An Accurate and Computationally Efficient Large-signal SPICE Model for Depletion-type Silicon Ring Modulators Including Temperature Dependence

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Abstract *We present large-signal SPICE model for ring modulators including temperature dependence. The model is verified with 25-Gb/s NRZ modulation at several different temperatures. With this model, the temperature-dependent eye diagrams together with the temperature control IC is successfully simulated in the standard IC design environment.*

Introduction

Depletion-type Si ring modulators (RMs) attract a great amount of research and development interests because they can provide superior performances for demanding optical interconnect applications with their large modulation bandwidth, small-footprint, and energy-efficient operation[1]. However, their performance is highly dependent on the temperature, so the RM temperature control (TC) that provides the stable and optimal modulation characteristics is an absolute necessity for any practical application of Si RMs[2]–[4]. Furthermore, the performance of the entire transmitter is greatly influenced by the modulator driving electronics. Consequently, for any optical interconnect application of Si RMs, there is a great demand for the capability of temperature-dependent electro-photonic co-simulation of RMs together with drivers and temperature controllers during the initial design stage preferably in the standard IC design environment[5], [6]. Previously, we demonstrated a large-signal SPICE model for Si RM that is easy-to-use in the standard IC design platform and allows accurate co-simulation of the RM and the driver circuit[7]. We expand this model by adding temperature dependence and demonstrate accurate SPICE-level simulation of the Si transient modulation characteristics together with the TC circuit.

Temperature-dependent Si RM parameters

The key parameters for describing the Si RM optical behavior are the effective index of the waveguide (n_{eff}), the field ratio after one round-trip in the ring waveguide (α), and the coupling coefficient in the directional coupler between the ring and bus waveguide (γ). The RM transmission characteristics is determined by these three parameters in the following manner,

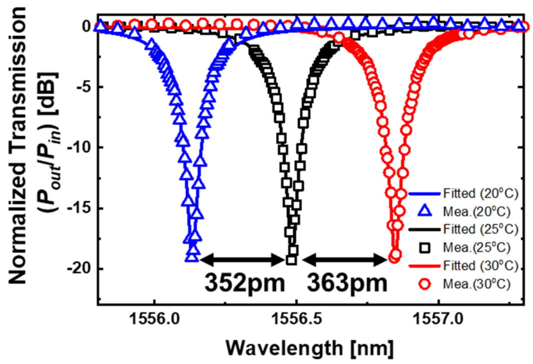

Fig. 1: Measured and fitted transmission curve for different operating temperatures at Voltage=0 V

$$T = \frac{P_{out}}{P_{in}} = \frac{\alpha^2 - 2\alpha\gamma\cos(\phi) + \gamma^2}{1 - 2\alpha\gamma\cos(\phi) + (\alpha\gamma)^2}, \quad (1)$$

where $\phi = \frac{2\pi n_{eff}}{\lambda} L_{ring}$ and L_{ring} is the ring circumstance. In order to determine temperature dependence of these three parameters, transmission characteristics of a sample Si RM are measured at three different temperatures and the results are shown in Fig. 1. The measured Si RM is fabricated in IHP's Si PIC technology. It has 8μm radius and 290nm gap between ring and bus waveguides. As shown in the figure, the resonance wavelength linearly shifts with temperature. The measured temperature dependence of 70 pm/°C agrees well with the value calculated from the Si thermo-optic coefficient. The temeprature dependence of n_{eff} can be determined from the resonance condition, $m\lambda_{res} = n_{eff} L_{ring}$, and the resulting n_{eff} values are

Table 1: Extracted parameters of Si RM with different temperatures at Voltage=0 V

Temper-ature	n_{eff}	alpha	gamma
20 °C	2.631470	0.9804	0.985
25 °C	2.632066		
30 °C	2.632679		

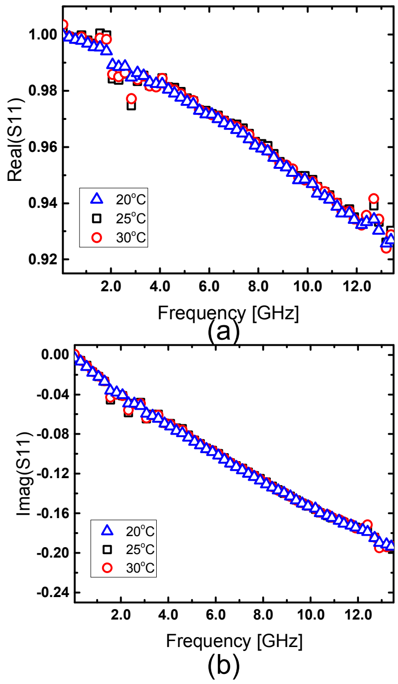

Fig. 2: Measured reflection coefficient (S11) of the Si RM, (a) real part and (b) imaginary part for different temperatures at Voltage=0 V

shown in Table 1. Numerical values for α and γ for different temperatures can be determined by fitting Eq. (1) to the measured transmission characteriestics but there is very little change for α and γ within the temperature range investigated here. Their numerial values are given in Table 1. With these results, n_{eff} can be regarded as the only temperature-dependent optical parameter for RM transmission characteristics.

Electrical characeristics of the Si RM such as series resistance (R_s) and p-n junction capacitance (C_j) also influence the Si RM modulation frequency response. Fig. 2 shows the measured reflection coefficient (S11) of the sample Si RM at different temperatures. As can be seen in the figure, there is very little change with temperature. Conseuqently, we can assume the Si RM electrical parameters do not change with temperature within the temperature range of interest.

Large-signal SPICE model with temperature dependence

The previously reported large-signal SPICE model[7] of the Si RM is based on the small-signal frequency modulation response derived from the RM coupled-mode equations given as

$$\frac{s+(2/\tau_l)}{s^2+(2/\tau)s+D^2+(1/\tau^2)}, \quad (2)$$

where D is the difference between the input light

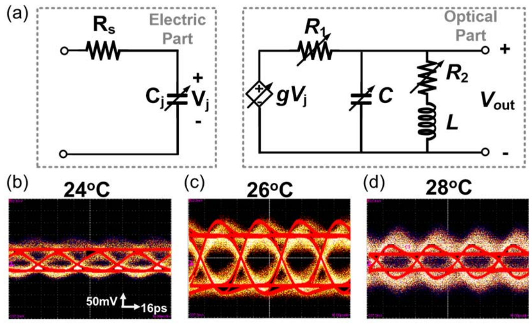

Fig. 3: (a) SPICE model and (b-d) its verification with NRZ 25-Gb/s data at different temperatures

wavelength and the resonance wavelength, τ_l and τ are the time-constants due to the ring waveguide loss and the total loss including coupler loss, respectively. τ_l and τ are related to α and γ as

$$\frac{1}{\tau_l}=\frac{(1-\alpha^2)c}{2n_{eff}L_{ring}}, \frac{1}{\tau}=\frac{(2-\alpha^2-\gamma^2)c}{2n_{eff}L_{ring}}. \quad (3)$$

Eq. (2) can be represented with an RLC circuit shown in the right side of Fig. 3(a). The R,L,C values can be obtained by matching Eq. (2) to the transfer function of the RLC circuit. Togther with the left side block representing the electrical frequency response, the circuit in Fig. 3(a) is the equivalent circuit for the RM modulation characteristics. In the equivalent circuit, variable electrical components are used since their values depend on the voltage applied to the Si RM. In short, by extracting numercial values for voltage-dependent α, γ, n_{eff} at different temperatures and with the given values of D and L_{ring}, all the circuit element values in Fig. 3(a) can be determined and, using the equivalent circuit, the entire large-signal Si RM modulation characteristics can be efficienty simulated in SPICE. Fig. 3(b),(c),(d) show such simulated results at three different temperarues along with measured results. For the simulatn, voltage-dependent parameters are modeled with the third-order polynomials and temperature dependence of n_{eff} is linearly modeled. With 25-Gb/s 2^{31}-1 PRBS NRZ input data having 4-$V_{peak\text{-}to\text{-}peak}$ swing, the resulting equation-based R,L,C values allow very efficient SPICE simulation at a given temperature, the result of which agrees well with the measurement result.

RM Co-simulation with TC IC

The real advantage of our model is the ease with which it can be used for co-simulation of RMs and electronic circuits such as TC IC. The lower block in Fig. 4 shows the block diagram of the RM TC IC fabricated in IHP's BiCMOS platform[3]. Fig. 5 shows the co-simulation results for the RM with this TC IC. For the simulation, the RM is

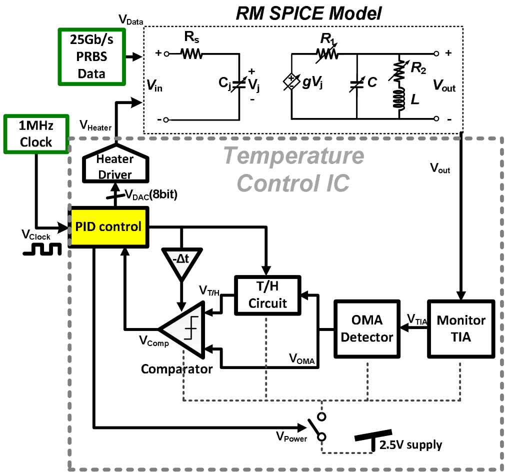

Fig. 4: Block diagram for co-simulation with SPICE model and temperature control IC

continuously modulated with 25-Gb/s 2^{31}-1 PRBS data and the RM output power is obtained with 1-ps resolution, which is shown in Fig. 5(a) with magenta lines and 10ns zoomed-in data is shown as well. Initially, the TC IC provides a temperature scan of the RM with the on-chip heater with 1-MHz clock update, and the RM OMA is monitored, where the OMA value is labeled with red lines. The TC IC determines the largest OMA (marked B in Fig. 5(a)) and controls the RM temperature so that this OMA is maintained. Simulated eye diagrams are also shown for three different points in Fig. 5(b), which shows that Point B has the largest OMA compared to the other points. With the RM SPICE model, such temperature-aware simlation was possible within three hours for over 100μs simulation with 1ps resolution, which is much computationally efficient compared to Verilog-A model. With such simulation, we can provide feasibilty of the co-simulation with temperature control IC as well as the RM's dynamics along the time-variant temperature, and this can extend to co-simulation with other complicated environments such as thermal perturbation due to the chip power dissipation.

Conclusion

We present a large-signal SPICE model for the Si RM including temperature dependence. With our model, electro-optic co-simulation of the Si RM with and electronic circuit is possible. In particular, we demonstrate that temperature-dependent Si RM eye-diagrams can be simulated together with the TC IC. Our model should be of great use for any Si electro-photonic integrated circuits including RMs.

Acknowledgements

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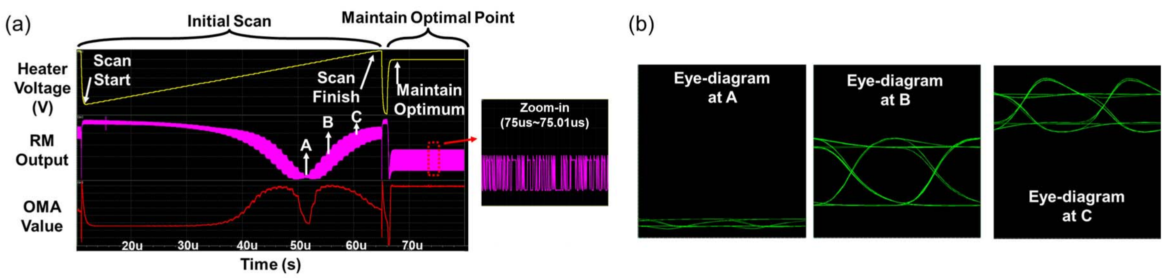

Fig. 5: Co-simulation with SPICE model and temperature control IC