Transmission of high-data-rate optical signals through a micrometer-scale silicon ring resonator

Benjamin G. Lee, Benjamin A. Small, and Keren Bergman

Department of Electrical Engineering, Columbia University, 500 West 120th Street, New York 10027

Qianfan Xu and Michal Lipson

School of Electrical and Computer Engineering, Cornell University, 411 Phillips Hall, Ithaca, New York 14853

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The effects of a micrometer-scale silicon ring resonator with a FWHM of 0.078 nm (9.6 GHz) on a nonreturn to zero amplitude-modulated optical signal with a modulation rate of 10 Gbps are experimentally investigated. By transmitting the optical signal through the device, significant spectral distortion and sideband attenuation is introduced, as characterized by amplitude Bode plots, and a power penalty of 0.8 dB is observed. Carrier wavelengths within the transmission resonance, but detuned from the center wavelength, are investigated as well. Numerical simulations further support the experimental results. © 2006 Optical Society of America

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Photonic devices with sharp spectral features have numerous applications in contemporary optical systems.[1] Most notably, it has been proposed that they can be used as active filters and switching elements in integrated high-bandwidth photonic systems.[1,2] To date, the most successful and easily integrable geometry for these resonant structures is the microring resonator, which can be incorporated into conventional waveguide-based photonic integrated circuit (PIC) platforms,[3,4] with possible applications in large-scale telecommunications systems and in silicon photonic interconnects within and between electronic integrated circuit dice.

Microring resonators with Q between approximately 1500 and 100,000 have been demonstrated using various technologies, including polysilicon ridge waveguides,[1] various silicon-on-insulator (SOI) structures,[4–7] and even exotic material systems.[1] Annular structures can be coupled to linear waveguides, and the interaction is described by simple coupling equations.[8] Particular wavelength modes can be removed from a broadband or multiple-wavelength optical signal when a single waveguide is coupled to a ring resonator. When another waveguide is coupled to the ring, these resonant modes can be extracted from the uncoupled light. This behavior is easily leveraged for wavelength filtering. Even more complex lightwave systems based on cascades of microring resonator devices have been envisioned[9,10] and demonstrated.[11] Furthermore, attempts have been made to tailor filter shape and reduce dispersion by using cascades of ring resonators in various geometries.[2,9,11]

The current discussion considers a single micrometer-scale ring resonator fabricated on a conventional SOI substrate using channel waveguides. The resonant structure consists of two parallel waveguides coupled to a ring, so that both drop (on resonance) and through (off resonance) ports are accessible (Fig. 1 inset). This device, or ones similar to it, could be used as a wavelength filter[2] or as an electro-optic or all-optical modulator.[6,7] In the current experiment, we seek to investigate the effects observed on a high-data-rate signal, which is transmitted through this microring resonator as a passive device.

When microcavities with narrow resonance characteristics are used for high-data-rate communications applications, it is absolutely critical that the interactions between the data channel and these devices be thoroughly understood. As a high-speed data signal passes through a resonator, fundamental degradation in the signal quality occurs due to the nonuniform attenuation of high-frequency sidebands. The power spectrum of an optical signal (Fig. 1), which

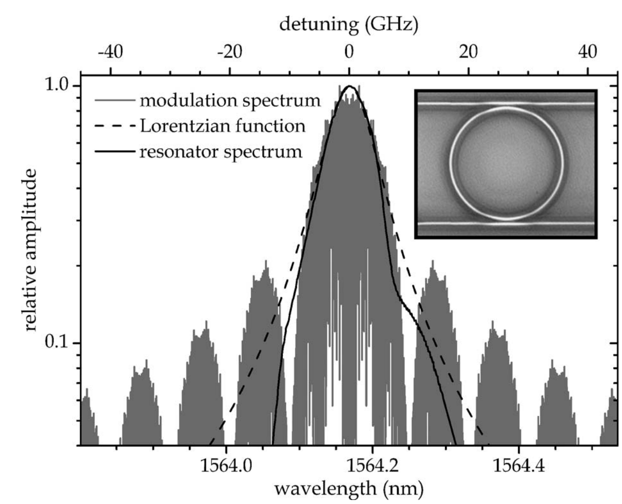

Fig. 1. Modulation spectrum for a 10 Gbps amplitude-modulated optical signal encoded with random NRZ data, a Lorentzian shape with $Q=20,000$, and the experimental resonance spectrum obtained from the fabricated silicon microring (inset) with a 20 μm diameter; waveguides have cross sections of 450 nm $\times$ 250 nm, and the gap is 180 nm.

can be obtained by the Fourier transform, is based on the relative intensities of the signal's sinusoidal components. As the optical signal passes through a ring resonator (Fig. 1), the higher frequency sidebands experience more attenuation than the lower ones, thus distorting the signal spectrum. When the FWHM of the resonator (in gigahertz) is similar to the incident optical signal data rate (in gigabits per second), even the first-order sidebands are attenuated by an order of magnitude more than the carrier frequency. The effects of this relationship on overall channel performance are investigated experimentally and with numerical simulations.

The SOI-based microring resonator structure used for this investigation has a Q of approximately 20,000, which corresponds to a FWHM of 0.078 nm (9.6 GHz) at a center wavelength of 1564.17 nm; contributions from waveguide and coupling losses are similar. As expected, when a 10 Gbps signal is transmitted through the drop port of this resonator, noticeable degradation occurs. The effects of the sideband distortion are distinctly observable in the time domain, where transition edges are smoothed and rise and fall times are lengthened. Successive bit transitions cause a damping of the signal amplitude and a decrease in the extinction ratio of the optical signal. Group velocity dispersion is negligible in these devices at 10 Gbps. This investigation, based on methodology first proposed by the authors in Ref. 12, attempts to elucidate the nature of the signal distortion resulting from sideband attenuation incurred by the transmission characteristics of the microring.

First, the resonance transmission spectrum of the drop port is recorded (Fig. 1) for use in the simulations. The optical signal is generated by an externally modulated tunable laser, and introduced to the chip through a tapered fiber. It is transmitted through a SOI waveguide, and passes through a number of bends before entering the resonator device. The light egresses from either the through port or the drop port of the microring, then exits the chip, where it is collected in a fiber; a polarizer ensures that only the TE signal component is used. The optical signal then passes through an erbium-doped fiber amplifier, a tunable filter, and a variable optical attenuator. At this point, some of the light is extracted for power measurements, while the rest is detected by a high-speed receiver. Polarization controllers are used throughout the setup to provide consistent results with the many polarization-sensitive components. The modulator receives amplitude-modulated nonreturn to zero (NRZ) data (2^{31}–1 pseudorandom binary sequence) from a pulse pattern generator (PPG), and the received electronic signal is analyzed by an oscilloscope and a bit error rate (BER) tester that is synchronized to the PPG. The effects of the narrowband transmission characteristics are investigated by setting the tunable laser to wavelengths within the resonance band (centered at 1564.17 nm), so that the signal passes through the drop port of the microring. To isolate these effects, measurements are also taken off resonance (~1563 nm) so that the signal egresses from the through port and is unaffected by the resonance characteristics.

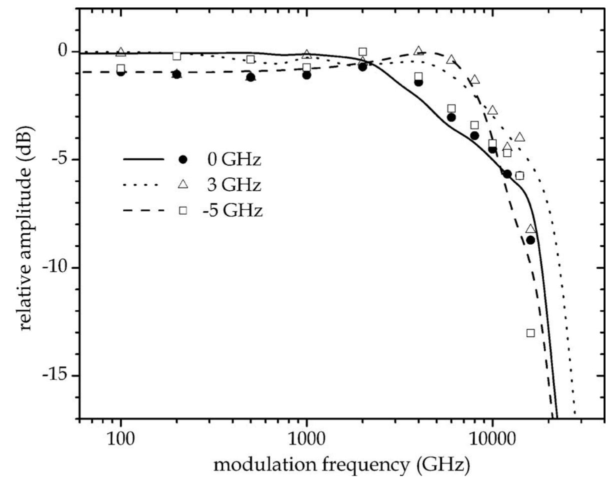

Fig. 2. Experimental measurements (points) and numerical simulations (curves) for amplitude Bode plots at detuning values of −5 GHz (1564.21 nm), 0 GHz (1564.17 nm), and 3 GHz (1564.14 nm).

To evaluate the attenuation imposed on each frequency component of an optical signal as it passes through a resonator, an amplitude Bode plot (Fig. 2) is generated from experimental data. The Bode plot, which shows the relative amplitudes of sinusoidal signals as a function of the modulation frequency, conveys information about the relative attenuation experienced by different frequency components of a high-speed data signal.[12] Since a sinusoidal signal has only a single sideband on each of the positive and negative sides of the fundamental frequency, increasing the modulation rate leads to greater attenuation as the sidebands move further away from the center of the resonance spectrum (Fig. 2); thus the microring resonator acts like a low-pass filter on the incident optical signal. Significant sideband distortion is expected for all frequency values near or above the FWHM of the resonator (9.6 GHz).

The overall effect of this signal degradation can be quantified by the power penalty, which is defined as the amount of extra power required at the receiver to overcome the data errors introduced by the device under test.[12] For these measurements, a 10 Gbps optical signal is transmitted through the drop port of the microring; data is also taken for the through port (Fig. 3 inset). For both the amplitude Bode plot and the power penalty experiments, many wavelengths within the passband of the resonator are investigated. Some measurements are taken at the center wavelength (1564.17 nm), as noted above, and additional results are observed for carrier wavelengths, which deviate from the center by a particular value of detuning (expressed in gigahertz). In these cases, the knee of the Bode plot occurs near the detuning value, because here one of the sinusoidal sidebands is centered in the resonance spectrum (Fig. 2). However, large detunings show higher power penalties than no detuning, because even more severe sideband asymmetry is incurred when carrier wavelengths are on the edges of the resonance spectrum (Fig. 3). Also,

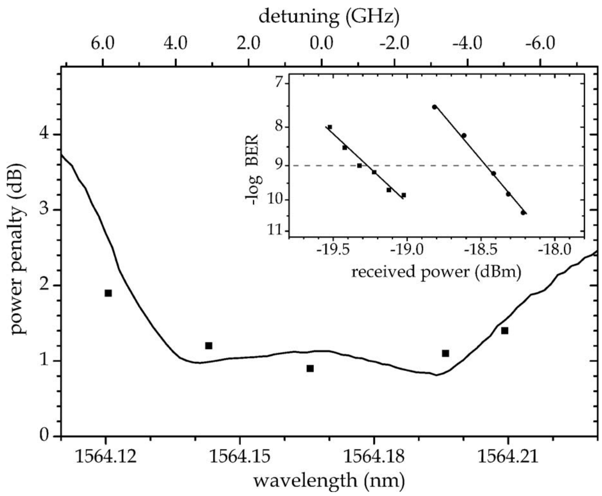

Fig. 3. Power penalty versus wavelength and detuning for experimental measurements (points) and numerical simulation (curve). The inset shows a single power penalty measurement, given as the difference between the two curves in decibel units.

the steepness of the lower wavelength side of Fig. 3, compared with the higher wavelength side, reflects the asymmetric shape of the microring's transmission spectrum. Nevertheless, even with no detuning, measurable signal degradation is observed, quantified by a power penalty of 0.8 dB (Fig. 3 inset).

A numerical model based on Fourier transform analysis was used to further investigate signal degradation in the resonator based upon its unique transmission spectrum (Fig. 1). The results from the numerical simulation are compared with the experimentally measured Bode plots (Fig. 2) and power penalties (Fig. 3). The rms discrepancy between the simulated results and the experimental data is approximately 4% for both the amplitude Bode plots and the power penalties. Notably, a Q of 20,000 is required to obtain a 20 dB channel suppression for a 50 GHz dense WDM grid. Furthermore, the numerical simulation predicts a power penalty of approximately 0.2 dB for microrings with Q of 10,000, which would be suitable for 100 GHz WDM spacing.

Although these degradations are noticeable, they are not insurmountable. In contemporary optical communications systems, cumulative power penalties of more than 10 dB are tolerable. Thus cascading many of these devices in a high-speed optical communications system could be challenging, but certainly not impossible. Most complex system designs[4,9,11] require high-speed signals to propagate through the drop port of only a few devices, and so the power penalty can likely be mitigated. On the other hand, systems such as the one proposed in Ref. 10 could face significant limitations because of successive signal degradation through a large cascade of resonators.

It is also important to note that for single resonators with smaller Q (larger FWHM), or for systems with lower data rates, the degradation is not as severe. Additionally, low-Q resonators allow a larger number of wavelength channels to be switched or filtered with a single microring. For systems that route multiple-wavelength signals, a resonance device with a wider transmission spectrum could be leveraged to switch an entire wavelength band. Moreover, tailoring the specific shape of the resonance spectrum by cascading or coupling resonators[2,9,11] may reduce the negative effects as well. Further analysis will also consider the degradation of different data modulation formats in microrings.

This investigation illustrates the interaction between a high-speed optical signal and a high-Q (narrow FWHM) microring. The signal degradation is described by the power penalty with further elucidation given by amplitude Bode plots. Numerical simulations reinforce the importance of this analysis. When designing high-speed optical communications systems utilizing ultranarrowband devices, the possible degradation incurred on the optical signals must be considered.

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