Uncertainty Quantification for Silicon Photonics

from Devices to Circuits & Systems

NEEDS 2012-2017 (needs.nanohub.org)

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May 2017

Background

Due to the need for high speed data transmission in data centers and in supercomputers and due to the speed limitations of current electronic devices, silicon photonics has become one of the most promising candidate technologies for the transmission of high volumes of data at low cost. To realize such a goal, Silicon optical modulators are undoubtedly the key components. They are crucial to introduce Wavelength Division Multiplexing (WDM) techniques, which can successfully expand the capacity of a communication network and therefore increase the aggregate data rate substantially beyond what can be achieved with electrical communications alone. The Photonic Microsystems Group at MIT, led by Prof. Michael Watts, had developed a high speed, very compact and ultralow power silicon modulator using vertical p-n junction microdisks [Watts11]. The idea was to use free carrier plasma effect to manipulate the material property of the p-n junction with a reverse bias, and therefore the input 0-1 electrical data can be modulated to 0-1 optical data because of the shifted spectrums. The most challenging part of this device modeling was the multi-physics nature of the electro-to-optical modulation. The scale of the input data is at several GHz, whereas the optical scale is around 193 THz if the 1.55 micrometer carrier wavelength is used. In other words, the output and input have approximately five orders of magnitude difference, which may cause simulations to become lengthy and unrealistic.

What were the goals?

The ultimate goal of this part of the project was to use the Model and Algorithm Prototyping Platform (MAPP), a Matlab-based platform for prototyping numerical and simulation algorithm developed by Prof. Roychowdhury's team at University of California, Berkeley, to develop and deploy compact models for electro-optical devices with the ability to simultaneously handle electrical and optical signals.

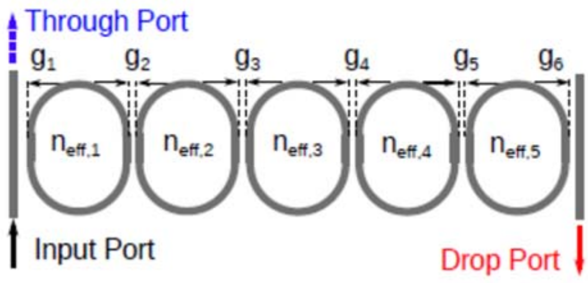
What was accomplished?

An Optical Ring Filter Modspec compact model has been developed in 2015 on the MAPP, the simulator developed by Prof. Roychowdhury's team. Two modules, coupler module and phase shifter module, were used to model the light propagation in an optical ring filter. The coupler module characterizes the amount of electric light field coupled into the ring resonator, while the phase shifter module describes the light propagation in the ring resonator through optical, geometrical and material parameters. By cascading the coupler and phase shifter module, the Modspec compact model outputs the power spectrum of the optical ring filter, which successfully captures the resonances in the concerned frequency range. The Optical Ring Filter Modspec compact model has been deployed in public domain on nanohub.org in September, 2015, and is now available at https://nanohub.org/publications/82/1.

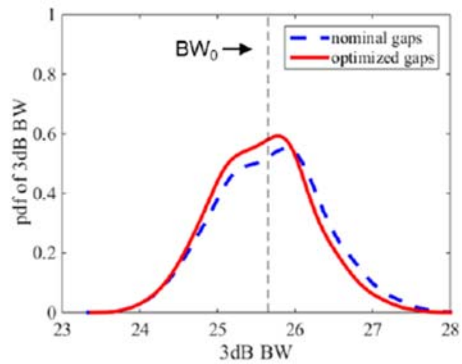
Based on the Optical Ring Filter Compact Model, a Modspec compact model of a carrier-depletion-based optical ring modulator was also developed in 2016. Similar to the optical ring filter compact model, the optical ring modulator has a coupler module and a phase shifter module. However, the phase shifter module is a voltage-controlled phase shifter module, which models the physics of the modulator. The physics underlying the optical modulator is the free carrier plasma effect [Soref87], which can engineer the optical property an optical ring filter with a reverse bias on the pn-junction silicon waveguide. The mechanism has been carefully studied to model the operation of the carrier-depletion-based optical ring modulator. The Optical Ring Modulator Modspec compact model has been deployed in public domain on nanohub.org in September, 2016, and is now available at https://nanohub.org/publications/157/1.

An Optical Ring Modulator employing MIT Virtual Source Model in the p-n junction of the ring was developed in 2017. MIT virtual source model is a semi-empirical model describing the current and voltage characteristics of a short-channel metal-oxide-semiconductor field-effect transistor (MOSFET), where the current and charges are functions of its terminal voltage. In 2014 and 2015, Dr. Shaloo Rakheja and Dr. Dimitri Antoniadis has published compact models for MVS in Verilog-A format [Weng15]. The MIT Virtual Source model is embedded in the inverter circuits which is used to drive the optical ring modulator. The Optical Ring Modulator with MIT Virtual Source ModSpec Compact Model has been submitted to nanohub.org in April, 2017, and will be available soon at https://nanohub.org/groups/needs/compact_models

Finally, we recognized that silicon-based optical devices are very sensitive to fabrication process variations due to the high refractive index contrast between silicon and silica. Such variations caused by imperfect lithography and non-uniform wafer thickness can lead to potentially significant device performance degradations and further systems failures. In order to obtain a high quality design of a photonic device or circuit (e.g. high yield or smaller performance variability, etc.), it is important to include such variations/uncertainties during the early design stages. For that purpose we developed uncertainty quantification techniques to obtain efficiently the statistical information of the circuits, as well as to achieve a high quality design. Some preliminary results includes designing the gaps of a photonic coupled ring filter whose 3dB bandwidth is robust to fabrication variations. The schematic of the optical coupled ring filter and the nominal/optimized gaps are shown in Fig 1 (a) and (b) respectively.



(a)



(b)

Fig 1: (a) Schematic of a photonic coupled ring filter (b) the probability density function of the 3dB bandwidth for nominal gaps (blue dash lines) and optimized gaps (red solid lines)

Why was it important?

The importance of developing compact models for photonic/optical devices has already been appreciated and had impacts on the traditional Electronic Design Automation (EDA) companies. The two biggest EDA companies such as Cadence and Synopsys have recently been moving forward from EDA to PDA, where P means photonics. They have been developing photonics design toolkits (PDK) collaborating with photonic simulation software companies including Lumerical Solutions, PhoeniX, Luceda Photonics, just to name a few. In the PDK, they have developed compact models for various photonics devices to perform optical simulations. Their next step is to develop variation-aware algorithms and integrate them with PDKs, which will make use of the uncertainty quantification techniques we have been developing.

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