Multiphysics Design and Simulation Methodology for Dense WDM Silicon Photonics

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***Abstract*—We present a novel design methodology covering multiphysics simulation workflows for microring-based dense wavelength division multiplexing (DWDM) Silicon Photonics (SiPh) circuits used for high-performance computing systems and data centers. The main workflow is an electronics-photonics co-simulation comprising various optical devices from a SiPh process design kit (PDK), electronic circuits designed with a commercial CMOS foundry's PDK, and channel S-parameter models, such as interposers and packages, generated by using a full-wave electromagnetic (EM) solver. With the co-simulation, electrical and optical as well as electro-optical behaviors can be analyzed at the same time because best-in-class electronics and photonic integrated circuit simulators interact with each other. As a result, not only optical spectrum and eye diagrams but also electrical eye diagrams can be evaluated on the same simulation platform. In addition, the proposed methodology includes a statistical- and thermal-aware photonic circuit simulation workflow to evaluate process and temperature variations as well as estimate the required thermal tuning power as those non-idealities can lead to microring's resonance wavelengths shifting. For this, thermal simulation is conducted with a 3D EM model which is also used for such signal and power integrity analysis as a channel link simulation and IR drop. Also, photonic circuit simulations are performed where a design exploration and optimization of such microring's design parameters as Q-factor, and bias voltages are required to select the most promising designs, for example, to satisfy a specific bit-error rate. With the proposed design methodology having those multiphysics simulation workflows, DWDM SiPh can be fully optimized to have reliable system performance.**

Keywords*—*silicon photonics (SiPh), electronics-photonics co-simulation, multiphysics simulation workflows.

I. Introduction

For future data centers and exascale high-performance computing systems, a dense wavelength division multiplexing (DWDM) Silicon Photonics (SiPh) has been recognized as a promising solution because of better energy efficiency, higher bandwidth, and lower cost [1], [2]. In particular, a microring-based DWDM SiPh circuit has been investigated as a good candidate since it requires a smaller footprint and provides better scalability. For this, an accurate design approach covering multiphysics is required as ring resonators' resonance wavelengths are sensitive to design parameters (e.g. operating bias point of electrical modulator driver) and both temperature and process variations. However, traditionally photonic devices and electronic circuits have been designed individually on separate simulation platforms. Therefore, the existing solutions either cannot capture electrical-to-optical (E/O) and optical-to-electrical (O/E) behaviors accurately or require an effort to behaviorally model photonic devices to evaluate E/O and O/E characteristics within an electronic simulation platform by adding the photonic devices' models.

In this paper, we propose a novel design methodology with multiphysics simulation workflows. Especially, an electronic-photonic co-simulation capability on a single design platform is presented with schematic diagrams, and optical and electrical simulation results. Also, signal and power integrity, thermal integrity, and design exploration and optimization workflows are covered.

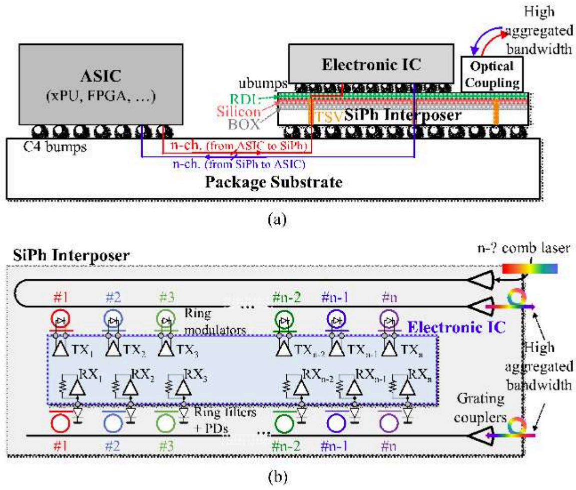

Fig. 1. (a) Cross-sectional block diagram of DWDM Silicon Photonics system. (b) Schematic diagram of SiPh package including an electronic IC and a SiPh interposer.

II. Microring-Based DWDM Silicon Photonics

Fig. 1(a) describes a simplified block diagram of a DWDM SiPh system. A SiPh package is composed of an electronic IC and a SiPh interposer, and both are flip-chipped using ubumps. The electronic IC includes transmitter (Tx) front-end circuits (e.g. pre-emphasis, modulator driver, etc.) and receiver (Rx) front-end circuits (e.g. transimpedance amplifier, equalizer, etc.). The SiPh interposer contains optical devices such as grating couplers, ring resonators, and photodetectors (PDs) in the silicon layer. Re-distribution layer and through-silicon vias are used for signal and power routing. The SiPh package and ASICs (e.g. CPU, GPU, and FPGA) are attached to the same package substrate, and both communicate with each other via parallel electrical channels in the package substrate. Fig. 1(b) shows a schematic diagram of the SiPh package. For n-channel DWDM SiPh, on the Tx side, n ring modulators are connected in series to a single bus waveguide, and each ring modulator is modulated by the Tx front-end circuits. The aggregated bandwidth for $n = 24$ and each channel using a PCIe4 protocol, is 384 Gbps data bandwidth in total. On the Rx side, once modulated optical signal is received via the grating coupler, n ring filters and n PDs convert from optical to electrical current signal. Then receiver circuitry generates a voltage signal and amplifies it further for the data decision circuits.

III. Multiphysics Design and Simulation Methodology

Fig. 2 depicts the proposed design methodology covering multiphysics simulation workflows. The main workflow is an electronic-photonic co-simulation using Cadence advanced mixed-signal simulator as well as a photonic integrated circuit

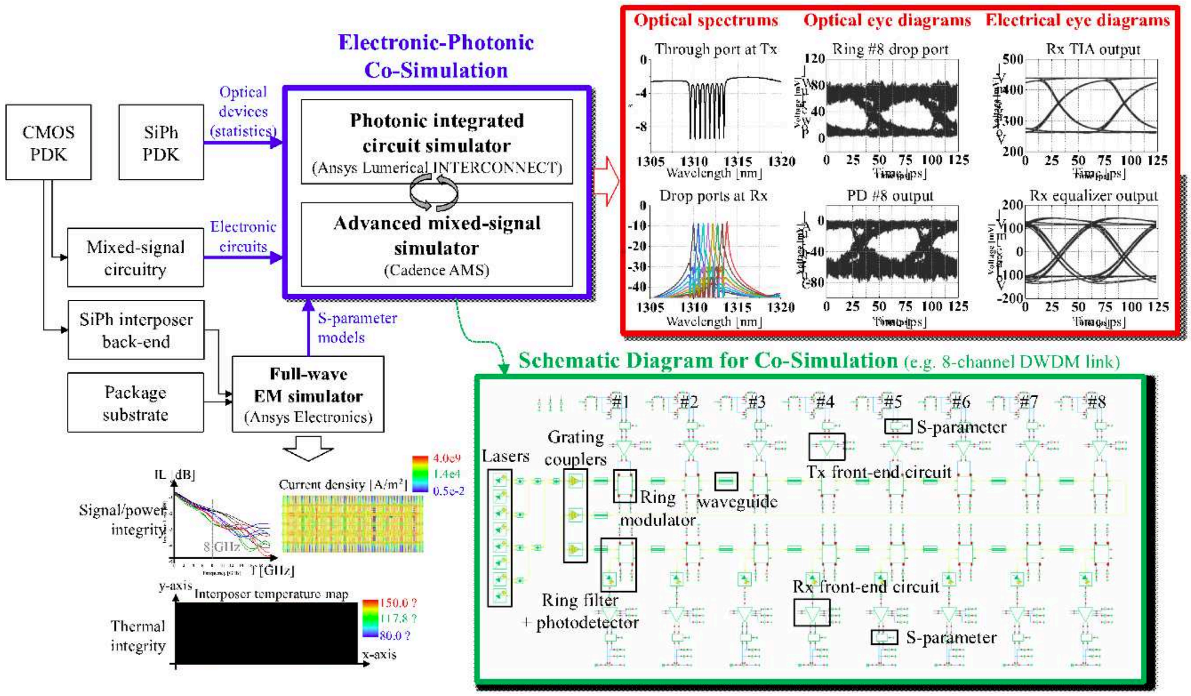

Fig. 2. Design methodology including multiphysics simulation workflows, schematic and simulation results for microring-based DWDM Silicon Photonics.

simulator from Ansys Lumerical INTERCONNECT. As both simulators interact with each other, E/O and O/E behaviors are analyzed and evaluated simultaneously. For the co-simulation, a SiPh process design kit (PDK) provides a variety of optical devices such as a laser source, a grating coupler, a waveguide, a ring resonator [3], and a PD [4] which are generated with an Ansys Lumerical CML Compiler based on simulation and measurement data. In addition, both electronic circuits designed with a CMOS foundry's PDK are included.

Fig. 2 shows a schematic diagram of an 8-channel DWDM SiPh link for co-simulation. An 8-λ comb laser is used to emit light towards the TX circuit. It is modelled by 8 individual continuous wave lasers each one having a wavelength from 1310 nm to 1313.83 nm with spacing of about 0.55 nm. Three grating couplers are required to receive light from the laser first, and then to send/receive the modulated optical signals to/from the optical fiber. On the Tx side, 8 ring modulators' resonances align with the corresponding wavelengths and front-end circuits drive each ring modulator. On the Rx, ring filters are placed to filter out the corresponding wavelengths and PDs convert signals from the optical domain to the electrical domain. Then, the Rx front-end circuit converts from PD current signal to voltage signal and also compensates bandwidth limits with equalization in order to improve voltage and timing margin. The channel characteristics and package parasitics are modeled as S-parameter which are included on Tx and Rx sides. The simulation results are shown on the top right of Fig. 2. As can be seen, both electrical and optical results can be verified on the same simulation platform. Thus, optical spectrums, transient waveforms, and eye diagrams can be evaluated at any input and output nodes of optical devices, for example, the grating coupler's output, ring modulator and filters' through and drop ports, and PD's output node. Also, electrical waveforms and eye diagrams can be plotted at any nodes, and timing and voltage margin can be evaluated. Even though co-simulation needs more simulation runtime due to data communication between AMS and INTERCONNECT solvers, it should be improved with an advanced problem-solving algorithm and better computing resources.

Full-wave EM simulator from Ansys Electronics Desktop is used for analyzing signal and power integrity and thermal simulation workflow [5]. As shown in Fig. 2, interposer and package's insertion and reflection losses can be evaluated, and IR drop (e.g. current and voltage density) is also evaluated. Moreover, based on a temperature map of the SiPh interposer acquired by running a thermal simulation and importing the temperature map into Ansys Lumerical INTERCONNECT, the ring resonator's thermal non-linearity can be verified, and the required thermal tuning power can be estimated using a photonic integrated circuit simulator. Also, in the early design phase, physical and electrical design parameters of ring resonator can be explored and optimized using a photonic integrated circuit simulator to meet the design specification, for example, a bit-error rate [6].

In summary, with the proposed design methodology with multiphysics simulation workflows, DWDM SiPh circuits can be fully verified and optimized to achieve better performance. This methodology can generally be used in many design fields that require both electronic and photonic domains once many optical devices are ready in SiPh PDK for co-simulation.

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