Optimization of Microring-based Filters for Dense WDM Silicon Photonic Interconnects

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***Abstract*— The article describes an experimentally validated approach for optimizing wavelength-selective microring filters based on optical signals power penalties. The methodology is used to analyze the performance of WDM links for various bit rates and channel-spacing.**

I. Introduction

SILICON photonic active and passive devices have been proposed and studied as a viable means of achieving low-cost energy efficient on- and off-chip optical interconnects [1]. Microrings in particular can be used both as active modulators and switches, as well as wavelength-selective passive filters. Due to their small size, many microrings can be cascaded on a single on-chip waveguide in order to achieve high-bandwidth through dense wavelength-division-multiplexing (WDM) [2], [3]. The key advantage that these architectures offer is the compactness and small footprint, but an important drawback is the spectral degradation of channels and the crosstalk that prevails as a result of such juxtaposition [3], [4]. These impairments eventually put an upper limit on the modulation speed and limit minimum spacing between channels, placing an upper bound on maximum bandwidth density [3]. Since the performance of a communication channel is determined by the bit error rate (BER) and that in turn is related to the optical signal to noise ratio (OSNR) at the receiver [4], one way to estimate the effect of the induced impairments is to translate them into the power penalties that should be added to the optical power budget of the link in order to maintain a desired BER [5], [6]. In this work, we investigate the role of wavelength-selective microring filters of a silicon photonic link and propose a way to optimize their Q-factor by characterizing their effects on the optical power budget of the WDM link. Moreover, the accuracy of the mathematical model is justified by presenting experimental measurements of BER penalties of a silicon microring filter at 10 Gb/s data rate [6].

II. Power Penalties of Microring Filters

Consider cascades of wavelength-selective demux ring filters on a shared waveguide at the receiver of a silicon photonic interconnect as shown in Fig. 1. Each one of these rings is tuned to filter out one of the WDM channels (non-return-to-zero on-off keying modulated) and pass it to the corresponding detector. According to the temporal coupled mode theory for microring resonators [7], these drop ring resonators can be accurately characterized by a Lorentzian power transfer function from the input port to the drop port. The main parameters of these Lorentzian spectra are the resonance frequency of the ring (f_0), full width at half maximum (FWHM) [3 dB bandwidth], and the peak transmission (p_0), as depicted in the inset of Fig. 2. If a channel passes by the ring, depending on its bit rate (r_b), average spectral power (P_S), and its relative detuning from the resonance of the ring ($f_\triangle$), part of its power is dropped by the ring. The amount of power that gets dropped from the spectrum of the signal can in general be described by $P_d = P_S \times p_0 \times \varepsilon$, where we calculate ε to be:

$$\varepsilon = \frac{1}{1+\beta^2} - \frac{1}{2\pi\alpha}\mathrm{Re}\left(\frac{1-\exp(-2\pi\alpha(1-j\beta))}{(1-j\beta)^2}\right) \quad (1)$$

in which α = FWHM/$(2r_b)$, Re$(\dots)$ indicates the real part, and $\beta = 2f_\triangle$/FWHM. Mathematical steps are not included here, but it can be shown that ε corresponds to the eye-closure of the NRZ channel. Note that the first term in this equation is a function of β only and is thus not dependent on the bit rate. This term reflects the filtering nature of the device outside its resonance. If a channel is perfectly tuned to the ring, then $f_\triangle = 0$ and this term becomes 1. The second term, in contrast, is bit rate dependent, as it highlights sideband degradation (truncation) of the spectrum of the NRZ modulation due to the limited bandwidth of the ring. If r_b gets small, α gets very large and this second term becomes negligible, as expected for spectrum limited signals. Next, we compare this mathematical formulation against experimental measurements. BER penalties associated with small detuning have been experimentally measured in [6] (FWHM = 9.6 GHz, r_b = 10 Gb/s) and are plotted in Fig. 2 as red circles. Raw power drops do not directly translate into BER power penalties, and an additional model is needed to achieve this conversion. The BER predicted by our approach is plotted in Fig. 2, with a solid line when coupled with the signal-dependent noise model (SDN) proposed by Downie [8], and dotted curve when combined with a signal-independent noise

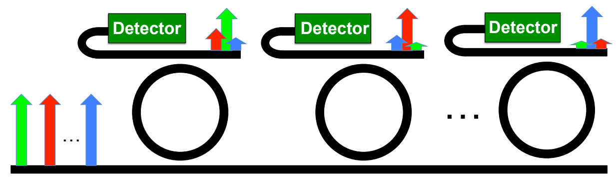

Fig. 1. Demux ring filters at the receiver side of a silicon photonic link. We assume that all channels are modulated with NRZ OOK and have the same average power when they arrive at the filter array.

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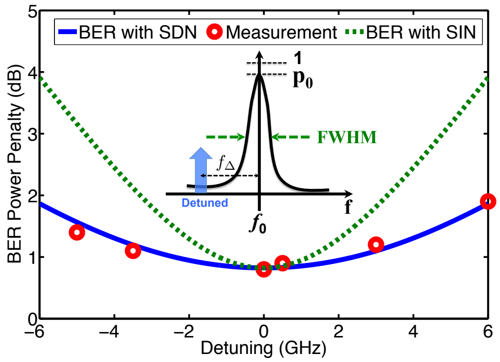

Fig. 2. Measurement of BER power penalty at 10 Gb/s (red circles) taken from [6] (FWHM = 9.6 GHz, $p_0 \approx 1$), and the calculated penalty. Inset shows a general picture of a channel whose relative detuning is denoted by $f_\triangle$. For simplicity, the spectrum of the channel is not shown.

(SIN) model [4]. One observes a good agreement with the SDN model. This comes from the fact that the experiment used optical amplification to compensate for power loss in the system, hence the optical amplifier's spontaneous emission noise is the dominant noise mechanism at the receiver, and it is signal dependent. Notably, at zero detuning, both power penalties correctly reflect the effect of sideband degradation. Since good agreement is observed between the measurements and calculations, we posit that Eq. (1) can serve as a basis for quantifying the penalties due to sideband truncation of a tuned channel and the crosstalk attributed to adjacent channels, as shown next.

III. Results and Discussions

We define the total BER penalty of each filter ring as the sum of penalty for sideband degradation of a tuned channel and the crosstalk penalty. From Eq. (1), it is inferred that increasing the bandwidth of the ring (by reducing its quality factor Q) decreases the truncation penalty but adversely increases the crosstalk. Thus, there exists an optimum Q of the ring that will yield the minimum penalty. Given the number of channels, the bit rate of each channel, and the spacing between them, it is possible to use Eq. (1) to find the optimum quality factor for microring filters. Here, we assume that channels are uniformly distributed over a bandwidth of 50 nm around the 1550 nm wavelength [3]. Therefore, with N channels, the spacing between two adjacent channels is 50 nm/N. Fig. 3(a) shows the plots of the total penalty of a demux ring versus the quality factor of the ring for N = 10 to 50 channels with a bit rate of 10 Gb/s. As shown in this figure, each curve exhibits an optimum point at which the power penalty is minimum. The black curve connects all these optimum points and exhibits a linear-like behavior. It can be seen that as the number of channels increases, both the optimum penalty and its corresponding quality factor increase. In Fig. 3(b) we calculate and plot the penalty curves for a fixed number of channels (50 channels, or equivalently a channel spacing of 1 nm) and different bit rates (from 10 Gb/s up to 40 Gb/s). As expected, higher bit rates require a lower quality factor at their optimum point (on the black curve). This means by increasing the bit rate, the sideband degradation becomes severe and

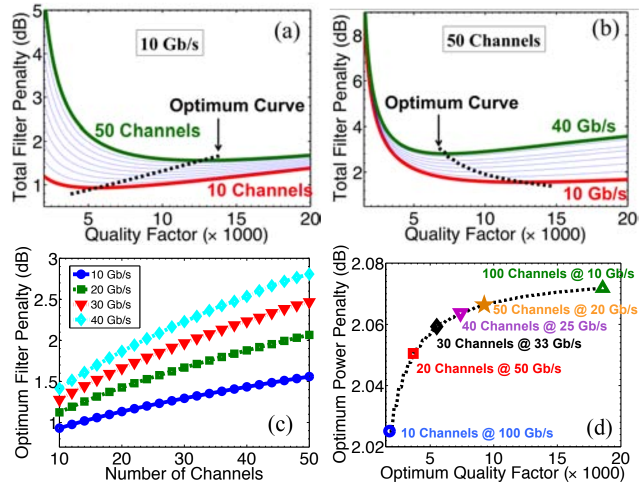

Fig. 3. (a) Total penalty of the demux ring vs quality factor at 10 Gb/s for different number of channels. Black curve connects all the optimum points. (b) Total penalty for a spacing of 1nm between channels and different bit rates. (c) Plots of the optimum penalty for different channel spacings and bit rates. (d) Optimum penalty and quality factor for a total aggregate bandwidth of 1 Tb/s. The number of channels varies from 10 to 100.

dominates over the crosstalk. Thus, a higher ring bandwidth is required to accommodate for the larger signal bandwidth. In Fig. 3(c) we depict the penalty of different bit rates and different number of channels for optimally set Q-factors on microring filters. The observation is that for a given bit rate, the penalty tends to increase as the spacing between channels decreases. This justifies the expectation of getting a higher crosstalk by decreasing spacing between channels. In order to compensate for additional crosstalk, the optimum quality factor should increase, resulting in a narrower filter. Finally, we perform the optimization on microring filter design with the assumption of having a fixed amount of total aggregate bandwidth of 1 Tb/s. In this case, increasing the number of channels from 10 to 100 should be accompanied by a decrease in the modulation speed. The results are shown in Fig. 3(d) where six cases are clearly marked on the plot. With the design of the rings optimized as in the method described previously, the penalty results in a narrow range around 2 dB. Meanwhile, the corresponding quality factors can vary over a wide range from 1800 to 19000. These general guidelines can be used to design a filter array of rings that seeks to optimally reduce power penalty, especially since the mathematical model agrees very well with the experimental measurements.

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