High-Power Micro-Ring Modulator and Multi-Channel Coupled Ring Resonator for WDM Design on a 300-mm Monolithic Foundry Platform

Qidi Liu[1*], Abdelsalam Aboketaf[2*], Shantanu Pal[3], Salman Mosleh[1], Seyedeh Fahimeh Banihashemian[1], Sakthivel Pavadai[3], Jui-Chu Lee[1], Yusheng Bian[2], Ming Gong[2], Bradley Orner[5], Colleen Wemple[1], Petar Ivanov Todorov[4], Kevin K. Dezfulian[2], Michal Rakowski[2], Won Suk Lee[2], Takako Hirokawa[2], Sujith Chandran[2], Crystal Hedges[1], Frank Pavlik[1], Pike Charles[1], Avijit Chatterjee[3], Riddhi Nandi[3], Ken Giewont[2], Massimo Sorbara[2], Karen Nummy[2], Jignesh Patel[5], Clifford Morgan[1], Gregory O'Malley[1], Frederick G Anderson[1]

[1] GlobalFoundries, 1000 River St., Essex Junction, VT 05452, USA
[2] GlobalFoundries, 400 Stone Break Rd Ext., Malta, NY 12020, USA,
[3] GlobalFoundries Outer Ring Road, Bangalore 560045, India
[4] GlobalFoundries, 59 G.M. Dimitrov Blvd, 1700, Sofia, Bulgaria
[5] GlobalFoundries, 2600 Great America Way, Santa Clara, CA 95054, USA
** qidi.liu@gf.com;* abdelsalam.aboketaf@gf.com*

Abstract: We present scaled, bidirectional silicon photonic ring modulator and multi-channel coupled ring resonator models, offering advanced simulation capabilities for high-power and thermal time constant analysis, facilitating comprehensive on-chip EO system design with GlobalFoundries PDK.
OCIS codes: (130.3120) Integrated optics devices; (250.3140) Integrated optoelectronic circuits; (250.5300) Photonic integrated circuits; (350.4800) Optical standards and testing; (120.4640) Optical instruments; (060.3510) Lasers, fiber.

1. Introduction

A complex functionality of photonic integrated circuits (PIC) is implemented in silicon photonics (SiPh) technology foundries leveraging monolithic integration with existing CMOS infrastructures. This makes SiPh well positioned to fabricate at low cost, high yield, with low power, and at the same time scale to large commercial volumes [1]. GlobalFoundries (GF) offers monolithic Fotonix™ technology supported with a full process design kit (PDK) that includes scalable layout, schematic pcells and hardware verified compact models for both passives and actives within a Cadence environment [2-5]. In this context, the microring resonator emerges as a highly promising component within these systems. Its appeal lies in its compact size, minimal power requirements, and precise wavelength selectivity. This unique combination empowers engineers to independently control and manipulate individual wavelengths by strategically cascading microrings on an optical bus, opening up new avenues for versatile and efficient photonic system design. Nevertheless, thermal dissipation and the challenges associated with high optical power nonlinear effects (i.e. self-heating) represent ubiquitous concerns in contemporary silicon photonic circuits and systems, with particularly profound implications in data center infrastructures and coherent optical communication networks [6]. The accurate evaluation and comprehensive characterization of these intrinsic features within PDKs are pivotal for achieving precise analyses, management and facilitating the design of differentiated systems and applications in the field of integrated photonics. This paper endeavors to address these critical aspects by offering advanced compact models for thermal and optical power performance in foundry ring modulator, enabling engineers and designers to harness the full potential of silicon photonic technology for diverse and demanding applications in emerging optical systems. Further, the models allow for electro-optical co-simulation with other Electronic Design Automation (EDA) tools interoperability. These state-of-the-art models are built based on fundamental physics and require both wafer and chip level measurements with wavelength, temperature, voltage and optical power dependencies. Signal bidirectionality, reflections, and multi-channel model simulation capability are also added. These new features allow the designers to build wavelength division multiplexing (WDM) systems and take advantage of advanced 300 mm CMOS process technology that provides manufacturing scale.

2. Comprehensive photonic-device library

GF PDK includes a comprehensive O-band and continue growing C-band libraries of passive and active photonic devices such as Si and SiN waveguides (WGs) [4-5], bends, couplers, splitters, phase shifters, photodetectors (PDs) [7], electro-optic (EO) modulators, optical I/O fiber attach [8] and laser attach [9] as shown in Fig. 1(a). Each of these devices has a model that is built in Verilog-A and Spectre hardware scripting languages to allow optical paths, EO/OE interactions, and more complex calculations to capture the physical behavior of the actual device. This library supports

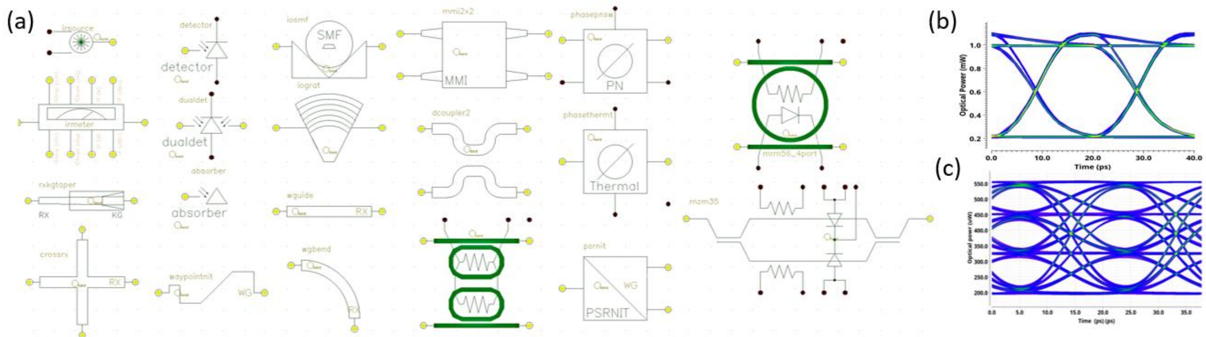

Fig. 1. (a) Passive and Active device library including I/Os, phase shifters, detectors, couplers and EO modulators; (b) high-power MRM dynamic simulation: the eye-diagram of 53Gb/s PRBS at 3dBm; (c) MZM simulation: The eye-diagram of 53Gb/s PAM4.

designing and simulating complicated SiPh systems. For instance, as depicted in Fig. 1(b), we present an optical ring modulator-based transceiver eye diagram of 53Gb/s NRZ signal. This performance was achieved at an input optical power of 3dBm, with the device biased at the operation wavelength corresponding to a 3dB insertion loss, taking into account the effects of optical self-heating generated by the high optical power within the ring. Additionally, Fig. 1(c) illustrates a probed eye diagram for a 53Gb/s PAM4 transmission signal, showcasing the versatility of our PDK library to simulate complex modulation schemes. Furthermore, it's worth noting that the GF Modeling and Characterization lab provides a streamlined and cost-efficient approach for wafer-level electro-optical testing of photonic devices, as discussed in [2]. We've developed passive and active photonics models that encompass dependencies on wavelength, temperature spanning from -25°C to 125°C, voltage, optical power, and TE/TM polarization states.

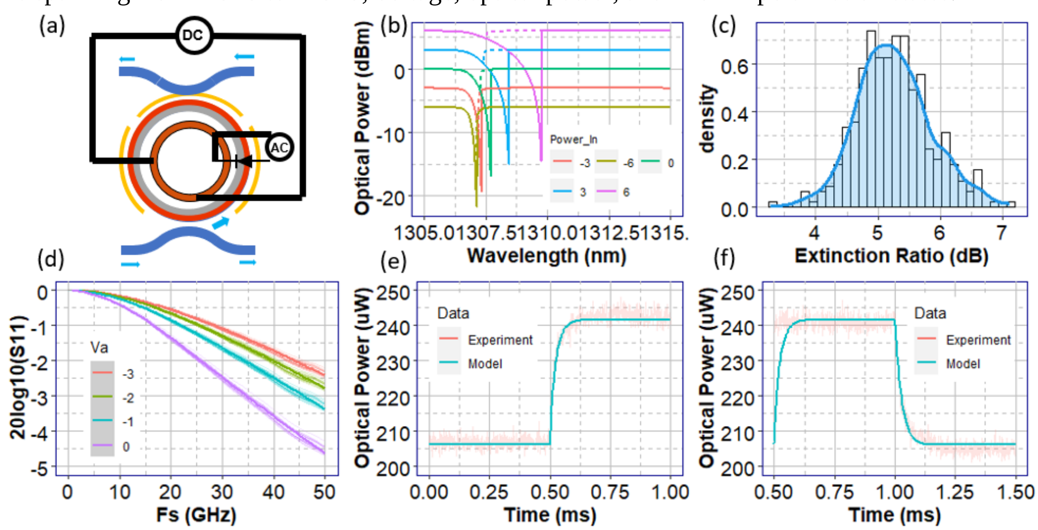

Fig. 2 Model-hardware correlations for: (a) a cartoon of GF Si MRM; (b) ring modulator transmission curve with bistable states at different power (-6,-3,0,3,6)dBm. (c) Micro-ring modulator extinction ratio at minimum transmission penalty; (d)Model hardware correlation: S11 parameter of ring PN junction with open-short deembedding. (e)(f) Thermal constant characterization (heating and cooling transient).

3. High-power microring modulator model with fast thermal response and model-hardware correlations

Depletion-type silicon micro-ring modulators (MRMs) encounter a significant challenge related to self-heating induced by free-carrier absorption (FCA) of the input light circulating within the modulator ring waveguides. This phenomenon leads to a temperature increase in the ring waveguide, causing an increase in its effective index. Consequently, this results in a red-shift of the ring resonance wavelength, with the extent of the shift dependent on the input optical power. The dynamic behavior can be modeled by the coupled mode equation,

$$\frac{d}{dt}a(t) = \left(j\omega_r - \frac{1}{\tau}\right)a(t) - j\alpha E_i(t)$$

$$E_o(t) = E_i(t) - j\alpha a(t)$$

Where $a(t)$ represents the optical field in the ring, ω_r is the resonance frequency, τ is the decay time constant, α is the loss of ring, $E_o(t)$ and $E_i(t)$ are the input and output optical field, respectively. Given that the characteristics of

Silicon MRMs are heavily reliant on the ring resonance wavelength, self-heating exerts a substantial impact on modulation performance. As a result, it is essential to establish a precise and easy-to-use model for understanding Si MRM self-heating. Here, the key device parameters for micro-ring modulator are characterized in foundry platform, for example, the insertion loss, extinction ratio, transmission penalty, eye-diagram as well as EE and EO bandwidth. Fig. 2(b) shows power-dependent model for high-speed MRM transmission spectrum from -6dBm to 6dBm. Additionally, MRM bistate behavior are also modeled based on testing (solid: forward sweep; dashed: reverse sweep). Fig. 2(c) shows the static extinction ratio distribution at minimum transmission penalty for micro-ring modulator. Further, Fig. 2(d) shows S11 parameter model-hardware correlation from de-embedded structure. Heating and cooling transient of ring thermal shifter using undercut design with 40 us are also characterized, as shown in Fig. 2(e)(f).

4. Bi-directionality and multi-channel enablement

In recent PDK releases, we have included bidirectionality in our models. This feature was added in order to support optical reflections, but there could certainly be other applications, such as stimulated Brillouin scattering (SBS), or wavelength up/down conversion. To facilitate this versatility, we have enabled the light propagating in the reverse direction to possess a distinct wavelength compared to the forward direction. Another feature added to the photonic PDK models is multi-channel simulation capability. This new enablement can be used for WDM simulations for the next-generation optical networks and wavelength routing. As shown in Fig. 3(a), the goal is to send optical signals with multiple wavelengths through a photonic device. The crosstalk and the interference between the channels can be captured by detected photocurrent in a multi-channel photodetector. The 2^{nd}-order coupled ring resonator is used to successfully demonstrate 200G and 400G WDM system based on our circuit design, enabling high-speed and high-capacity connections in data center, enhancing faster connectivity in high-performance computing, as well as extending high-bandwidth long-haul and metro optical networks. Figs. 3 (b) shows an example of 4-channel dWDM simulation circuit with independent thermal control capability. Fig. 3(c) shows the result of forming 8λ (FSR=1.6THz) with 10dB crosstalk that can be used for complex and flexible WDM system designs.

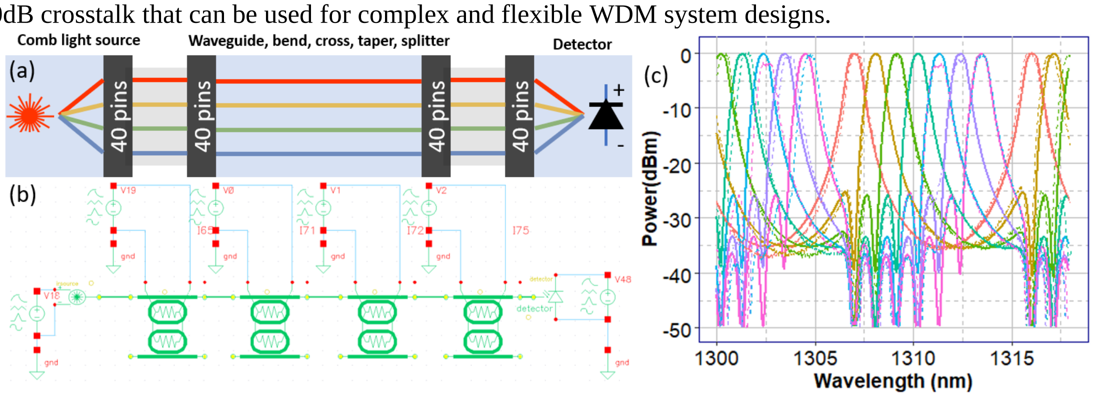

Fig. 3. (a) 4-channel light-source, waveguide and photodetector schematic as an example of multichannel enablement; (b) Schematic of the 4-channel WDM; (c) 8-λ model-hardware correlation: with adjustable flatness, channel spacing and channel width (model: solid; hardware: dashed).

5. Conclusion

An industry-leading GF Fotonix™ has been developed and qualified to 85C for general availability. This paper presented comprehensive characterization of mirco-ring modulator including optical power-dependent self-heating and thermal responses through scalable, multi-physics compact models. Multi-channel functionality enablement has also been correlated, particularly in WDM system design. Our state-of-the-art PDK offers an electro-optical co-design environment with access to a comprehensive photonics device library supporting a wide range of features.

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