Discovery at the Interface of Science and Engineering: **Science Matters!**

Microelectronics and Microsystems
Photonics

Silicon Photonics for Low-Energy Optical Communications for National Security Applications

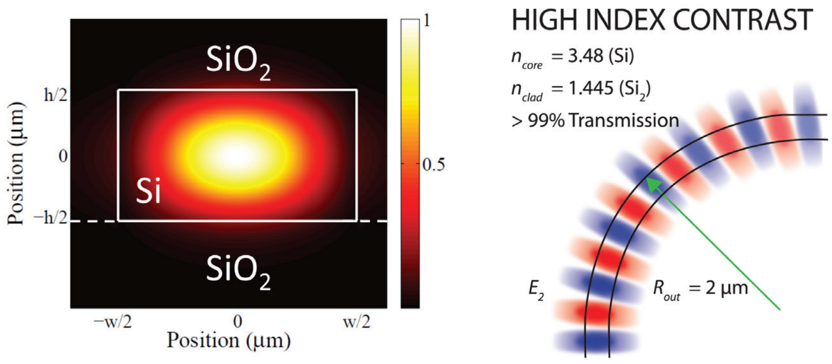

Figure 1: Silicon photonics waveguides. *(Left)* cross section showing the optical mode for waveguide dimensions, width=450 nm and height=250 nm. The SiO_2 layer on the bottom is 3 µm above the silicon substrate, and the cap layer on the top is 3 µm above the waveguide. *(Right)* Top view of a silicon photonics waveguide bend of radius 2 µm showing the confinement of light in the waveguide

Silicon photonics offers breakthrough interconnect capability for high performance computing and satellite applications

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As integrated circuit chips now incorporate over a billion transistors and single boards provide multi-teraflop (10^{12}) compute capacity, the bandwidth and energy required to communicate data within and between integrated circuits are becoming a primary performance bottleneck. Silicon photonics offers a potential breakthrough in data interconnection performance, not just for supercomputer applications, but also for other high-complexity problems of interest to national security such as high-speed data encryption, aircraft and satellite internal communications, reconfigurable networks, and optical beam steering. Importantly, silicon photonics can ride on the progress of silicon electronics and, when mature, will likely achieve the high yield, high reliability, and low costs common in the electronics industry.

To support the needs of next generation national security applications, researchers have developed a Sandia Silicon Photonics platform that leverages the semiconductor and nanotechnology capabilities of Sandia's MESA (Microsystems and Engineering Sciences Applications) complex. The core devices are comprised of silicon nanowire waveguides clad in silicon dioxide (SiO_2) as shown in Figure 1 (left). The large refractive index contrast between the silicon waveguide and the oxide cladding allows light to be routed in the waveguide, even for small devices with bend radii as tight as 2 µm (Figure 1, right). One key device, a resonant disk modulator, confines the light inside a 4 µm diameter micro-disk shown in Figure 2 (left). When input light from an off-chip laser is coupled to a bus waveguide at the resonant optical wavelength of the disk, light is coupled from the bus waveguide to the disk; otherwise, light passes by the disk without perturbation. By constructing the disk within a vertical p-n diode, a reverse bias voltage can change the carrier concentration in the diode, in turn changing the index of refraction of the disk and shifting the resonant frequency as shown in Figure 2 (right). Using an input wavelength shown by the dashed green line in Figure 2 (right), one can convert this resonant frequency shift of the disk into an intensity modulation of the input light, creating a series of logical 1's and 0's under electrical drive.

Because the micro-disk resonators are so small, they can have capacitances as low as 20 femtofarads (10^{-15} F), and can operate with an electrical power usage of as little as 3.2 femtojoules (fJ) per bit or 40 µW for 12.5 gigabits per second of information (Reference 1), which is about three orders of magnitude less power than it takes to electrically communicate information at the same data rate. This power savings is critical in high performance computing and satellite communications, especially in the latter case for communications from cooled focal plane arrays. Using wavelength division

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multiplexing to combine the modulated signals from multiple disks on one line as shown in Figure 3, one can achieve bandwidths per optical line greater than 1 terabit per second, more than 100 times greater than what electrical connections can achieve.

Sandia has demonstrated many additional leading-edge silicon photonics devices for applications in communications, sensing, and computing. Included are full C-band tunable resonant second-order filters (Reference 2), reconfigurable 2 x 2 wavelength selective switches (Reference 3), the integration of a micro-heater and sensor with the modulator for thermal stabilization over 55 degrees C (Reference 4), and low voltage compact broadband phase modulators and 2 x 2 thermo-optic switches (Reference 5). Sandia has integrated silicon photonics modulators with radiation-hardened 0.35 µm CMOS structures (complementary metal oxide semiconductor, Reference 6), and has recently integrated germanium detectors in its Silicon Photonics Platform.

References:

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2. M. R. Watts, W. A. Zortman, D. C. Trotter, G. N. Nielson, D. L. Luck, and R. W. Young, "Adiabatic Resonant Microrings (ARMs) with directly integrated thermal microphotonics," in *Conference on Lasers and Electro-Optics*, Optical Society of America, 2009.

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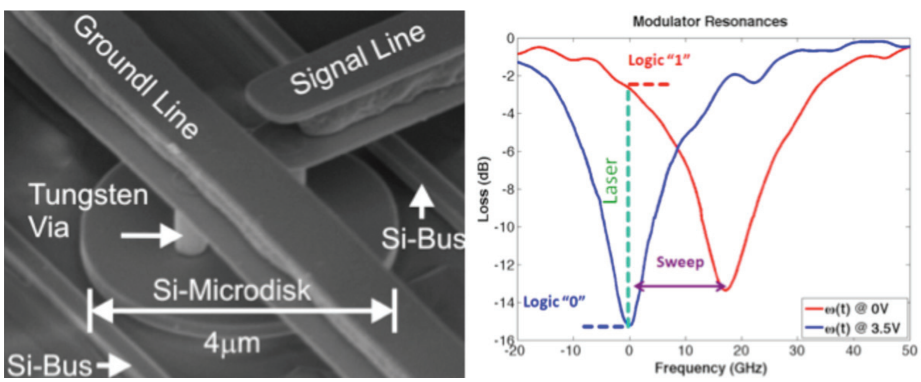

Figure 2: Silicon Photonics Micro-disk modulator. (*Left*) Scanning electron micrograph of the modulator with the top oxide removed. Light is incident on the modulator on either of the silicon busses and the modulated light output is on the lower left bus as indicated by the arrow. (*Right*) Optical response for light incident on the same bus as the output without bias (red) and with bias (blue), as a function of optical frequency shift from the laser wavelength. The absolute optical frequency is ~ 193 THz or 1550 nm. With an input wavelength shown by the green line, the shift in resonant peak position with bias is changed into an amplitude modulation of the incident laser source.

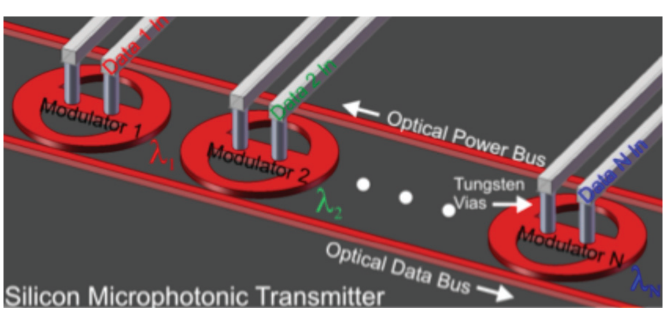

Figure 3: Wavelength division multiplexing of optical transmitters. The optical power bus contains off-chip lasers of different frequencies (wavelengths), denoted by λ_1, λ_2 and λ_N. These lasers are modulated to produce a wavelength-division multiplexed optical data bus output by modulators 1 thru N in the figure. For a practical limit of ~100 wavelengths at ~10 gigabit/s per modulator, each optical data bus can consist of 1 terabit/s of data, and each set of off-chip lasers can potentially supply ~100 data busses simultaneously or 100 terabits/s of data.

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