New high-speed nanophotonic silicon modulator offers low-voltage operation

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Photonic crystals that enhance the interaction of light and matter achieve the low driving voltage desirable for on-chip applications.

Generations of scientists and engineers have dreamed of electronics and optics that work together on one silicon chip. Such devices may make help computers run faster, iPods and cell phones deliver crisper pictures, and fiber-to-the-home arrive sooner and cheaper. A technology that is key to these advances is silicon optical modulators, which can make a laser beam blink by driving a small electric current into the silicon chip. The blinking rate, interval, or intensity of the light through an optical modulator can be changed by varying the injected current. As a result, information could be encoded onto the light beam, which would then carry it around the chip.

Recent developments in gigahertz silicon modulators have promised monolithic integration of microelectronic and photonic devices on a single silicon substrate. Nonetheless, the voltage and power consumption of these silicon modulators are too high for on-chip applications due to the intrinsically weak optical properties of silicon materials. We previously invented an ultracompact modulator by exploiting the slow light effect in photonic crystal waveguides. More recently, by investigating the photon-electron interaction in the photonic crystal approach, we demonstrated the first p-type/intrinsic/n-type (p-i-n) diode–embedded photonic crystal silicon modulator that reaches gigahertz speed under a low driving voltage.

Our research on photon-electron interactions has revealed that the fundamental nature of light and certain intrinsic properties of silicon set a minimum current density for high-speed silicon modulators. For gigahertz modulation, this minimum current density is 10,000A/cm², which falls in the so-called high-injection regime of a silicon diode. This explains why conventional devices ran into high-voltage issues (peak voltage ∼20V) accompanied with high power. A technique using photonic crystals, periodic lattices on the wavelength scale, is capable of shrinking the device interaction length to tens of microns and the device height to hundreds of nanometers. This significantly reduces the overall current and thus the driving voltage for the same current density.

To realize the silicon modulator, we employed the Mach-Zehnder interferometer (MZI) structure, which regulates light by controlling the phase shift between two coherent light beams propagating through two device arms. In our approach, the electric current injected into the silicon chip controls the phase shift of the light. Photonic crystals have demonstrated the ability to slow down the light speed significantly. As the light travels...
down a given distance in a longer time, the electric current can exert more influence on the light. This helps reduce the amount of current needed for the targeted phase shift.

The p-i-n diode–embedded photonic crystal silicon MZI modulators, shown in Figure 1(a), were fabricated on a silicon-on-insulator wafer with a 260nm-thick top silicon layer. A line-defect photonic crystal waveguide (PCW) replaced a strip-waveguide segment in each arm of the MZI, as shown in Figure 1(b). The PCW was formed in a hexagonal lattice photonic crystal having a period of 400nm and an air-hole diameter of 220nm. Electron-beam lithography and dry etching patterned the optical waveguide layer. p⁺ and n⁺ regions were defined using photolithography and implanted to a concentration N of about N_a = N_d = 5 × 10¹⁹ cm⁻³ (where a and d are acceptor and donor). The intrinsic region was n-doped to N_{id} ~ 10¹⁵ cm⁻³.

We optically characterized the p-i-n diode–based MZI modulator. A maximum modulation depth of 93% was obtained at a static injection current of 7.1mA. Two-level digital electrical signals having V_{on} = 2V, V_{off} = −1V, and a duty cycle of 50% were used for high-frequency modulation characterization. A high modulation depth of 85% at 2Mbit s⁻¹ was obtained. The modulation depth decreased by 3dB as the modulation frequency increased to 1Gbit s⁻¹, which marked the 3dB bandwidth of our device.

Gigahertz optical modulation represents a fundamental speed benchmark for almost all active silicon integrated optical systems. Very few research groups in the world have succeeded in breaking the gigahertz barrier for silicon modulators, and doing so often imposed the cost of a high driving voltage. The compact, low-voltage, high-speed photonic crystal silicon modulator we developed may bring optical interconnects and other on-chip optical applications a step closer to reality.

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Ray T. Chen holds the Cullen Trust Endowed Professorship at the University of Texas at Austin. His group has been awarded 84 research grants and 17 patents, and has published more than 440 papers, including more than 60 invited papers. Thirty students have received PhD degrees in electrical engineering under his supervision.

References


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