Power Penalty Measurement and Frequency Chirp Extraction in Silicon Microdisk Resonator Modulators

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Abstract: We demonstrate 5Gbs and10Gbs error free operation of silicon photonic microdisk resonant modulators to a distance of 70km, measure dispersion power penalties and compare the experimental results with theoretically derived values.

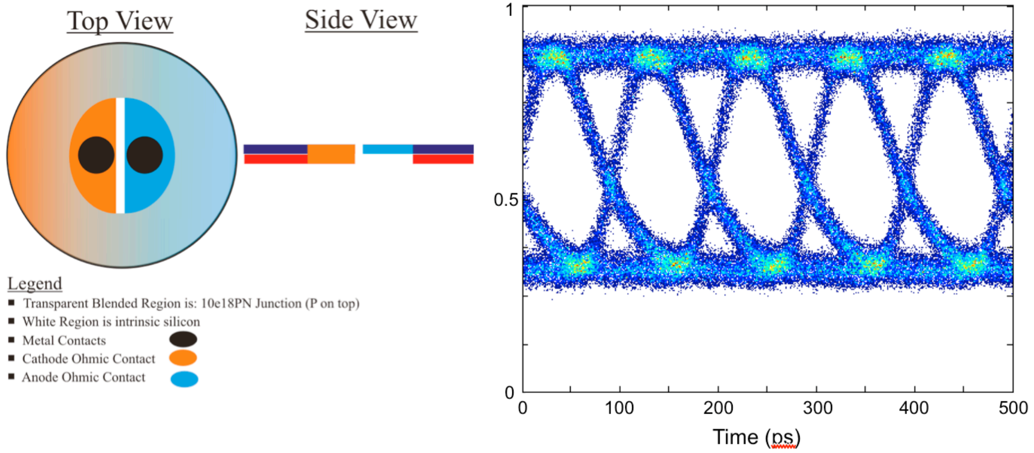
OCIS codes: (130.3120) Integrated Optical Devices; (130.4110) Modulators; (230.7370) Resonators

1. Introduction

A broad range of silicon microphotonic devices is being developed for both telecom and datacom applications, including filters [1], modulators [2-4], and high-speed bandpass switches [5]. Many such devices have been based on microring and microdisk resonators because of their ability to modulate and actively multiplex and demultiplex wavelength division multiplexed (WDM) signals with high-fidelity and minimal power while consuming little chip real-estate and the potential for low cost in volume manufacturing. While silicon photonic resonant modulators have been proposed for short-reach applications, such as multiprocessor and data center interconnects, to date, we are not aware of any evaluation of their performance over a significant fiber length as required for applications in metropolitan, regional, or long distance telecommunications networks. In this paper we measure the power penalty of silicon microdisk resonant modulators over distances up to 70 km and data rates to 10 Gb/s and compare the dispersion penalty with theory.

2. Device Testing

The tested device was a 3.5um diameter microdisk resonator (Fig. 1a) with a 245nm thick silicon layer coupled to a ~370nm wide silicon waveguide with a separation distance of ~350nm between waveguide and the microdisk. These devices are similar to those presented in [4]. Fabrication was done on 150mm SOITEC Silicon on Insulator (SOI) consisting of a 260nm thick silicon layer and one micron buried oxide. The waveguide and disk were defined using optical lithography from a 248nm ASML laser scanner-stepper. Etching was performed using a reactive ion etcher. The patterned silicon was subsequently oxidized (~15nm silicon loss) and dopants were implanted to create a vertical PN junction and ohmic contacts for active structures. The structures were then buried in 2um of oxide, and contacts were made with tungsten vias and subsequently connected with aluminum lines as described in [5].



(a) (b)

Figure 1: (a) Diagram of the microdisk modulator indicating the doping profile and (b) a 10Gb/s eye diagram for the microdisk modulator.

Figure 2 shows the test setup. The devices were tested using an Agilent 81600B series laser source outputting a 100KHz linewidth continuous wave signal at the biased modulator's resonant frequency (wavelength) of 1572 nm. The laser was coupled to the microdisk chip using lensed fibers. Insertion loss for the fiber coupling and the modulator was ~20dB, resulting from the fiber coupling. The electrical input to the modulator is biased at 2.1 volts

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and connected through a bias tee with a pseudorandom bit stream signal from a Centellax TG1B1A 10G Bit Error Rate Tester (BERT) amplified by an external power amplifier to 3.5V. The optical output of the device was connected to an L-Band Erbium Doped Fiber Amplifier (EDFA) followed by a variable length of fiber and a second EDFA. A tunable filter with 1.5nm (~ 180 GHz) optical bandwidth was connected to the output of the second EDFA to minimize amplifier noise and achieve an optical signal to noise ratio (OSNR) at the input of the receiver of a minimum of 32dB for 70 km. Power at the receiver was controlled using a variable attenuator. The receiver was connected back into the Centellax BERT. Power levels at the different parts of the system can be seen in Figure 2.

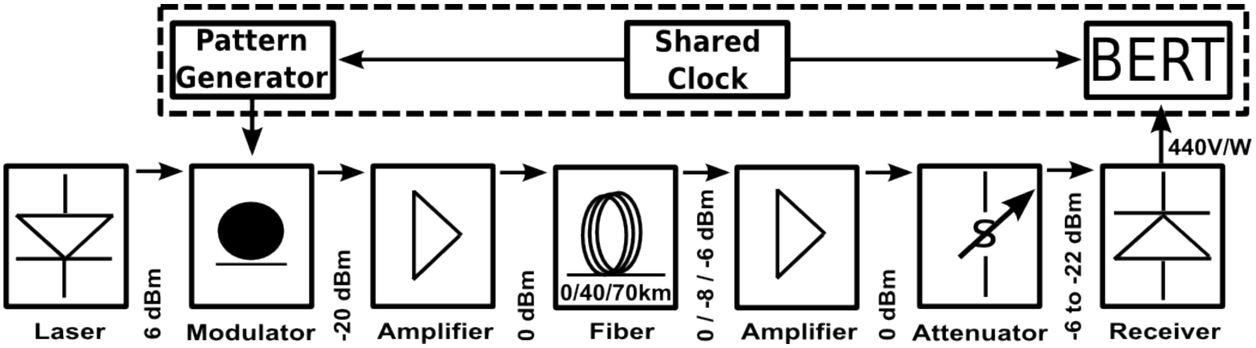

Figure 2: Block diagram of the test setup. Devices were tested back to back, 40km and 70km with variable received power. Constant power levels were maintained at the source, modulator, and erbium doped fiber amplifiers at the beginning and end of the fiber length.

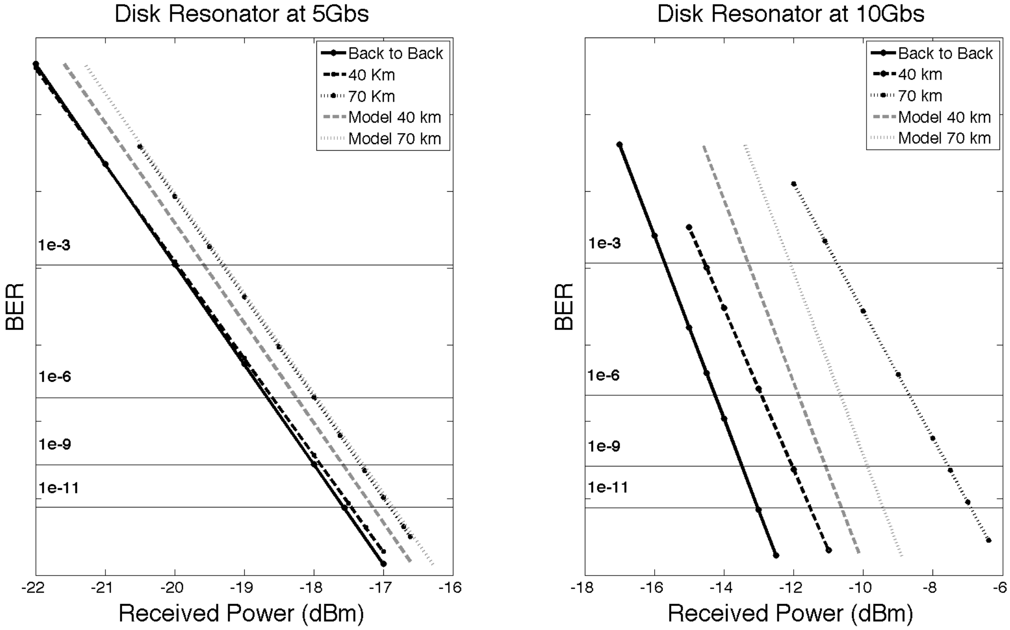

Figure 3: The BER performance of the disk resonator (a) at 5Gbs and (b) at 10Gbs. Measurements are in black and the model data is plotted in gray. Model data and measurement overlay each other for the 5Gbs 70km plot. Because of thermal drift in the resonant modulators, it was occasionally necessary to slightly vary the optical frequency between measurement sets. The phase alignment of the receiver clock was also re-optimized to account for drift in the delay of the fiber.

The device was tested at 10Gbs and 5Gbs. Through simulation and analysis it was determined that the electrical 3 dB bandwidth of the resonator is about 7.5GHz and is much lower than the optical bandwidth of about 20GHz. Figure 2a shows the 5 Gbs performance of the modulator. A power penalty of less than a tenth of a dB from "back to back" (BTB) to 40km was observed followed by a penalty of ~ 0.5dB to 70km. The performance at 5Gbs matched that at 3Gbs indicating that the device is not bandwidth limited running at 5Gbs. At 10Gbs the power penalty for 40km and 70km is about 1.5dB and 6dB respectively as seen in Figure 3. This greater power penalty is due to the electrical bandwidth limitation of the modulator as well as the normal frequency dependence of the dispersion penalty. The inability of the capacitances to fully charge leads to a peaked pulse shape and greater dispersion. A LiNiO3 Mach-Zehnder modulator was also tested as a 'reference' with 70km power penalties of 0.25dB at 5Gbs and 3dB at 10Gbs . The power penalties of the silicon photonic disk resonant modulator are only 1-2dB higher than the values recorded for commercially available modulators, but with much smaller size, lower power dissipation, and potentially lower cost. All of the measurements were performed with a 2^{31}-1 pseudorandom bit stream pattern.

3. Analysis

Because the linewidth of the source is on the order of 100KHz, it does not contribute to the dispersion penalty. Other factors such as RIN and external cavity reflections are not significant either because the laser source has a RIN on the order of -175dB/Hz and reflections in the fiber coupler was only 2%.

This leaves frequency chirp, which is more significant in the bandwidth limited 10Gbs performance than the data taken at 5Gbs. To determine the power penalty contributed by frequency chirp the time constant (from simulation as noted above) of the reverse biased modulator was used to model the sweep of the resonance across the laser line. This information was then fed into the coupled mode theory in time approximation [6] where it is assumed that all of the power on resonance is absorbed into the modulator

$$S_{12} = \frac{j(\omega - \omega_0)}{j(\omega - \omega_0) + 1/\tau} S_i \tag{1}$$

where S_{12} is the transmitted power, S_i is the incident power, ω is the varying frequency determined by the charging and discharging of the capacitor, ω_0 is the laser frequency, τ is the photon lifetime inside the resonator (measured from the quality factor) and j is the imaginary phase component. Once the real and imaginary power evolution over time was known the phase angle could be extracted at each point in time. This phase angle change with time $d\phi/dt$ was then used in the equation for frequency chirp

$$\Delta\upsilon_c = \frac{1}{2\pi}\frac{d\phi}{dt} \tag{3}$$

Finally, the frequency chirp is converted to wavelength (nm) and inserted into a simple model describing the power penalty induced by chirp [7]

$$\delta_c = -10\log_{10}(1 - BLD\Delta\lambda_c) \tag{2}$$

where B, L and D are the bit-rate, fiber length and dispersion, δ_c is the chirp induced power penalty and υ_c is the frequency chirp quoted in GHz. The dispersion is ~ 17.2 ps/nm/km for Corning SMF-28 fiber at 1572nm. The output of this simple approach is plotted with the resonator results in Figures 3a and 3b. The predicted power penalty is within 0.5db at 5Gbs but begins to differ at 10Gbs at 70km. The time domain approximation breaks down at high frequencies and imperfections in the amplitude and phase response of the modulator driver and receiver that contribute to the power penalty. These additional considerations have not been modeled yet.

3. Conclusions

The dispersion penalties of silicon microdisk resonant modulators were measured and evaluated for the first time at fiber lengths to 70km for data rates up to 10 Gb/s. Modeling the modulator chirp by the capacitively driven resonance sweep across a delta function laser line gives reasonable agreement to experimental data. The performance shows the potential for low cost silicon photonic optical modulators to be applicable to metropolitan or regional telecommunications systems in addition to their well-known applications in short-reach interconnects. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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