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Silicon Photonics for Next Generation Computers

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1. Introduction

The continued Moore's Law scaling of microprocessor performance and the corresponding need to balance the communications to compute performance within high performance computers is straining current communications technologies, from electrical links to parallel VCSEL (Vertical Cavity Surface Emitting Laser) array-based fiber communications, in terms of bandwidth density, power consumption, and cost. It is becoming increasingly clear that wavelength division multiplexed (WDM) photonics will be needed to address the bandwidth limitations and cost scaling of future interconnects. Further, in order to meet the power efficiency metrics, a single-mode solution is needed. As perhaps the only viable solution to meeting all of these needs, silicon photonics is rapidly emerging as the solution for addressing chip-to-chip communication bottlenecks in next generation computers.

Here, we discuss recent results on ultra-low power silicon microphotonic communications with emphasis on wavelength division multiplexed (WMD) implementations. In particular we address several key issues associated with implementing WDM communication systems on a chip including wavelength division multiplexing (WDM), modulation, detection, and thermal control.

2. A Microphotonic Communication System

To achieve ultra-low power high-bandwidth communications between, for example, the nodes of an exascale computer, it is essential to eliminate electrical transmission lines. To do so, close integration of CMOS to silicon microphotonics is needed. Direct integration and hybrid integration of silicon photonics have each previously been demonstrated. In either case, parasitics can be negligible if properly implemented. Since advanced CMOS and silicon photonics do not share equivalent layer thicknesses and other characteristics, hybrid integration will likely take hold first. Such an approach is depicted in Fig. 1.

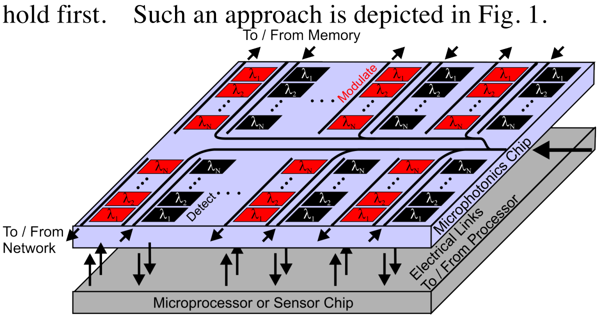

Fig. 1 A close, wavelength division multiplexed (WDM) connection between a microprocessor and a silicon microphotonics chip can enable ultra-low power optical communications with unparalleled bandwidth.

Close electrical communications serves two purposes: (1) Short electrical lines provide low capacitance connections to the electronics chip thereby greatly reducing power consumption, and (2) the substantial density of vias that can be achieved through 3D integration enables very high data rate electrical communications out to the WDM optical network for longer distance communications.

Numerous passive components can be implemented in a silicon photonic platform. Examples include short couplers for power dividing, polarization beam splitters, filters, and waveguide crossings. In particular, the sharp bends (Fig. 2a), made possible by the high index contrast silicon material system, can be wrapped around into a loop to form a microring-resonator-based filter (Fig. 2b). By cascading microrings, high-order filters can be constructed (Fig. 2c), and designed utilizing microwave filter theory [1]. These filters are critical components for future DWDM communication systems and are in many ways unique to the silicon material system.

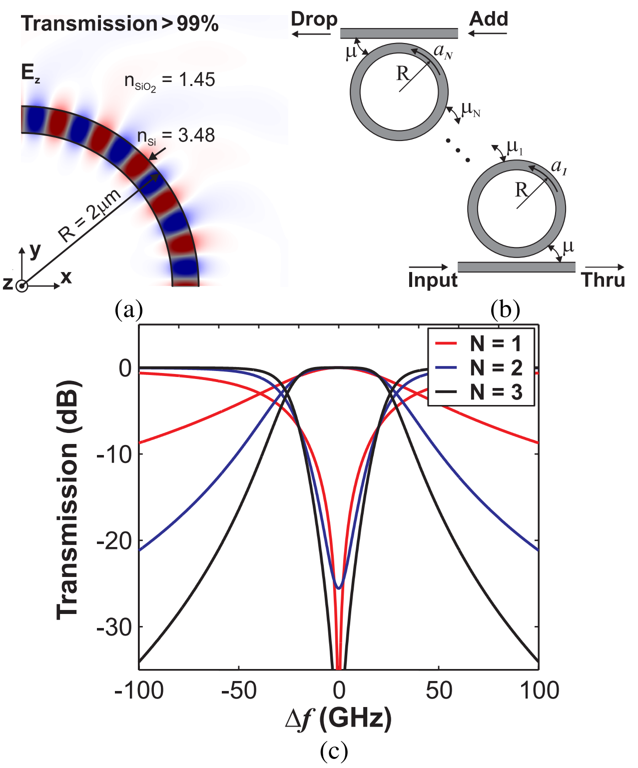

Fig. 2 (a) Simulation of a silicon-to-silicon-dioxide high index contrast bend (b) diagram of a high-order microring-resonator filter, and (c) filter responses of 1st, 2nd, and 3rd order filters obtained using microwave filter theory.

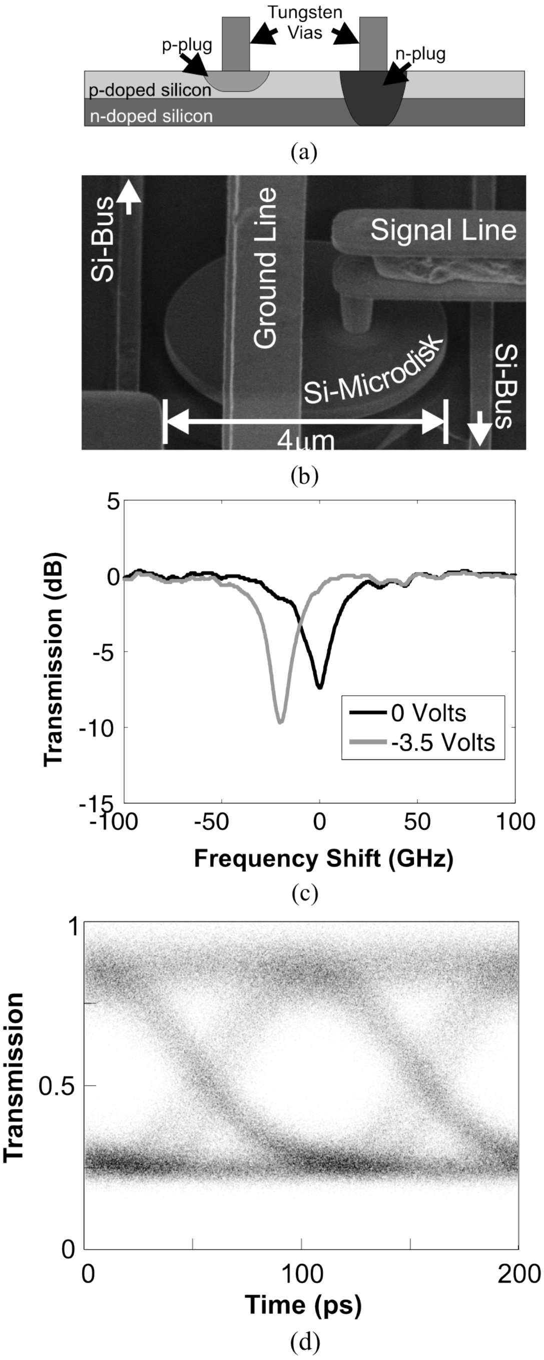

Fig. 3 (a) Cross-sectional diagram of the microdisk modulator, (b) a scanning electron micrograph of the fabricated 4μm diameter microdisk modulator, (c) the optical spectra of the microdisk with no bias and a 3.5V reverse bias applied, and (d) an eye-diagram for the modulator with a 10Gb/s NRZ data format with a PRBS pattern length of 2^{31}-1. More recently, we have achived 12.5Gb/s data rates with only 1V peak-to-peak drive voltages [].

In addition to the numerous passive elements, active structures, such as microring-resonator-based modulators, can be constructed using *p-n* junctions and carrier injection [2,3] or carrier depletion [4,5], as depicted in Fig. 3. Microring-resonator-based modulators have been demonstrated with power efficiencies below 10fJ/bit, data rates as high as 12.5Gb/s, and drive voltages approaching CMOS logic levels [6,7]. These features, in addition to their small size (~3μm), makes these devices highly attractive for DWDM applications requiring low power consumption and a high degree of integration, such as communications within computer networks. In addition, while targeted for computer networks, these devices are not limited to local communications alone. Very successful demonstrations of long distance communications with microdisk [8] and microring [9] modulators have been performed, highlighting their utility as a technology that spans the traditionally separate short and long distance markets.

Finally, several groups have successfully demonstrated the integration of germanium detectors with silicon photonic and even full CMOS processes [10,11]. In all, silicon photonics has emerged as a viable ultralow power communications platform that lacks only an integrated source. And, given the operating temperatures of typical microprocessors, it is unclear whether a source should be directly integrated on CMOS platform.

3. Conclusions

The need for high data rate, low-power communications in embedded systems is clear. Many significant challenges in the development of ultra-low power WDM silicon microphotonic communications have been surmounted in recent years and we project that >1-Tb/s silicon microphotonic communication lines will be demonstrated in the near future with link energy efficiencies approaching 100fJ/bit, more than two orders of magnitude lower than what is achieved in VCSEL-based communication links today.

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