Optimization of power coupling coefficient of a carrier depletion silicon ring modulator for WDM optical transmissions

Jean-Baptiste Quelene, Jean-François Carpentier, Yannis Le Guennec, Patrick Le Maitre

Optimization of Power Coupling Coefficient of a Carrier Depletion Silicon Ring Modulator for WDM Optical Transmissions

Jean-Baptiste Quélène[1,2], Jean-François Carpentier[1], Yannis Le Guennec[2], and Patrick Le Maître[1]

[1]*STMicroelectronics, 850 Rue Jean Monnet, 38920 Crolles, France*
[2]*Univ. Grenoble Alpes, IMEP-LAHC, F-38000 Grenoble, France*

***Abstract*—The presented method allows to evaluate the impact of power coupling on the performances of a carrier depletion ring resonator transmitter. From a measurement-based modulator model, coupling coefficient is varied and optimized maximizing modulation amplitude and reducing the impact of its process variability.**

I. Introduction

Optical interconnect technology is a potential candidate for short distance data communications such as DRAM interface with per-pin data rate of the order of 10Gbit/s [1]. In particular, silicon photonics transmitters based on carrier depletion ring resonators offer high aggregate bandwidth using dense wavelength division multiplexing (*DWDM*) [2]. The design of such a link requires a careful evaluation of power budget through the calculation of numerous optical power penalties, including crosstalk [2], [3].

Process variability of ring resonators [4], [5], and modulators [6] has been shown to induce significant changes of cavity group index (n_g), effective index (n_{eff}) or quality factor (Q). But it is necessary to quantify its impact on the power budget considering a variability-related penalty; in particular, the impact of the power coupling coefficient (K) variability, resulting from directional coupler geometrical variations, has not been estimated so far.

In this paper, we introduce an analysis method capable of predicting the modulator's dynamical performance under usual experimental conditions [6], i.e. data rate far below its overall bandwidth including photon lifetime limited bandwidth (BW_{opt}) [7] to minimize inter-symbol interference and linear response thanks to input laser power (P_{in}) of the order of 1mW [8]. After the presentation of this method and the comparison of simulation results with measurements in section II, we discuss the choice of K in section III in terms of performance and process variability. The precision required on the gap of the corresponding directional coupler to reach a given penalty is then evaluated. Finally, intermodulation crosstalk penalty is estimated at each K.

II. Transmitter Modeling with Given Coupling Coefficient

An ideal Lorentzian model of an all-pass modulator has been implemented with commercial software [9]. The 11 pm/V modulator efficiency, 2600dB/m cavity loss and the coupling coefficient K_{fit} of ~5% are chosen to fit with a given 8µm-radius modulator fabricated in a 300 mm industrial photonic platform [6] (Fig.1). Ring modulators require an accurate positioning of their resonance peak with respect to laser wavelength through the control of n_{eff}, using mechanisms such as local heating with resistors [6]. To evaluate the optimal detuning position in a single ring configuration, a routine varies n_{eff} starting from laser wavelength alignment and runs two static simulations corresponding to ON and OFF states for each resonance peak position for On-Off Keying (*OOK*) modulation. Then, an optical power penalty (P) based on optical modulation amplitude (*OMA*) and normalized by P_{in} is computed [10] as:

$$P = -10\log_{10}\left(\frac{OMA}{2P_{in}}\right). \quad (1)$$

The minimum optical penalty (P_{min}) evaluated from (1) gives the optimal detuning. A 1-dB detuning range corresponding to an additional 1-dB power penalty from P_{min} and accounting for the precision required for the positioning is provided. Additionally to this static power analysis, the modulator's Q and its related BW_{opt} are computed. Experimental *OMA* and thus P were calculated from eye-diagram measurements performed at 10Gbit/s and $2V_{p\text{-}p}$ driving voltage with different laser wavelengths. The simulation results are in agreement with the behavior observed experimentally which validates our method (Fig. 2).

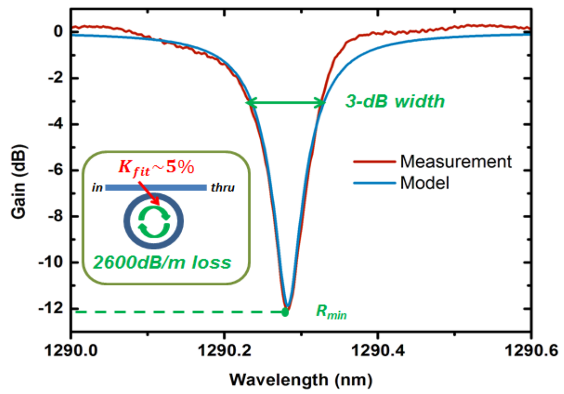

Fig. 1. Measurement and model transmission spectra of all-pass modulator. Inset : schematic of ring modulator with fitting parameters.

In the case of a common-bus WDM transmitter [11], additional modulators are placed on either side of the modulator allocated to the considered channel with a given channel spacing. The voltages applied on them (corresponding to ON or OFF state) are defined to operate in the worst crosstalk configuration regarding the central channel, i.e.

maximizing the optical signal lower level, minimizing the higher one and thus minimizing its *OMA*.

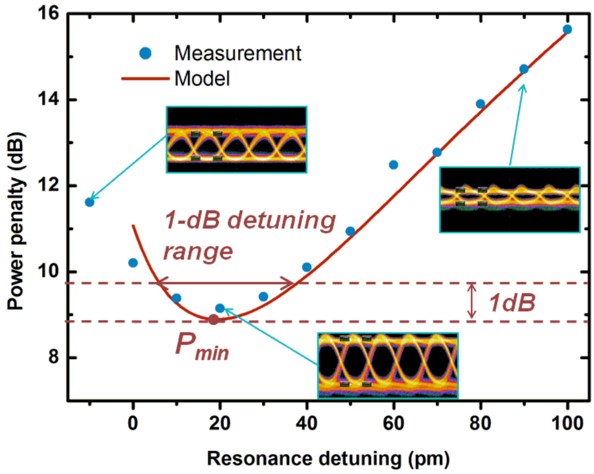

Fig. 2. Transmitter penalty as a function of resonance detuning: measurements (blue dots) and simulation (red curve).

III. Coupling Coefficient Variation

A. Single ring simulation results

Coupling is varied in the model described in section II. Fig. 3 plots P_{min} as a function of K. An optimal coupling of K_{opt} ~2% is found for P_{min}~7dB, Q~24000, BW_{opt} ~10GHz and a ~20pm 1-dB detuning range. Since the resonance 3-dB width (Fig. 1) decreases with K, under-coupling at K_{opt} compensates the minimum resonance transmission (R_{min}) rise due to mismatch with critical coupling resulting in a maximized resonance transmission slope. Critical coupling at K_{cc}~3% thus suffers from a higher P_{min}~7.5dB with Q~17000 and BW_{opt} ~13GHz. Considering a 5% coupling close to K_{fit} lowers Q (~14000) and hence raises BW_{opt} up to 17GHz.

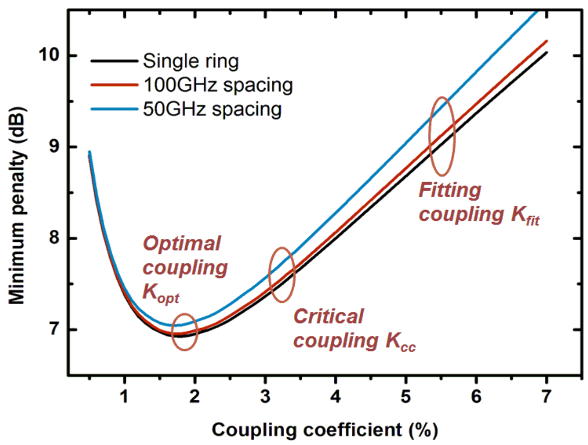

Fig. 3. Simulated minimum modulator penalty vs coupling coefficient for a single ring (black), and a 100GHz spaced (red) and 50GHz spaced (blue) WDM transmitter.

B. Process sensitivity

A slope of ~0.7dB/% is observed on Fig. 3 for K larger than 2% pointing out a high sensitivity to process variability. However, coupling coefficient variations decrease with the targeted K. Therefore, a 5%-coupled modulator will suffer from larger penalty variations than a critically coupled one. Targeting K_{opt} benefits from both advantages of lower coupling, meaning lower coupling variations, and zero-slope since it corresponds to the minimum value of Fig. 3. The same behavior is expected for rings designed for higher data rates [7] and the higher required K would be compensated by a more elongated curve involving lower slopes. We can then relate a power penalty to the variation of a given geometrical parameter of the directional coupler according to simulations using [9]. For instance, ensuring less than 0.5dB additional penalty related to coupling variability is equivalent to controlling the gap separating both waveguides within a distance on the order of ~50nm for a targeted K_{opt}, ~30nm for K_{cc} and ~7nm for K_{fit}.

C. Evaluation of DWDM crosstalk penalty

Crosstalk penalty at 100GHz spacing stays below 0.1dB in the coupling range considered (Fig. 3). For a tighter spacing of 50GHz, crosstalk penalty reaches ~0.1dB, ~0.2dB and ~0.35dB at K_{opt}, K_{cc}, and K_{fit} respectively showing a coupling-dependent impact of crosstalk. The performances corresponding to those coupling rates are summarized in Table I.

TABLE I. Summary of Performances

	K_{opt} ~2%	K_{cc}~3%	K_{fit}~5%
Minimum penalty	7dB	7.5dB	9dB
Gap tolerance for 0.5dB penalty	~50nm	~30nm	~7nm
Crosstalk penalty @100GHz spacing	<0.1dB	<0.1dB	0.1dB
Crosstalk penalty @50GHz spacing	~0.1dB	~0.2dB	~0.35dB

IV. Conclusion

The system-level analysis method presented evaluates the WDM transmitter power penalty optimizing position of resonance with respect to laser wavelength and estimates sensitivity to positioning accuracy. This method has been validated with dynamical measurements. From a modulator model based on a characterized modulator, the minimum power penalty is calculated for different coupling rates. For the first time, we show that when appropriately under-coupled the ring modulator achieves 0.5dB better performance than a critically coupled one and a lower sensitivity to coupling process variability. On the contrary, an over-coupled modulator will be less performant and more sensitive to this variability. We then relate a 0.5dB penalty due to coupling variations to the tolerance allowed on the gap of the corresponding directional coupler. Finally, we estimate the intermodulation crosstalk penalty for 50GHz and 100GHz spacings.

References

[1] H. Byun *et al.*, *Photonics Research*, vol.2, no. 3, pp. A25-A33, (Jun. 2014).

[2] N. Ophir *et al.*, *IEEE Micro*, vol. 33, no. 1, pp. 54–67 (Jan./Feb. 2013).

[3] S. Menezo *et al.*, *IEEE OIC*, pp. 21-22, (Mai 2013).

[4] A. V. Krishnamoorthy *et al.*, *IEEE PJ*, vol. 3, no. 3 pp. 567-579 (2011).

[5] L. Chrostowski *et al.*, *OFC 2014*, paper Th2A.37.

[6] P. Le Maître *et al.*, *ECOC 2015*, paper 7341725.

[7] G. Li *et al.*, *IEEE JSTQE*, vol. 19, no. 6, pp. 95-113 (Nov./Dec. 2013).

[8] X. Zheng *et al.*, *Opt. Exp.*, vol. 20, no. 10, pp.11478-11486, (2012).

[9] https://www.lumerical.com/

[10] M. Pantouvaki *et al.*, *OFC 2014*, paper Th1C.5.

[11] Y. Liu *et al.*, *OFC 2014*, paper Th4G.6.