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Circuit modeling for neuromorphic photonics in Verilog-A as a scalable simulation platform

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***Abstract*—We demonstrate a Verilog-A based approach to perform electro-optical co-simulation for neuromorphic architectures. Verilog-A models of primary photonic devices are discussed along with comparing the simulation and experimental results.**

I. Introduction

Recent advances in integrated photonic neuromorphic architectures promise to deliver computations with higher speed (higher bandwidth, and lower latency) than electronics by exploiting the parallel nature of light through wavelength-division multiplexing (WDM) and the passive nature of optical waveguides [1].

For a successful experimental demonstration of a large-scale neuromorphic photonic integrated circuit (PIC), it is imperative to first simulate the PIC by capturing the underlying physics of the individual devices and their interactions, and predict the system behaviour in the presence of external stimulus, namely electrical and optical signals. Most of the commercially available photonic simulation software are based on finite-difference time-domain (FDTD) methods that are time-consuming and computationally expensive. An efficient approach is to work with compact models of photonic devices, which can provide maximum detail along with incorporating the physics behind the devices.

In this work, we demonstrate a Verilog-A based approach that is capable of performing large scale electro-optical co-simulation for neuromorphic architectures. Model parameters for different photonic devices are extracted and tuned by analyzing the experimental data. The simulated and experimental results are also compared for validation of Verilog-A models.

II. Verilog-A Models and Simulation of Photonic Devices

The methodology of our work is based on representing optical signal as an analytic signal using electric field representation of light [2], [3]. The optical signals propagate as a real and imaginary part of the electric field carrying information about magnitude and phase of the electric field [2], [3]. The wavelength of the light is defined as an explicit signal which passes across all the devices [9].

The fundamental photonic devices in neuromorphic computing are lasers, waveguides, couplers, splitters, combiners, and photodetectors, that are modeled based on Ref [2], [3]. Phase shifters are modeled as a waveguide where the effective refractive index n_{eff} and attenuation α_{eff} depends on the perturbation to the system which can be due to thermo-optic effect, plasma-dispersion effect, carrier-depletion, etc., such that [4] $n_{eff} = a_0 + a_1V + a_2V^2 + a_3V^3 + a_4V^4$ and $\alpha_{eff} = b_0 + b_1V + b_2V^2 + b_3V^3 + b_4V^4$, where V is the voltage applied across the phase-shifter and the coefficients can be extracted from experimental or device simulation data by performing polynomial-fit. Microring resonator (MRR) is modeled by combining discrete components that includes couplers, waveguides, and phase shifters as shown in Figure 1 [2].

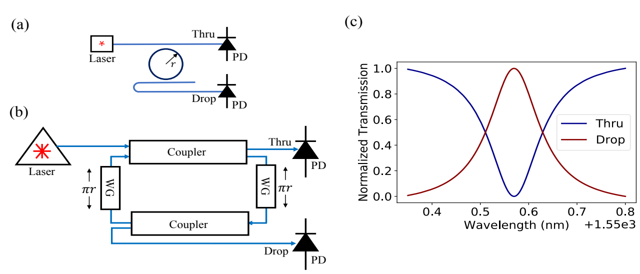

Fig. 1. (a) Add-drop ring resonator (b) Circuit schematic for the ring resonator by combining couplers and waveguides (WG) [2], [3]. (c) Spectrum of the add-drop ring resonator implemented in Verilog-A.

A. Mircoring Weight Bank

In Verilog-A, an MRR weight bank is created by combining N number of microrings (combining couplers and phase-shifters) in series. Each microring in a weight-bank represents a weight, and weighting mechanism is performed by changing the resonance wavelength [7]. A n-doped heater embedded in the microring alongside the waveguide is used to change the temperature of the silicon to affect the refractive index (Δn_{eff}) of the silicon which leads to change the resonance wavelength ($\Delta\lambda_{res}$) according to the equation [6], [8]:

$$\Delta\lambda_{res} = \frac{\Delta n_{eff} L}{m} \tag{1}$$

where $L = 2\pi R$ is the length of the microring waveguide, and m is the order of resonant mode. The $\Delta\lambda_{res}$ is extracted experimentally by doing a current sweep. A 4th order polynomial fit is performed to find Δn_{eff} from Eq.1 and is implemented in the Verilog-A phase shifter model. Figure 2 shows the comparison between the experimental and simulated spectrum of the n-doped heater.

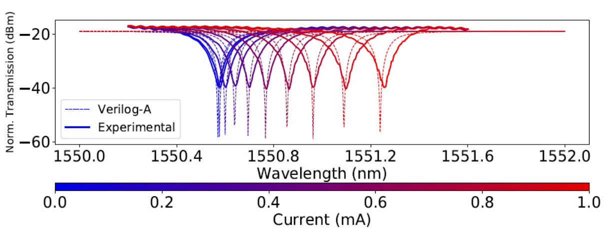

Fig. 2. Comparing the Verilog-A simulated and experimental spectrum of a n-doped microring resonator where the current to the heater is swept from 0-1 mA.

B. Mircoring Modulator

The p-n junction microring modulator is constructed by combining the coupler and p-n junction phase shifter [2]. The p-n phase shifter exploits plasma-dispersion and carrier depletion effects, and the parameters ($n_{eff}(V)$, $\alpha_{eff}(V)$) are extracted experimentally and implemented in Verilog-A model. Figure 3 shows the comparison between the simulated and experimental spectrum of microring modulator.

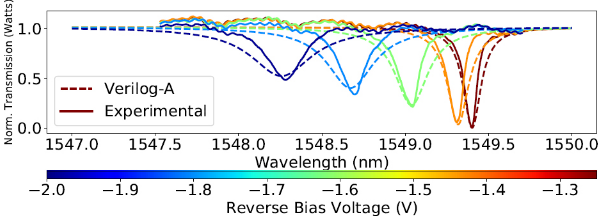

Fig. 3. Comparison of the simulated and experimental spectrum of microring modulator for different reverse bias voltages.

III. Photonic Neuron Simulation

A single photonic neuron is simulated in Verilog-A. Figure 4 shows the schematic of the single photonic neuron with electrical components. The laser power (P_{amp}) represents the input (x_i) to the neuron, the current (I_{heat}) to the n-doped heater represents the weight (w_i), summation operation is performed by balanced photodetectors, and the transfer function of the modulator represents the activation function (σ). Circuit parameters such as parasitic resistance and capacitors are also included based on literature [5]. This approach can be easily scaled to perform multiple neuron circuit simulations.

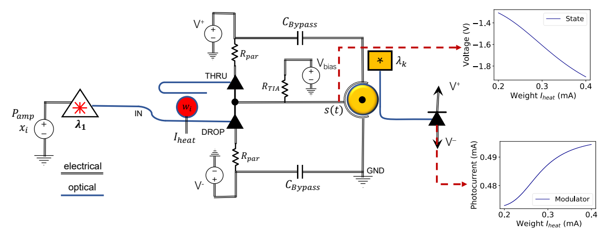

Fig. 4. Circuit schematic of the photonic neuron with one microring weight implemented in Verilog-A.

IV. Conclusion

We demonstrate a Verilog-A based approach for simulating neuromorphic architectures by modeling lasers, waveguides, couplers, photo-detectors, microring weight bank, and modulator. The simulation results are found to be consistent with the experimental results. Furthermore, electrical circuit parameters and parasitic are also included by showing the simulation of the single photonic neuron. The capability of optical-electrical rapid co-simulation would greatly improve the efficiency of optimizing the devices and provide an accurate simulation of the circuit performance.

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