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Equivalent Circuit Modelling of Integrated Traveling-Wave Optical Modulator in InP Foundry Platform

Weiming YAO[1*], Giovanni GILARDI[1], Meint K. SMIT[1], Michael J. WALE[2]
[1]COBRA Institute, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands
[2]Oclaro Technology Ltd., Caswell, Northamptonshire, NN12 8EQ, United Kingdom
[*] w.yao@tue.nl

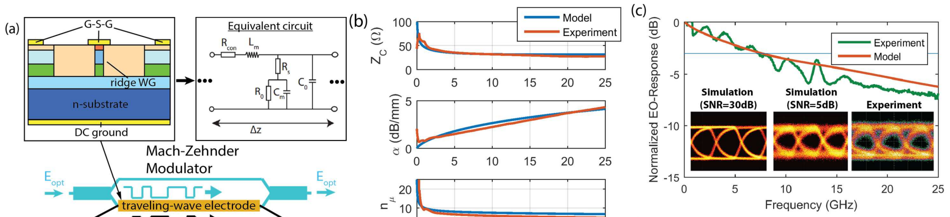
In this paper we present an electro-optical model for traveling-wave modulator devices utilizing measurement-based equivalent circuit model extraction in conjunction with microwave CAD simulation techniques. Model verification is performed with frequency-domain and time-domain characterization of an integrated Mach-Zehnder modulator from an InP Foundry process.

Introduction

Traveling-wave electro-optic modulators are essential components in photonic integrated circuits. They provide high modulation speed, large optical extinction and high efficiency, based on co-propagation of the optical signal along the waveguide with the electrical data along the modulator electrode [1]. Electrically, they behave like high-speed transmission lines so that the speed limitation is not anymore governed by the lumped element RC constant but is rather restricted by transmission line effects such as impedance matching, microwave attenuation and velocity mismatch between the optical and electrical signals [2]. Proper understanding of these underlying effects is essential for extending modulator speeds beyond 10 Gbps. An equivalent circuit approach for modeling the electrode structure has proven to be well suited, based on data obtained from microwave measurements [3]. We adopt this technique and implement a large signal time-domain model in a microwave CAD environment similar to the approach described in [4] to simulate for the first time the optical modulation output of a Mach-Zehnder modulator in InP material. The results are verified with experimental frequency response measurements and modulation eye diagrams on a fabricated modulator from a generic InP foundry.

Equivalent Circuit Model

The electro-optic phase shifter structure of the fabricated device is shown in Fig. 1a and comprises of a coplanar electrode on top of an optical ridge waveguide that is formed on n-doped InP substrate. It is modeled by a transmission line equivalent circuit shown in Fig. 1a with per unit length parameters R_s, C_m, R_{con}, L_m, C_0 representing the series resistance of the p-doped cladding, the depletion capacitance of the ridge under bias, the conductor series resistance and the inductance and stray capacitance of the ground and signal metal. To obtain the proper values for the given modulator design, s-parameter measurements with on-chip probing and short-open-load-thru calibration have been performed on electrical test structures with the same cross section and two different length L and 2L, so that after subsequent de-embedding the influence of the probing fixture can be compensated for [5]. The equivalent circuit values are extracted and shown in Fig. 1c after fitting initial values to the measurement data and using them in a quasi-Newton optimization algorithm in the microwave CAD package ADS. The resulting transmission line parameters of the model are shown in Fig. 1b and agree well with the experimental values.



R_S (Ω mm)	C_m ($\frac{\mathrm{pF}}{\mathrm{mm}}$)	L_m ($\frac{\mathrm{nH}}{\mathrm{mm}}$)	R_{con} ($\frac{\Omega}{\mathrm{mm}\sqrt{\mathrm{GHz}}}$)	C_0($\frac{\mathrm{pF}}{\mathrm{mm}}$)
29.85	0.19	0.53	9.40	0.52

Fig. 1. (a) Cross section and equivalent circuit, (b) microwave parameters, (c) frequency response, eye diagram and extracted parameters of Mach-Zehnder modulator.

Simulation Results and Conclusions

After determining the electrode's microwave parameters its normalized electro-optic frequency response $r(f)$ can be calculated according to [6] as

$$r(f) = \left| \frac{1-\rho_1\rho_2}{1+\rho_2} \cdot \frac{V_+ + \rho_2 V_-}{e^{j\beta_e L} - \rho_1\rho_2 e^{-j\beta_e L}} \right| \quad (1)$$

with ρ_1, ρ_2 the input and output reflection coefficient, β_e the electrical propagation constant, L the electrode length and $V_\pm$ the phase relations of the forward and backward traveling-waves incorporating the velocity mismatch information. The frequency response is shown in Fig. 1c and agrees well with the measurements. A large-signal model with 32 unit cells of the discussed equivalent circuit has been implemented in ADS where the voltage drop along the depletion capacitance C_m is used to calculate the optical time-domain response to a PRBS input along the electrode length L. The simulated eye diagrams, as shown in Fig. 1c, exhibits similar rise and fall times as the experimental one and agrees well after noise-loading the output. The presented equivalent circuit model can be used to accurately predict modulator frequency and time-domain behavior and its validity has been verified experimentally. The simulation methodology can be used together with full-wave electro-magnetic simulations to test future modulator designs for high-speed capabilities.

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