivers that



Sicoya's monolithically integrated 100G electro-photonic IC (Image: Sicoya)



Sicoya's one-chip 100G QSFP28 transceiver (Image: Sicoya)

use those chips to web-scale companies. They can only accept transceivers — typically, they are not accepting any engines —and we found that selling into transceiver companies was a difficult sell, as we were competing against their internal technology," said Otte.

Sicoya products include the 100G transceiver line that launched in 2017 and a line of three 400G transceivers that debuted last month at OFC '19. The 400G models are currently in qualification and are due to start shipping in the second half of the year. There is also a product designed for 5G infrastructure: a 28G single-channel, single-mode transceiver, with a CWDM version in the works.

"The architecture has changed, from copper cables between the antenna and the remote station, then optical connections to the metro network, [and] now an RF front end with the antenna connected directly to an optical transceiver ... and the data rates are much higher," said Otte. "The majority of these connections are point-to-point, single-channel. Sometimes in metropolitan areas, there are multiple antennas on one mast, and in that case, you need a CWDM transceiver to use one fiber only to the remote station."

Otte highlighted several advantages that silicon photonics can offer 5G infrastructure. Silicon photonic chips are inherently insensitive to temperature, so they can survive the often extreme environmental conditions experienced by 5G deployments, from snowstorms to deserts. The technology is easily scalable, an obvious benefit for 5G, and it offers the ability to future-proof designs. There is also the matter of cost. For the traditional, discrete solution, the packaging accounts for a huge portion of the cost. Silicon photonics chips, with laser die attached, can use electronics packaging, which requires minimal process steps by comparison.

Otte was clear that 5G infrastructure isn't a future application — it's happening now. "We are ramping our product for the 5G market; it will be rolled out into the field by the end of the year by one of our Chinese telecom customers," he said. "5G is one of the largest-volume drivers that we see in the market ... For us, volume-wise, 5G is bigger than the data center market by a factor of two or three."

Sicoya just announced plans to open an assembly and test facility for optical modules and engines in Tianjin, China, in addition to its facility in Berlin. The new facility will serve the Chinese market for 5G wireless fronthaul and 100G/400G data center transceiver applications.

"China is particularly ahead in terms of deploying 5G, while we don't necessarily see that they are ahead in silicon photonics technology," Otte said. "In fact, I see Europe and the U.S. as certainly two to three years ahead of China in terms of having silicon photonics technology available. So that's a huge opportunity for us."

THE FUTURE

Despite the tantalizing possibilities for the future of the technology, there is a limit to what is physically possible. Rockley Photonics CEO Andrew Rickman's view is that the future of optical connectivity is in-package optics, with optimized silicon photonics and microelectronics dice in the same package rather than on the same die.

"The behavior of photons and electrons is vastly different," said Rickman. "As a result, the process that is needed to develop the most optimized electrical ICs will be different from the process needed to develop the most optimized photonics ICs. This is why monolithic integration — while it is a seductive idea — can never realize the full potential of silicon photonics. We now have significant innovation in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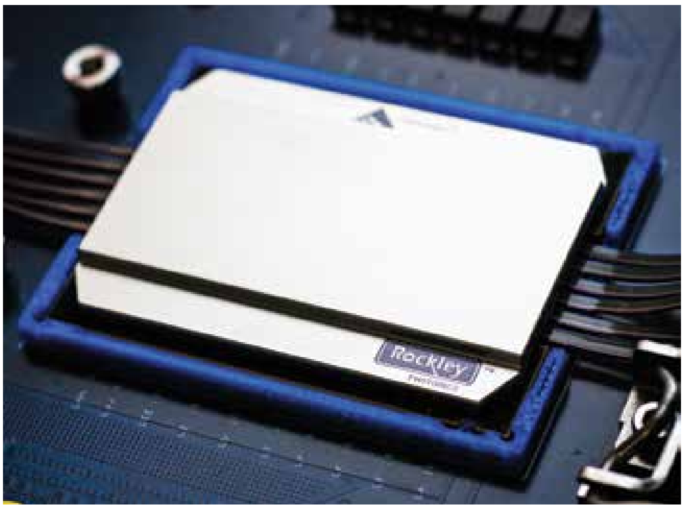
packaging technology, such as 2.5D and 3D wafer-level packaging, that can be used to develop and manufacture the most effective overall solution, and we see this approach lasting for some time."

Rickman noted that lasers need to be implemented in direct-bandgap (III–V) materials, so all silicon photonics solutions will need multiple dice anyway. Instead of further integration, correct partitioning of the solution onto different dice is key, he said.

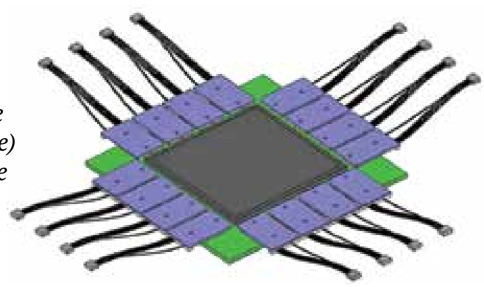
"We believe that, ultimately, the optimal solution will monolithically integrate the digital content and the analog front end, while the silicon photonics and lasers remain in separate processes — this is the approach we demonstrated with Topanga," Rickman said, referring to the company's demonstrator device from OFC '18.

Topanga is a 12-port 100G Ethernet switch with all 12 100G transceivers pre-installed. It uses an in-house–designed 1.2-Tb/s Ethernet switch ASIC with Layer 3 routing capability, plus the analog front ends (AFEs) for all 48× 25-Gb/s electrical channels. The ASIC is co-packaged with silicon photonic ICs implementing optical interfaces based on parallel single-mode fiber. The optical power is provided by external laser modules. The PICs are mounted directly adjacent to the CMOS die to minimize the length of the high-speed electrical channels, simplifying their design and reducing power consumption.

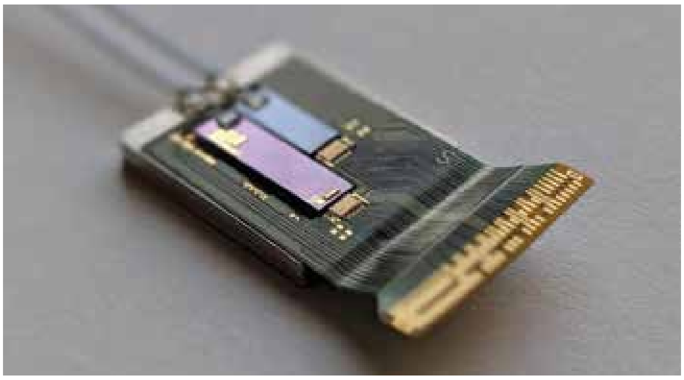
Until such time as Rockley's vision of in-package optics becomes widespread, Rickman said, a likely intermediate solution would use separate dice for the AFE and silicon photonic PICs, assembled into the same package, with a standard electrical interface for interoperability with a third-party switch chip. Rockley is pursuing this approach with its LightDriver offering, a switch-agnostic platform for multiple segments, including data center connectivity, consumer sensors, and LiDAR. The company demonstrated a transmit-receive optical subassembly using this platform at OFC '19. Future systems built on the platform may be further optimized at the system level,



Rockley Photonics showed its Topanga 12-port 100G Ethernet switch at OFC '18. (Image: Rockley Photonics)



Rockley Photonics' in-package optics platform allows the transceivers (purple) to be mounted close to the ASIC (gray). (Image: Rockley Photonics)



Transmit-receive optical subassembly (TROSA) for data communications using Rockley Photonics' silicon photonics platform (Image: Rockley Photonics)

perhaps with denser integration with the digital ASIC or via optimized electrical interconnects, Rickman said.

Rickman also argued that despite any hype to the contrary, silicon photonics is not compatible with advanced CMOS nodes, because of the properties of light. "Most companies building silicon photonics chipsets come from a microelectronics legacy based on an old but still unproven strategy to leverage existing silicon CMOS foundries and processes," he said. "The problem is that photons and electrons have vastly different behaviors and, therefore, CMOS nodes optimized for electrons are not necessarily the best choice for highly optimized photonics circuits."

There are several resulting practical considerations. Silicon photonics requires an SOI CMOS process, which is not available at the same advanced nodes as standard CMOS, and certain processing steps are required that are not available in the standard process flow. Also, for a high-speed modulator to work in silicon, the waveguide must shrink to submicron sizes, much smaller than the wavelength of the light passing through it. At these tiny geometries, the propagation losses increase and efficiency decreases.

"It's important to keep in mind that photonic devices are large compared to transistors," said Rickman. "Using up extremely valuable area on a 7-nm die to implement photonic circuits leaves less room for the chip's high-speed digital content. We believe that this is not an economically viable approach. While the Rockley platform is fully capable of producing all the functional elements that are possible in a standard CMOS-derived process flow, a benefit of our platform is that it also has all the elements, design features, and material systems available for photonic-optimized solutions."

Rockley is commercializing its technology through a joint venture (JV) it started in 2017 with Chinese fiber-optic cable manufacturer Hengtong Optic-Electric Co. The JV, funded by a US$42 million investment led by Hengtong, aims to deliver low-power, cost-effective transceivers to the market. Hengtong invested a further US$30 million in Rockley's Series E funding round earlier this year as part of the same deal.

"The JV is well under way to deliver products to the 100G sector, which will help drive business in the China telecom and data center markets," Rickman said. "We recently announced the expansion of our relationship to also enable the JV to build 400G DR4 transceivers using Rockley's LightDriver technology. These products will start shipping at the end of the year and will accelerate our footprint in China and the rest of the world."

After decades of R&D, silicon photonics is ramping in fabs around the world and delivering step-change benefits to data center connectivity and fronthaul. Or, as Sicoya's Otte put it, "Silicon photonics is now in prime time." ■

Sally Ward-Foxton *is a contributing editor at EE Times Europe.*