# Silicon Photonic Components and Networks

**Michael R. Watts**

*Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139*
*mwatts@mit.edu*

**Abstract:** Significant progress in silicon photonics has led to flattop filters, polarization independence, low power modulators and switches, and low dark current germanium detectors. Future challenges reside in implementing silicon photonic networks.

**OCIS codes:** (130.3120) Integrated optics devices; (230.4110) Modulators; (230.5750) Resonators

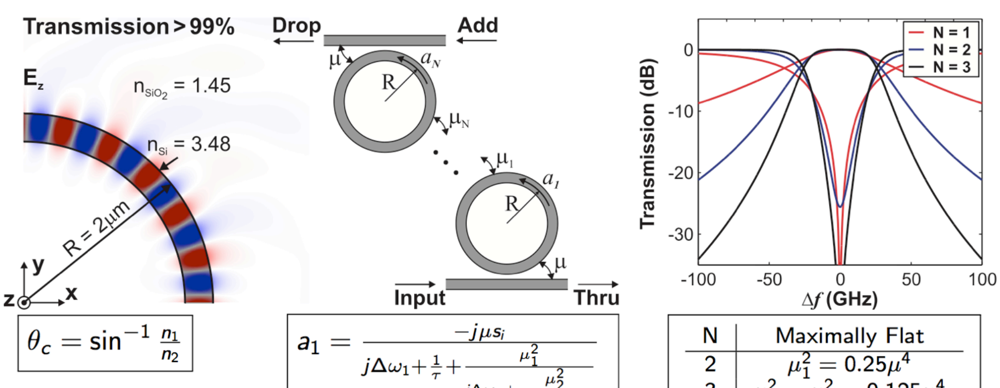
## 1. Introduction

In long-distance communication networks, the cost of the link is dominated by the fiber installation. For the limited number of terminations in long-haul telecom networks, the demand has been insufficient to drive integration. As a result, expensive, bulk-optic implementations have historically been accepted and deployed. Yet, as optical networks move from long-distance to short-reach applications, the demand for high-speed, low-power, and low-cost dense wavelength-division-multiplexed (DWDM) chip-scale solutions is rapidly increasing. In high performance computing applications the need to reduce the power consumption of the communication links and to aggregate bandwidth in the network is the dominant issue threatening to limit future machine scaling. Moreover, even in longer distance applications the complexity of advanced higher-order modulation formats coupled with DWDM implementations is providing impetus for a densely integrated photonics platform.

The high index contrast offered by silicon with its native silicon dioxide cladding enables almost metallic-like walls that facilitate nearly right-angle bends [1], bend-radii on the order of the wavelength of light propagating in the guide (Fig. 1a). Compared to traditional silica waveguides, the bend radius is decreased by 4-orders of magnitude corresponding to an increase in component density of nearly 8-orders of magnitude. In addition, silicon photonics has the beneficial properties of being compatible with CMOS fabrication and in some cases, even direct integration with CMOS electronics [2], resulting in a low-cost and low-power solution. For reasons of both dense integration and CMOS compatibility, silicon photonics is rapidly becoming a mainstream technology capable of addressing many of the challenges facing optical communications.

## 2. Passive Components

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,




| N | Maximally Flat |
|---|---|
| 2 | $\mu_1^2 = 0.25\mu^4$ |
| 3 | $\mu_1^2 = \mu_2^2 = 0.125\mu^4$ |

**Figure 1.** (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.

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. 1b). By cascading microrings, high-order filters can be constructed (Fig. 1c), and designed utilizing microwave filter theory [3]. These filters are critical components for future DWDM communication systems and are in many ways unique to the silicon material system.

While compact, microring-resonator filters do suffer from inherent polarization sensitivity, this sensitivity can be overcome with the use of integrated polarization splitters and rotators (Fig. 2), in a polarization diversity scheme [4,5]. Highly compact, low-loss, polarization splitters and rotators can be integrated within the silicon platform enabling complete freedom to manipulate polarization states on a silicon photonic chip. The ability to integrate polarization components directly on-chip is important not only for achieving polarization independence, but also for advanced modulation formats such as dual polarization quadrature phase shift keying (DP-QPSK) and for detecting and compensating deleterious effects such as polarization mode dispersion.

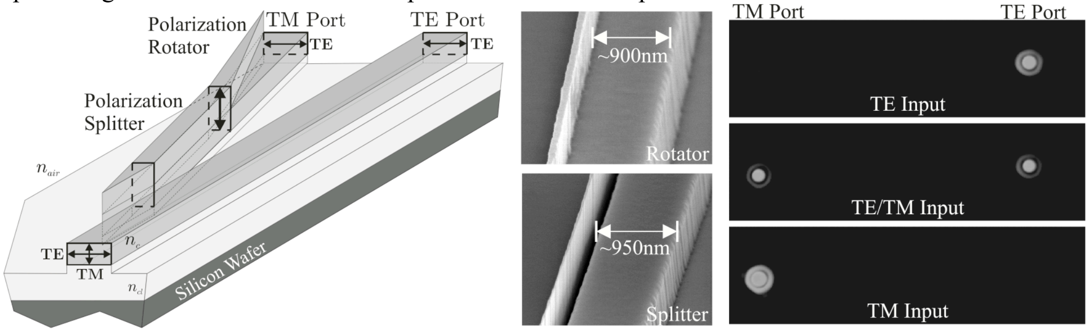



**Figure 2.** (a) Diagram of a combined polarization splitter and rotator that enables a single on-chip polarization, (b) scanning electron micrograph (SEM) images of the fabricated polarization splitters and rotators, and (c) output IR images of the end facet of the combined polarization splitter and rotator highlighting the polarization separation as a function of input polarization. This polarization splitter-rotator was demonstrated in the Research Laboratory of Electronics at the Massachusetts Institute of Technology.

## 3. Active Elements

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 [6] or carrier depletion [7], as depicted in Fig. 2. Microring-resonator-based modulators have been demonstrated with power efficiencies below 10fJ/bit, data rates exceeding 12Gb/s, and drive voltages approaching CMOS logic levels [8]. 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 [9] and microring [10] modulators have been performed, highlighting their utility as a technology that spans the traditionally separate short and long distance markets.

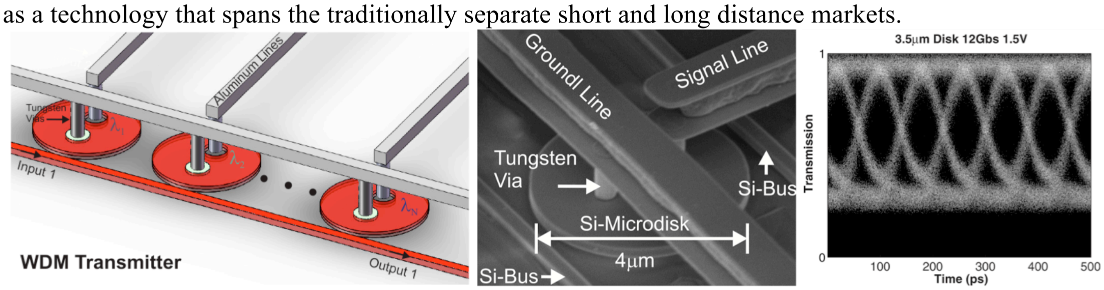



**Figure 3.** (a) Diagram of a DWDM microdisk modulator array, (b) SEM image of a fabricated microdisk modulator, and (c) an eye-diagram from a 3.5µm microdisk modulator running at 12Gb/s. This modulator was demonstrated at Sandia National Labs.

These modulator structures can also be coupled together to form active filters [11]. By driving the filters in the forward bias direction large (~200GHz) frequency shifts can be induced to enable high-speed channel-by-channel switching and routing of DWDM optical signals. While driving the modulators in the forward bias direction limits the recovery time of the element to the free carrier lifetime in SOI silicon, the free-carrier lifetime is still quite fast, enabling ~2ns switching speeds. In computer networks, the reconfiguration time of a switch is typically on the order of hundreds of nanoseconds. Given a switch latency of only ~2ns, high-speed optical domain switches in computer networks can be envisioned. While many implementation issues remain, the potential benefits of such a switch include the possibility for higher aggregate switch bandwidth, lower power consumption, and lower cost.

In addition to modulators and switches, significant progress has been made in numerous other devices, including tunable filters and thermal switches, along with germanium detectors [12]. The principal challenge that remains is the successful implementation of silicon photonic components in highly integrated systems of elements such as modulator (Fig. 3a) and switch (Fig. 4) arrays, to achieve complex functionality.

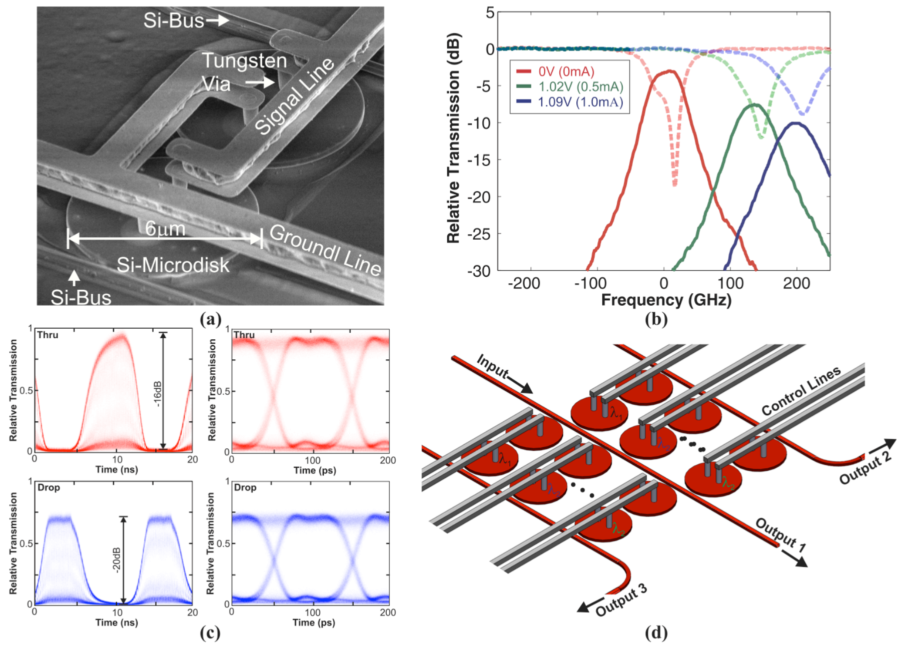



**Figure 4.** (a) Scanning electron micrograph (SEM) image of a focused ion beam (FIB) cut through the center of the silicon microdisk switch. (b) Measured spectral response of 2nd order microdisk switch as a function of applied voltage ($\lambda_0$ = 1501nm). (c) Thru and Drop port output versus time switching a 10Gb/s data stream every 6.4ns demonstrating an extinction of -16dB in the Thru port and -20dB in the Drop port. (d) A conceptual diagram of a high speed optical domain router. This switch was demonstrated at Sandia National Labs.

## 4. Conclusions

While much work remains at the system-level, the performance and yield of silicon photonic components has reached a maturity level ready for production. Challenges remain in the integration of silicon photonic elements in complex photonic microsystems capable of generating, routing, and detecting DWDM signals on a large-scale. However, given the rapid progress of silicon photonics in the past few years, even this challenge is likely to be overcome in short order.

## 5. References

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