Discovery of a novel silicon photonic-crystal waveguide modulator

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Photonic-crystal waveguides that significantly slow light have been exploited to make a silicon modulator with an interaction length of 80 μm and a peak drive current of less than 150 μA.

Silicon, a material that has carried the entire electronics industry for the latter half of last century, has only recently been considered a favorable choice for functional optics. Silicon has no $\chi^2$ electro-optic effect, and converts injected electrons into light with extremely low efficiency. Both of these are great disadvantages for modulating and generating light. Thus far, integrated optical functions have primarily been performed on III-V materials such as gallium arsenide. This separation of photonics and electronics has been a big stumbling block for many important applications in telecommunications, optical interconnects, and consumer electronics.

As the intrinsic material properties of silicon do not favor photonic applications, many techniques to artificially pattern silicon with extremely fine optical structures have been investigated. However—unless these fine structures can be produced with controllability, consistency, and high precision—these devices cannot serve their designed purpose. With current nano-fabrication technology, this remains a practical challenge for most material-engineering approaches. Silicon modulators based on micro-ring resonators can reduce the device size: however, their extremely narrow bandwidth (≈ 0.02 nm) means that, for practical applications, they require a laser with accurate wavelength control. This is expensive.

Photonic crystals, artificial dielectric periodic lattices on the wavelength scale, provide a solution to this problem. The lattice creates photonic bandgaps—similar to energy bandgaps for electrons in solids—that cause photons to be reflected regardless of their incident angle on the photonic crystal surface. This unique property provides a novel combination of abilities: to confine, guide, and decelerate light. A typical photonic crystal is made by etching arrays of holes with diameters of a few hundred nanometers (or smaller) into silicon. With the advent of electron beam nanolithography, it now becomes possible to fabricate such photonic crystals with high precision.

Exploiting photonic-crystal nanostructures, we recently designed and demonstrated a silicon modulator that is one to two orders of magnitude smaller than conventional silicon modulators in size and power consumption. Light enters into an integrated Mach-Zehnder interferometer (MZI) through a conventional silicon waveguide. As shown in Figure 1, short segments of silicon photonic-crystal nanostructures are incorporated in the two arms of the MZI to alter the phase of light. One arm is controlled by an external oscillating electrical signal applied across two electrodes (see Figure 2) so that the phase of light is modulated in time. When light from the two arms combines at the exit of the MZI, the time-varying phase of one arm causes the combined light intensity to undulate.

To modulate light, electrons (holes) are injected into silicon at a density around $10^{-17}$ cm$^{-3}$ to cause the refractive index of the silicon to be modified noticeably. This is commonly known as the plasma-dispersion effect. However—over an interaction length of a few dozen micrometers—the change of refractive index is too low to produce an adequate phase change through any conventional approach.

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In our device, a photonic-crystal waveguide is formed on the top layer of a silicon-on-insulator wafer by etching two periodic blocks of air holes around an air-hole-free waveguide core. The photonic-crystal waveguide slows the speed of light traveling inside it by 40 times: this means that electrons can exert more influence on the light over a short interaction length. This markedly enhances the ability of electrons to alter the phase of light, and results in sufficient light modulation both over a short segment of the photonic-crystal waveguide and at a low driving current (see Figure 3).

The integration of electronic control structures with photonic crystals was a challenging task, as this required a complicated sequence of processing steps. These included e-beam nano-lithography, photolithography, metal deposition, and dry and wet etching. To reduce the fabrication difficulties and improve the device yield, a planarized structure was designed.

Many consider optics to be a promising means of transmitting high-speed signals on a silicon chip: optical interconnect technology is projected to overcome the metal-wire-interconnect bottleneck that is plaguing the computer industry. The modulator we have demonstrated—through support from the Air Force Office of Scientific Research, the State of Texas, and the National Science Foundation—is an important building block for a low-cost all-silicon optical interconnect technology with extraordinarily low power consumption and small device size. Further advances in the area of silicon lasers will eventually realize a dream of many generations of scientists: let there be light, on silicon!