Impact of High-Speed Modulation on the Scalability of Silicon Photonic Interconnects

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Recent developments achieved in silicon photonics have shown that the realization of compact, low-cost and low-energy transceivers is possible [1]. The main underlying optical device is the compact microring resonator (MRR) that can enable not only active operation such as modulation [2] and wavelength routing, but also passive filtering [3]. A schematic of a chip-to-chip link based on MRR is shown in Fig. 1(a). A comb laser [4] (or an array of DFB lasers) is coupled into the silicon waveguide through edge or vertical couplers [5]. The injected multi-λ light then passes by an array of ring modulators. Each ring is tuned to a specific wavelength of the incoming light and imprints ON-OFF keying digital modulation on that wavelength. The modulated light is then sent to the destination. If this destination is located onto another chip, modulated signals are coupled to a fiber connecting the two chips. These WDM signals may also be spatially switched, by means of multi-λ MRRs or using other spatial optical switches [6], [7]. At the receiver side, an array of demultiplexing MRRs is designed such that each ring drops one of the incoming wavelengths. Each dropped signal finally reaches a photodetector [8].

This generic design can be adapted along multiple dimensions: number of wavelengths, modulation speed, and, in presence of spatial switching, network topology [9]. However, each design along these dimensions is associated with its own set of optical impairments. To estimate these impairments, the effects of each device involved in the design on the quality of the optical signal should be taken into account. Fig. 1(b) shows our general approach in modeling each device along an optical path. The input contains an optical signal with a certain level of power (P_S^{in}) and some possible optical noise (including crosstalk noise from other channels). The device imposes some insertion loss (IL = P_S^{out}/P_S^{in}) on the optical signal and may add additional optical noise at the output. In addition, to track how the quality of OOK modulation changes by passing through the optical device, the extinction ratio (er) of the modulation must be evaluated at the input and the output. This parameter is related to the opening of the eye diagram of the OOK modulation.

When applying this approach to a set of designs, we observed that the demux ring filters at the receiver have an important impact on the quality of the high-speed OOK signal when they drop it to the photodetector. This is largely due to the rings' narrow bandwidth which can potentially reject a large portion of the high frequency contents of the OOK modulation. This is the truncation effect. The higher the bit rate is, the more severe this effect becomes. Fig. 1(c) shows how the extinction ratio is reduced by the demux ring. Based

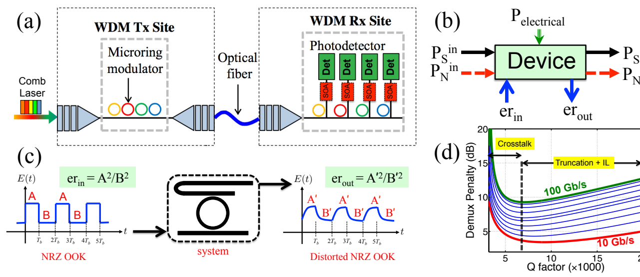

Fig. 1. (a) Schematic of a chip-to-chip MRR-based silicon photonic link. (b) High-level modeling of an optical device along the link. (c) Effect of the narrow bandwidth of the demux ring on the extinction ratio of modulation. (d) Calculation of the total demux penalty for various Q-factor and bit rates.

on the Lorentzian spectrum of the ring resonators, the relation between the er_{in} and er_{out} can be established as

$$\frac{\sqrt{er_{out}}-1}{\sqrt{er_{out}}+1} \approx \frac{\sqrt{er_{in}}-1}{\sqrt{er_{in}}+1} \times \sqrt{\gamma} \qquad (1)$$

where γ = 1-(1-exp(-2$\pi\xi$))/(2$\pi\xi$) and ξ = BW_{3dB}/(2Rate) [10].

To overcome truncation, filtering shapes can be adapted by adopting MRRs with lower Q-factors. However, besides power truncation, the detrimental effects of the demux ring on the OOK digital signaling includes the insertion loss of the drop path and the power penalty due to the crosstalk from other channels. These two effects being also related to the Q-factor, the overall impact of MRR filters can be optimized, as shown in Fig. 1(d) for 50 channels with 1 nm spacing between them. In this example we assume a bending loss of 8 dB/cm for the ring structure. At 100 Gb/s signaling rate, the minimum demux penalty is around 10 dB, which can severely limit the scalability of such optical link. But moreover, at 10Gb/s only, PP of even 5 dB can be observed if unsuited rings (with low Q) are selected.

Note that in this example, we assume that the input extinction ratio is infinite and the power penalty due to the finite input extinction ratio is captured into the power penalty of the imperfect ring modulators [10]. To put more perspective on how the output extinction ratio of the demultiplexer ring evolves as a function of the input extinction ratio, 3dB bandwidth of the ring, and the modulation speed, we use Eq. (1) for a case where $Q \approx 20000$ (corresponding to $BW_{3dB} \approx$ 10 GHz) and 10 Gb/s and 100 Gb/s bit rates. The results are plotted in Fig. 2(a) where the extinction ratios are given in dB. The blue curve refers to 10 Gb/s and the red curve corresponds to 100 Gb/s. For an input extinction ratio of 15 dB, the output extinction is about 13 dB at 10 Gb/s and drops to below 5 dB at 100 Gb/s. The power penalty due to a drop in the extinction

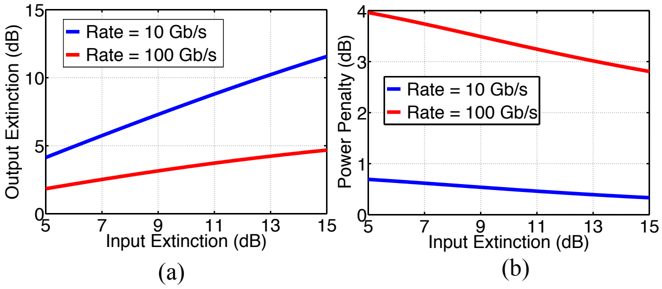

Fig. 2. (a) Calculation of the output extinction ratio (in dB) as a function of the input extinction ratio (in dB) for 10 Gb/s (blue) and 100 Gb/s (red) data rate. (b) Power penalty as a function of the input extinction ratio for 10 Gb/s and 100 Gb/s.

ratio can be estimated as

$$\text{PP} \approx 10\log_{10}\left(\frac{er_{in}-1}{er_{in}+1}\right) - 10\log_{10}\left(\frac{er_{out}-1}{er_{out}+1}\right). \quad (2)$$

The power penalty for different input extinction ratios is plotted in Fig. 2(b) for both 10 Gb/s and 100 Gb/s. As the input extinction ratio increases, the power penalty decreases.

The presented examples reveal the high sensitivity of MRR to global link parameters, in particular the modulation speed. Moreover, as apparent on Fig. 2(b), at high rates, the evolution of the extinction ratio across the link can provoke power penalties to vary in excess of 1dB. This generally indicates that at high rates, the usage of constant values for ring power penalties will in most cases lead to incorrect or to the least severely overestimated estimations.

In this talk, we will further expand on the necessity of integrating crosstalk and truncation effects in silicon photonics network modeling approaches, as well as of tracking the evolution of the extinction ratio. We will introduce our methodology, which permits to run optimizations at design stage to mitigate these effects [11].

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