Highly efficient optical modulators in silicon for next-generation networks

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Careful configuration of the semiconductor junction in electro-optic resonators and interferometers enables fast operation.

Demand for cost-effective and environmentally sustainable communication applications has increased significantly in the past decade, as the number of data centers and enterprise networks increases. Interest in silicon-based optical links is rising, mainly due to inherent limitations of copper wires and cables such as high power consumption, low heat dissipation, and low data transmission rates, combined with the need for continuous miniaturization of transistors and wide use of multi-core architecture. As one of the key components of optical links, optical modulators are used to change the intensity or phase of the continuous wave output of a laser to generate a digital signal for transmission in a fiber. Next-generation optical networks require highly efficient, high-bandwidth optical modulators that are compatible with electronic integrated circuits on silicon substrates. Highly efficient optical modulators will also be required for future high-throughput interconnects in large-capacity data centers and high-performance computers.

However, electro-optic (EO) effects are absent or very weak in silicon. Only the plasma dispersion effect of free carriers in silicon optical waveguides—in which the optical absorption coefficient and refractive index of silicon change as the free carrier density varies—offers a potential mechanism for high-speed EO modulation with a subnanosecond response time. In most recent research work focusing on silicon modulators, high-speed EO modulation is performed by one of three types of configurations, each of which uses an applied voltage to control the free carrier density at a semiconductor interface. These are MOS (metal oxide semiconductor) capacitors (with a cumulated charge region), forward-biased (current-driving) ‘p-i-n’ diodes, and reverse-biased ‘p-n’ junctions (with a free carrier depletion layer). For these, p means a semiconductor with positively charged ‘hole’-type carriers, i means an intrinsic conductor, and n means a semiconductor with (negatively charged) electrons as carriers. When a p-n junction is reverse-biased (i.e., has a voltage across it such that the voltage at the n-type region is higher than at the p-type region), the number of carriers at the junction...
is depleted. This depletion-type configuration is regarded as the best candidate for high-speed optical modulation with a 3dB bandwidth at more than 50GHz.\textsuperscript{3–6} Two common types of optical modulator are Mach-Zehnder interferometers (MZIs) and micro-ring resonators (MRRs). An MZI splits a propagating light beam into two, induces a phase shift in one beam by a change in the refractive index of the medium, and recombines the two beams. If the two beams’ relative phase shift is \( \pi \), the two beams will cancel and the output will be zero. An MRR is made up of a ring resonator adjacent to a waveguide. When light propagates along the waveguide, its transmission past the ring will be greatly reduced if its frequency matches one of the resonant frequencies of the coupled ring resonator. It is possible to control the resonant frequencies of the ring resonator by changing its refractive index. For both these types of optical modulator, the refractive index can be changed by depleting the carrier region using reverse-biased p-n junctions. These devices can operate at a data rate of about 30–44Gb/s.\textsuperscript{3, 6, 7} However, most optical modulators based on reverse p-n junctions are relatively inefficient, are several millimeters long, and require a potential difference of at least 5V to achieve a phase shift of \( \pi \) in MZI configuration. Power consumption is defined by the square of the driving voltage, and the integrated circuit length is inversely proportional to the driving voltage. As a result, the large potential difference required by the MZI limits the reductions in power consumption and size that can be achieved.

In fact, modulation efficiency can be determined by the configuration of the p-n junction.\textsuperscript{5} For light propagating along the p-n interface (either horizontal or vertical), the depletion region (doping level \( \sim 1 \times 10^{17} \text{cm}^{-3} \)) is usually much smaller than the optical field of the silicon waveguide (\( \sim 500 \text{nm} \)). As a result, the overlap between the area of variable refractive index and the light is relatively small. In these cases, to achieve the maximum phase shift of \( \pi \), the product of the applied voltage and the p-n junction length is normally more than 1.8V/cm. In addition, there is only a small reduction of the optical absorption loss induced by doped regions embedded in silicon optical waveguides, offering negligible improvement on optical modulation for both MZIs and MRRs.

We therefore proposed a device design with interleaved p-n junctions to maximize the interface and the depletion region (see Figure 1).\textsuperscript{5, 8, 10} Silicon optical modulators with this junction type require low driving voltages and short active regions and, thanks to our work, are now available commercially. Fortunately, this type of junction improves MRR- and MZI-based optical modulators, mainly due to the high modulation efficiency, and also the large reduction in absorption loss that results when a reverse bias is applied to the modulator. Although the trade-off for higher efficiency is lower roll-off frequency (i.e., the frequency threshold, at which high-frequency signals are reduced in amplitude, is lower), the bandwidth of optical modulators can be improved by optimizing the shape of p-n junctions with the help of electrical circuit analysis models.\textsuperscript{6–8, 10}

Recently, we developed a novel MRR-based optical modulator with a ‘zigzag’ junction.\textsuperscript{9} We obtained clear eye diagrams at a data rate of 44Gb/s at a reverse bias of \(-3\text{V}\) (see Figure 2). Our device achieved an extinction ratio of \( \sim 3\text{dB} \) at more than 40Gb/s operation with driving signals as low as 3V (peak-to-peak). We estimated electrical bandwidth of up to 51GHz\textsuperscript{9} after finding a low junction capacitance of 30–50fF at reverse bias between \(-6\) and \(0\text{V}\). A limitation of this type of modulator is the intrinsic optical bandwidth or optical cavity lifetime, given by the resonance shift range of an MRR and its sensitivity to index change and absorption variation. By detuning the center wavelength of

\begin{figure}[h]
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\caption{(a) Top view of a micro-ring resonator-based modulator with zigzag p-n junctions\textsuperscript{5, 9} and (b) 44Gb/s eye diagram of modulation by non-return-to-zero pseudorandom binary sequence \( 2^{31} – 1 \) signals with a peak-to-peak voltage (\( V_{pp} \)) of 3V at a bias of \(-3\text{V}\). G: Ground. S: Source.}
\end{figure}

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input light from the MRR resonance, we found an EO modulation bandwidth of $\sim 24.6$GHz.\(^9\) (In addition, we previously obtained $\sim 100$GHz broadband optical operation of MRRs.\(^10\))

To summarize, we have obtained highly efficient MRR-based optical modulators operating at more than 40Gb/s and even 100Gb/s. These offer an opportunity to meet demands for high bandwidth in next-generation optical transmission and switching networks in data centers and supercomputers. In the near future, we will use wavelength division multiplexing technology to demonstrate silicon modulator arrays integrated with other photonic functions on a single chip that is capable of more than 200Gb/s.

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References