Continuous Silicon Laser

Intel researchers create the first continuous silicon laser based on the Raman effect using standard CMOS technology.

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Overview

Researchers at Intel have announced another advance in silicon photonics by demonstrating the first continuous silicon laser based on the Raman effect. This research breakthrough paves the way for making optical amplifiers, lasers and wavelength converters to switch a signal's color in low-cost silicon. It also brings Intel closer to realizing its vision of "siliconizing" photonics, which will enable the creation of inexpensive, high-performance optical interconnects in and around PCs, servers and other devices.

Fiber-optic communication is the process of transporting data at high speeds on a glass fiber using light. Fiberoptic communication is well established today due to the great capacity and reliability it provides. However, the technology has suffered from a reputation as an expensive solution. This view is based in large part on the high cost of the hardware components. These components are typically fabricated using exotic materials that are expensive to manufacture. In addition, these components tend to be specialized and require complex steps to assemble and package.

These limitations prompted Intel to research the construction of fiber-optic components from other materials, such as silicon. The vision of silicon photonics arose from the research performed in this area. Its overarching goal is to develop high-volume, low-cost optical components using standard CMOS processing – the same manufacturing process used for microprocessors and semiconductor devices.

Silicon presents a unique material for this research because the techniques for processing it are well understood and it demonstrates certain desirable behaviors. For example, while silicon is opaque in the visible spectrum, it is transparent at the infrared wavelengths used in optical transmission, hence it can guide light. Moreover, manufacturing silicon components in high volume to the specifications needed by optical communication is comparatively inexpensive. Silicon's key drawback is that it cannot emit laser light, and so the lasers that drive optical communications have been made of more exotic materials such as indium phosphide and gallium arsenide. However, silicon can be used to manipulate the light emitted by inexpensive lasers so as to provide light that has characteristics similar to more-expensive devices. This is just one way in which silicon can lower the cost of photonics.

Intel's silicon photonics research is an end-to-end effort to build integrated photonic devices in silicon for communication and other applications. To date, Intel has demonstrated tunable filters, photo-detectors and optical packaging techniques using silicon. In February 2004, the prestigious scientific journal *Nature* published results of an Intel breakthrough in optical modulation. The present breakthrough builds on these innovations.

The Raman Effect

The term "laser" is an acronym for **Light Amplification through Stimulated Emission of Radiation.** The stimulated emission is created by changing the state of electrons – the subatomic particles that make up electricity. As their state changes, they release a photon, which is the particle that composes light. This generation of photons can be stimulated in many materials, but not silicon due to its material properties. However, an alternate process called the Raman effect can be used to amplify light in silicon and other materials, such as glass fiber. Intel has achieved a research breakthrough by creating an optical device based on the Raman effect, enabling silicon to be used for the first time to amplify signals and create continuous beams of laser light. This breakthrough opens up new possibilities for making optical devices in silicon.

The Raman effect is widely used today to make amplifiers and lasers in glass fiber. These devices are built by directing a laser beam – known as the pump beam – into a fiber. As the light enters, the photons collide with vibrating atoms in the material and, through the Raman effect, energy is transferred to photons of longer wavelengths. If a data beam is applied at the appropri-

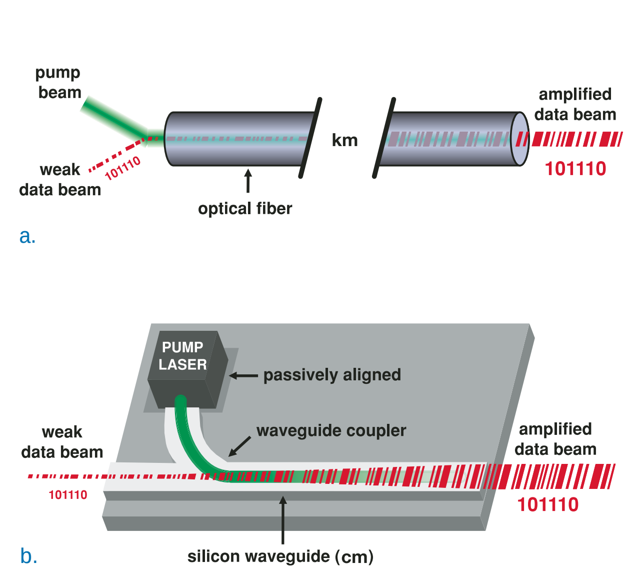

Figure 1. The Raman effect allows energy from a pump beam to amplify data at longer wavelengths in glass fiber (a). This could now be done in silicon as well (b).

ate wavelength, it will pick up additional photons. After traveling several kilometers in the fiber, the beam acquires enough energy to cause a significant amplification of the data signal (Figure 1a). By reflecting light back and forth through the fiber, the repeated action of the Raman effect can produce a pure laser beam (see sidebar on lasers). However, fiber-based devices using the Raman effect are limited because they require kilometers of fiber to provide sufficient amplification.

The Raman effect is more than 10,000 times stronger in silicon than in glass optical fiber, making silicon an advantageous material. Instead of kilometers of fiber, only centimeters of silicon are required (Figure 1b). By using the Raman effect and an optical pump beam, silicon can now be used to make useful amplifiers and lasers.

The Challenge

The process of building a Raman amplifier or laser in silicon begins with the creation of a waveguide – a conduit for light – in silicon. This can be done using standard CMOS techniques to etch a ridge or channel into a silicon wafer (Figure 1b). Light directed into this waveguide will be contained and channeled across the chip. In any waveguide, some light is lost through absorption by the material, imperfections in the physical structure, roughness of the surfaces and other optical effects. The challenge that Intel researchers surmounted is making a waveguide in which the amplification provided by the Raman effect exceeds the loss in the silicon waveguide.

How Lasers Work

Lasers generate a beam of a single wavelength by amplifying light. As shown in Figure 2, electrical or optical energy is pumped into a gain medium which is surrounded by mirrors to form a "cavity." Initial photons are either electrically generated within the cavity or injected into the cavity by an optical pump. As the photons stream through the gain medium, they trigger the release of duplicate photons with the same optical properties (wavelength, phase and polarization).

As the photons move back and forth between the mirrors, they gather additional photons. This gain has the effect of amplifying the light. Ultimately, the light is sufficiently strong to form a "coherent" laser beam in which all the photons stream in parallel at the same wavelength. This laser beam is shown exiting the cavity by the red beam at the right of the figure below.

The world's first laser was built by Ted Maiman in 1960. This device used a white flash lamp to optically pump a ruby crystal and generate red laser light.

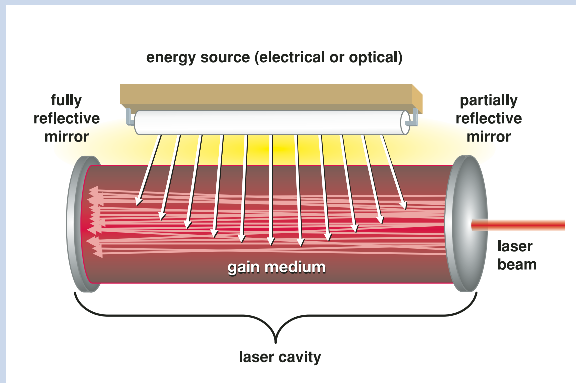

Figure 2. A laser beam is a stream of coherent, monochromatic photons that have been amplified by the repeated acquisition of new photons in the gain material.

In mid-2004, Intel researchers discovered that increasing the pump power beyond a certain point no longer increased the amplification and eventually even decreased it. The reason turned out to be a physical process called two-photon absorption (see next section), which absorbs a fraction of the pump beam and creates free electrons. These electrons build up over time and collect in the waveguide. The problem is that the free electrons absorb some of the pump and signal beams, reducing the net amplification. The higher the power density in the waveguide, the higher the loss incurred. Intel's breakthrough is a solution that minimizes the extra electrons caused by two-photon absorption – so that an amplified, continuous laser beam can be generated. In fact, Intel recently demonstrated the first silicon device with a continuous net amplification with a gain that more than doubled the input signal power.

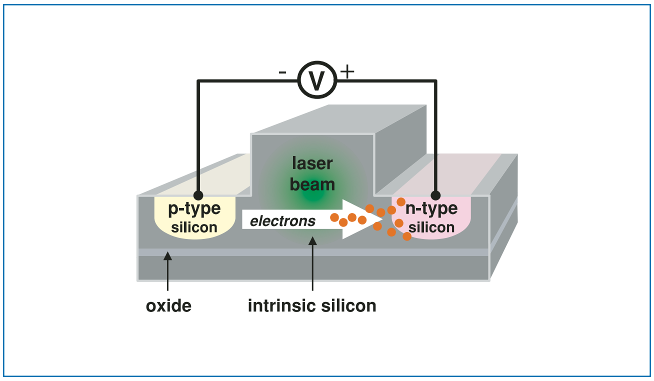

Figure 3. By inserting a diode-like PIN device in the wave guide, Intel removed the electrons generated by two-photon absorption and produce continuous amplification.

Two-Photon Absorption

Usually, silicon is transparent to infrared light, meaning atoms do not absorb photons as they pass through the silicon because the infrared light does not have enough energy to excite an electron. Occasionally, however, two photons arrive at the atom at the same time in such a way that the combined energy is enough to free an electron from an atom. Usually, this is a very rare occurrence. However, the higher the pump power, the more likely it is to happen.

Eventually, these free electrons recombine with the crystal lattice and pose no further problem. However, at high power densities, the rate at which the free electrons are created exceeds the rate of recombination and they build up in the waveguide. Unfortunately, these free electrons begin absorbing the light passing through the silicon waveguide and diminish the power of these signals. The end result is a loss significant enough to cancel out the benefit of Raman amplification.

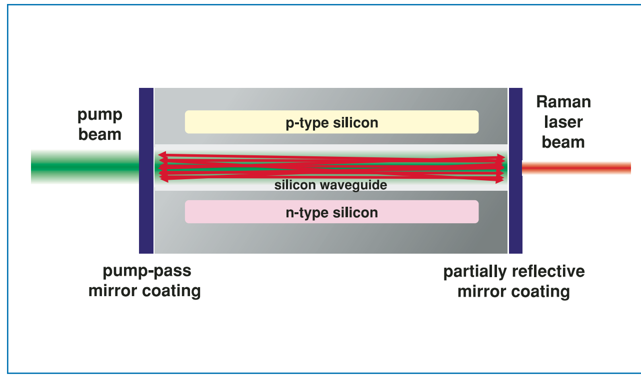

Figure 4. The breakthrough silicon laser used a PIN device and the Raman effect to amplify light as it bounced between two mirrors coated on the waveguide ends, producing a continuous laser beam at a new wavelength.

Intel's Breakthrough Laser

Intel's solution is to change the design of the waveguide so that it contains a semiconductor structure, technically called a PIN (P-type – Intrinsic – N-type) device. When a voltage is applied to this device, it acts like a vacuum and removes the electrons from the path of the light. Prior to this breakthrough, the two-photon absorption problem would draw away so many photons as to not allow net amplification. Hence, maintaining a continuous laser beam would be impossible. Intel's breakthrough is the use of the PIN to make the amplification continuous.

Figure 3 is a schematic of the PIN device. The PIN is represented by the p- and n- doped regions as well as the intrinsic (undoped) silicon in between. This silicon device can direct the flow of current in much the same way as diodes and other semiconductor devices do today in common electronics. Hence, the manufacture of this device relies on established manufacturing technologies and it reinforces the basic goal of silicon photonics: inexpensive, high-performance optical components.

To create the breakthrough laser, Intel coated the ends of the PIN waveguide with mirrors to form a laser cavity (Figure 4). After applying a voltage and a pump beam to the silicon, researchers observed a steady beam of laser light of a different wavelength exiting the cavity – the first continuous silicon laser.

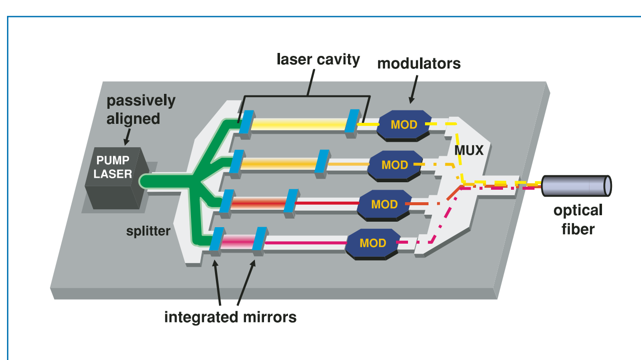

Figure 5. An example of creating multiple silicon laser sources from one pump beam. A pump beam that contains multiple wavelengths (similar to ordinary white light) could power four lasers of different wavelengths via the Raman effect.

Applications

Fundamentally, Intel researchers have demonstrated silicon's potential as an optical gain material. This could lead to many applications including optical amplifiers, wavelength converters, and various types of lasers in silicon.

An example of a silicon optical amplifier (SiOA) using the Raman effect is shown in Figure 1b. Two beams are coupled into the silicon waveguide. The first is an optical pump, the source of the photons whose energy will cause the Raman effect. The spectral properties of this pump determine the wavelengths that can be amplified. As the second beam, which contains the data to be amplified, passes through the waveguide, energy is transferred from the pump into the signal beam via the Raman effect. The optical data exits the chip brighter than when it entered; that is, amplified.

Optical amplifiers such as this are most commonly used to strengthen signals that have become weak after traveling a great distance. Because silicon Raman amplifiers are so compact, they could be integrated directly alongside other silicon photonic components, with a pump laser attached directly to silicon through passive alignment. Since any optical device (such as a modulator) introduces losses, an integrated amplifier could be used to negate these losses. The result could be lossless silicon photonic devices.

The Raman effect could also be used to generate lasers of different wavelengths from a single pump beam. As the pump beam enters the material, the light splits off into different laser cavities with mirrors made from integrated silicon filters (Figure 5). The use of lasers at multiple wavelengths is a common way of sending multiple data streams on a single glass fiber. In such a scenario, Intel's silicon components could be used to generate the lasers and to encode the data on each wavelength. The encoding could be performed by a silicon modulator unveiled by Intel in early 2004. This approach would create an inexpensive solution for fiber networking that could scale with the data loads of large enterprises.

In addition to communications, there are other potential applications for silicon Raman lasers. Because the Raman effect involves the conversion of a pump beam to a longer wavelength, this could be used to create new laser beams at wavelengths that cannot be attained by compact semiconductor lasers at room temperature. Lasers with wavelengths greater than 2 µm have applications in medical spectroscopy but must be made from bulky bench-top components because semiconductor lasers are not available at such long wavelengths. However, a compact silicon Raman laser could be made to reach these wavelengths, enabling the creation of more portable medical devices.

The Optical Future

As Moore's Law continues to push microprocessor performance, and as increasing volumes of data are sent across the Internet, the demands placed on network infrastructure will increase significantly. Optical communications and silicon photonic technology will allow enterprises to scale bandwidth availability to meet this demand.

In addition, due to the low cost of silicon solutions, servers and high-end PCs might one day come standard with an optical port for high-bandwidth communication. Likewise, other devices will be able to share in the bandwidth explosion provided by the optical building blocks of silicon photonics.

By creating the PIN device to sweep away free electrons in silicon waveguides, Intel delivered a significant breakthrough: a silicon component that can create continuous-beam Raman lasers and optical amplifiers.

Intel's research into silicon photonics is an end-to-end program that pushes Moore's Law into new areas. It brings the benefits of CMOS and Intel's volume manufacturing expertise to fiber-optic communications. The goal is not only achieving high performance in silicon photonics, but doing so at a price point that makes the technology a natural fit – even an automatic feature – for all devices that consume bandwidth. Intel's breakthrough continuous silicon Raman laser will undoubtedly contribute to the reality of this vision.

For additional information about Intel's work in silicon photonics, see **intel.com/technology/silicon/sp**

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