Signal Integrity of RZ Data in Micron-Scale Silicon Ring Resonators

Benjamin G. Lee, Benjamin A. Small, and Keren Bergman
Department of Electrical Engineering, Columbia University, New York, NY 10027
benlee@ee.columbia.edu; 212-854-2768

Introduction

Compact lightwave components that provide very narrow frequency passbands are integral elements of photonic integrated circuits (PICs) for use in inter- and intra-chip networks. These high bandwidth optical interconnections, which rely on dense wavelength division multiplexing (WDM) in order to fully capitalize on the large optical domain transmission capacity, require filters and switches with narrow bandwidths in order to route optical signals to their appropriate destinations. This routing functionality can be achieved by leveraging the sharp spectral features of resonator devices. Microring resonators, in particular, have produced exceptionally narrow bandwidths, corresponding to ultra-high *Q* factors [1]-[3]. When this is combined with the high confinement provided by the silicon-on-insulator (SOI) platform [3], very high spatial and spectral density can be achieved.

As the data capacity scales in optical networks, both the density of wavelength channels and the single-channel data rate must increase, causing the spectral width of each channel to broaden and necessitating the inter-channel wavelength spacing to decrease. For these systems to maximize their data capacity, the bandwidth of the photonic components used to route individual channels must approach the channel's modulation bandwidth. However, as this occurs, the high-speed optical signal degrades, sometimes severely. We have previously shown experimentally that, as high speed non-return-to-zero (NRZ) on-off-keying (OOK) optical data signals pass through high-*Q* silicon microring resonators, they are distorted by the non-uniform attenuation of the modulation sidebands [4],[5]. In addition, we have experimentally verified a numerical model, which predicts the degree of signal distortion incurred by microring resonators as quantified by the power penalty [4],[5].

Signal Distortion

When the spectral width of a resonator is on the order of the modulation bandwidth of an incident wavelength channel, an investigation of the interactions between the resonator and the data channel becomes extremely important. As the optical signal passes through the resonator, the high frequency sidebands of the modulation spectrum experience more attenuation than the low frequency components, so that the resonator functions as a low-pass filter (Fig. 1a). As a result, smoothing and broadening in the time domain (Fig. 1b) cause a decline in the extinction ratio and degradation in signal quality.

Since return-to-zero (RZ) data transmission occupies more bandwidth than NRZ data transmission [6], it is expected that a particular device will be more degrading to RZ data than to NRZ data. The RZ data format can be advantageous, however, in many applications. It has been shown to outperform NRZ data in specific regimes containing dispersion and nonlinearities [6],[7]. Additionally, RZ signals with short pulse durations can be used in optical time division multiplexed (OTDM) systems by interleaving a number of short RZ pulses into a single bit period [8]. Given the usefulness of RZ data transmission in specific applications such as these, it is important to compare the degradation of RZ and NRZ signals in microrings. Therefore, this paper quantifies the signal degradation that results from sideband attenuation imposed on high speed RZ-OOK optical signals as they pass through high-*Q* microring resonators.

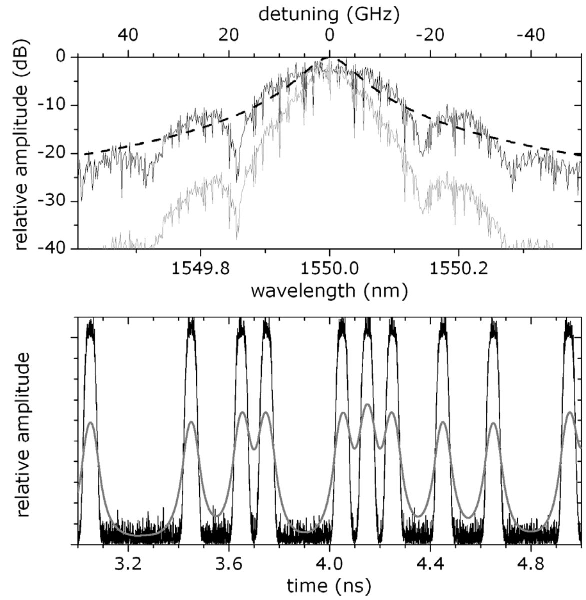

Fig. 1. (a) Modulation spectra and (b) time domain representations of 10 Gbps 50%-RZ optical signals, shown before (black) and after (gray) passing through a microring, modeled by a Lorentzian (dashed) with a *Q* factor of 20,000 (FWHM of 10 GHz).

Results

The experimentally verified numerical model based on Fourier transform analysis quantifies the degradation of high speed optical signals by calculating predicted power penalties [8]. Since we determine only the power penalty associated with the device (not the entire system), we also consider the overall attenuation resulting from sideband distortion, because the signal will be further degraded if additional amplification is required. The model assumes input signals of various data formats with signal-to-noise ratios (SNRs) of 23 dB constructed from fourth-order super-Gaussian pulses. The RZ label for each data format is the percentage of the bit period filled by the full-width-half-maximum (FWHM) of the pulse. For example, a pulse with a 10-ps FWHM and a 10-GHz repetition rate is labeled 10%-RZ.

We ascertain both the power penalty (Fig. 2) and the

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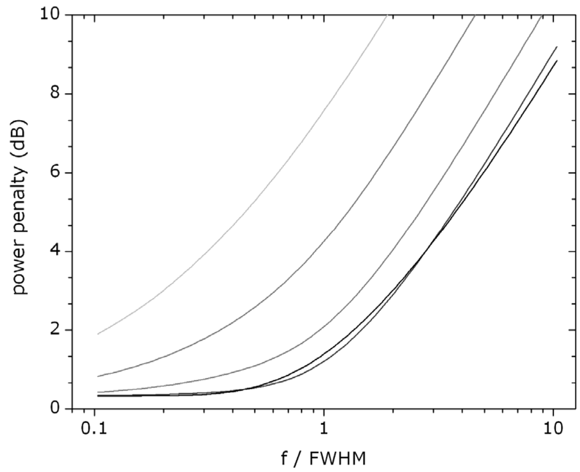

Fig. 2. Power penalty as a function of the bit rate, *f*, normalized to resonator FWHM for optical signals after passing through a microring. From heaviest to lightest, the contours represent the NRZ, and the 33%-, 10%-, 3%-, and 1%-RZ data formats.

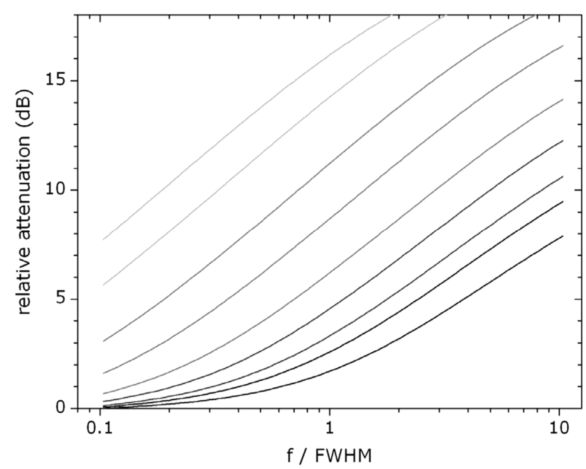

Fig. 3. Relative signal attenuation due to sideband distortion versus bit rate, *f*, normalized to resonator FWHM for optical signals after passing through a microring. From heaviest to lightest, the contours represent the NRZ, and the 67%-, 50%-, 33%-, 20%-, 10%-, 5%-, 2%-, and 1%-RZ data formats.

attenuation (Fig. 3) for NRZ-OOK and RZ-OOK signals with varying pulse durations. Plotting these as a function of the single-channel bit rate *f* (in Gbps) normalized to the resonator FWHM (in GHz) gives insight into how a specific microring affects optical signals with varying bit rates, and it also depicts how optical signals with constant bit rates are affected by microrings of various bandwidths.

The results indicate that RZ data provide a power penalty comparable to NRZ data when the pulse duration fills a large part of the bit period, but incurs a much larger power penalty for shorter pulse durations (Fig. 2). The 33%-, 50%-, and 67%-RZ signals exhibit very similar power penalties to NRZ data, and may even overlap at certain values of the normalized bit rate. (Only the NRZ and 33%-RZ formats are shown in Fig. 2). For networks with single-channel bit rates (in Gbps) on the order of the resonator bandwidths (in GHz), these power penalties must be considered in the system design, but they are not a limiting factor. However, as the pulse width nears one tenth of the bit period, these large bandwidth signals, which are typically used in OTDM systems, are affected more significantly by the narrowband resonator, causing the power penalty to rise. Furthermore, for even the lowest bandwidth data formats, the power penalty increases sharply as the data rate exceeds the resonator bandwidth.

Although the power penalty can be similar for some RZ data pulse widths, the signal attenuation due to sideband distortion increases steadily as the pulse width shortens (Fig. 3). If more amplification is required to overcome the additional losses, further signal degradation will result. Therefore, system designers must carefully consider both power penalty and attenuation when choosing an optical data format for a specific network.

Conclusion

We have determined the power penalty and signal attenuation of microring resonators with RZ-OOK and NRZ-OOK data using an experimentally verified model. The predicted power penalties are noticeable, but not catastrophic, for signals with modulation spectra on the order of the resonator bandwidth. However, for RZ signals with short pulse durations, the signal degradation, as quantified by the power penalty, and the signal attenuation, incurred by sideband distortion, are more difficult to overcome. The authors would like to acknowledge the support of the National Science Foundation under contracts CCF-0523771 and ECS-0532762.

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