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News & Highlights

Pushing the Data Capacity Limit with Lasers on Silicon

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On 9 September 2016, global Internet data traffic flew past the milestone of 1 ZB, or 10^{21} bytes—a trillion gigabytes—per year. If you imagine every one of those gigabytes as a brick, a trillion of them would allow you to build 258 Great Walls of China, one analyst estimated [1]. It took nearly 40 years for the Internet to hit that mark. By 2022, annual Internet traffic is expected to reach almost 5 ZB [2].

Faced with this soaring global demand, scientists and engineers are working to develop higher data-rate technology to handle the load. Lasers are the central components of the transceivers that carry the world's digital information flow, but current devices are not fast enough to keep up. Recently, however, a prototype microscopic laser on silicon was unveiled, demonstrating advanced design features that may help keep pace with the world's surging hunger for data.

Lasers on silicon have proved difficult-to-create but are a focus of research because of their potential to provide high data capacity at an affordable price. The new prototype combines "low cost, high capacity, and low energy. This is a great direction to take," said electrical and computer engineering professor John Bowers. At the University of California, Santa Barbara (UCSB), Bowers leads one of the world's foremost laboratories developing lasers and other components for light-based circuitry, or "photonics." He and his team described the laser, which is about 3 μm high by 3 μm wide by 2 mm long, in an open-access paper published in the 20 February 2019 issue of the journal *Optica* [3].

This is not the first time Bowers has pushed the photonics envelope. Back in 2006 [4], his group unveiled an earlier prototype laser on silicon that news reports at the time said would lead to inexpensive "avalanches of data" reaching homes and widespread computing innovations [5]. Commercialized with the chipmaker Intel, the landmark device became the first laser on silicon used in mass-produced products—transceivers that began shipping by the millions in just the last few years [6].

Bowers said that the global data surge is expected to exceed the capabilities of today's photonics equipment in just a handful of years. Currently stepping up to 100 $\text{Gb}\cdot\text{s}^{-1}$ photonic transceivers, the industry expects to ramp up to 400 $\text{Gb}\cdot\text{s}^{-1}$ in the next two years and then to double or quadruple that rate in just two more [7]. That is when the features of a laser like this new one will become vital, in about four years, Bowers said.

Today, rapid growth of data centers (Fig. 1), warehouses packed with thousands of servers connected to each other, the Internet, and other global networks mainly drives the need for transceiver acceleration, said Bowers. However, anticipated innovations, such as next generation, or 5G, mobile phone technology, will require a leap in data capacity like the new laser demonstrates. "As 5G becomes widely deployed, the interconnects to antennas will need higher capacity than exists today, and that is the opportunity for this technology," Bowers said.

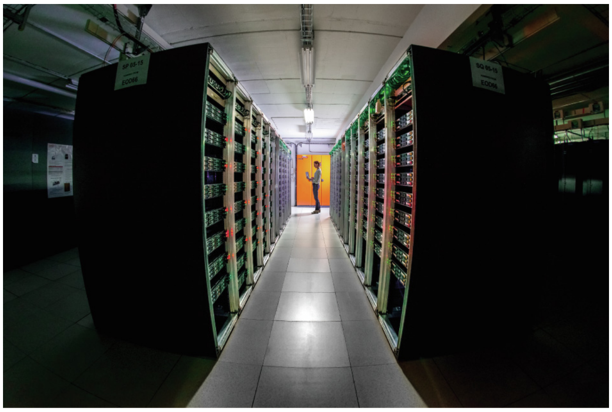

Fig. 1. A look inside the data center serving the vast particle physics laboratory European Organization for Nuclear Research (known as CERN) near Geneva, Switzerland. To handle skyrocketing traffic to, from, and within such data centers worldwide, the photonics industry currently plans to double or quadruple data capacities of laser-based transceivers about every two years. Credit: ©Robert Hradil and Monika Majer/ProStudio22.ch, CERN, with permission.

The new prototype attains an information-carrying capacity of 4.1 $\text{Tb}\cdot\text{s}^{-1}$. The device simultaneously transmits 64 different wavelengths, each bearing its own information stream, thanks to a feature called mode-locking. Those qualities enable the novel light source to support "probably the highest data transmission capability in the world right now," said photonics expert Di Liang. A post-doctoral fellow with Bowers 12 years ago, Liang now investigates improved connectivity among supercomputer components as a senior research scientist for Hewlett Packard Labs, a division of Hewlett Packard Enterprise, one of the world's leading supercomputer manufacturers, in Palo Alto, California, USA.

Because silicon itself is a poor light emitter, photonics makers typically fabricate lasers on silicon from high-performance light-emitting substances known as III–V compounds due to where their constituent elements reside in the Periodic Table. Examples of such

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compound substances include gallium arsenide, indium arsenide, and aluminum gallium arsenide. Tightly integrating a III–V laser with silicon enables photonics manufacturers to use the vast design, fabrication, and testing infrastructure of silicon-based electronics to mass-produce photonic chips at high volumes and low cost.

To achieve secure and effective coupling at the atomic level, or "monolithic integration," between lasing materials and silicon, Bowers' team grew its new prototype laser directly on silicon using a process called molecular beam epitaxy (MBE). That involved an apparatus that directed multiple beams of different molecules or atoms onto a silicon substrate that was heated to specific temperatures between 500 and 580 °C during different phases of growth. With MBE, the researchers built the prototype device one atomic layer at a time.

One of the problems Bowers and his team have worked to overcome is structural defects known as dislocations that arise during monolithic integration. These flaws, which degrade laser performance, result from mismatches between the crystal lattices and thermal expansion coefficients of silicon and III–V compounds. Dramatically lowering the concentration of dislocations in the 4.1 $\mathrm{Tb \cdot s^{-1}}$ laser allowed it to perform well at room temperature. But photonics components in commercial applications must tolerate heat generated mainly by electronic circuits, with "typical commercial optical transceivers qualified to work properly up to 80 °C," Liang said. Bowers said he is optimistic that further progress in reducing dislocations will allow the new laser prototype to meet that standard before something like it is needed in commercial products roughly four years from now. Achieving reliable 80 °C performance "would clear the last concern for successful commercial application," Liang said.

Cutting-edge nanocrystals containing indium and arsenic atoms called quantum dots [8] serve as the device's photon source (or gain medium). About 2 million of the nanostructures (Fig. 2) occupy one of nine thin layers of III–V compounds that comprise the laser and run the length of the device. An electric current stimulates the dots to emit light that is amplified by the structure and fed into a waveguide. Instead of quantum dots, the lasers in today's commercial transceivers typically draw their light from so-called quantum wells made of ultrathin layers of compound semiconductors. But quantum dots are far less affected by dislocations than quantum wells. That plus superior mode-locking by dots and lower sensitivity to reflections, which makes costly components called isolators unnecessary, will help dots to supplant quantum wells in commercial transceivers, Bowers said.

Quantum dot lasers integrated with silicon and emitting abundant wavelengths like the new 4.1 $\mathrm{Tb \cdot s^{-1}}$ device could lead to more intertwined and compact photonic and electronic circuitry, said professor of electrical engineering Keren Bergman, head of the Lightwave Research Laboratory at Columbia University in New York City. Convergence of electronic and light-based circuits could relieve data traffic bottlenecks in current systems, Bergman said, making the new laser "potentially a game changer in terms of how optics, especially silicon photonics, will be used in future data centers and high-performance systems architectures."

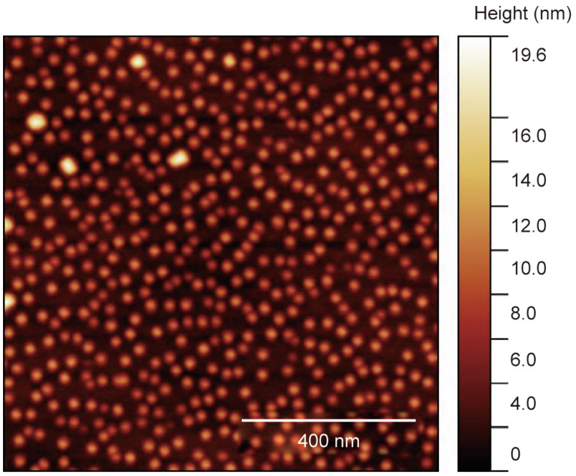

Fig. 2. Atomic force microscope image of indium-arsenide quantum dots like those that act as the photon source (or gain medium) of the new, prototype 4.1 $\mathrm{Tb \cdot s^{-1}}$ laser on silicon. The scale indicates by color how high (on an axis coming up from the page) different portions of the dots are. Fabricated by means of molecular beam epitaxy, these stump-shaped nanocrystals flatten into disks in the laser. Credit: Justin Norman/Bowers' group/UCSB, with permission.

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