Equivalent Circuit Modelling of Electrical Crosstalk in Photonic Integrated Circuits

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ABSTRACT

In literature, the problem of equivalent circuit modelling of electrical crosstalk has already been debated with respect to microelectronics [1][2] but not in the field of microphotonics. In this paper, measurements performed on single and coupled Mach-Zehnder modulators (MZMs) are shown, and an equivalent circuit model that can take into account the electrical crosstalk between two close-by MZMs is developed. This model is easily implementable in state-of-the-art circuit simulation tools and can help the user during the circuit design by estimating the level of electrical crosstalk between MZMs, using a physical model of the MZM with additional crosstalk parameters. In this way, it is also possible to simulate an arbitrary level of crosstalk and perform, for instance, an electro-optical analysis of coupled modulators.

Keywords: microphotonics, electrical crosstalk, PIC, MZM.

1. INTRODUCTION

The problem of electrical crosstalk has gained more attention in recent years with the rapid development of densely-integrated multi-channel transmitter and receivers [3][4]. With smaller devices and closer placement, one of the challenges is to be able to integrate multiple MZMs in a single photonic integrated circuit (PIC) without impacting its performance. In particular, this paper deals with measurements and simulations performed to develop an equivalent circuit model that takes into account electrical crosstalk in coupled MZMs; a simple yet effective empirical model will be obtained, which can be used to help the designer estimate the broadband behaviour of electrical crosstalk.

2. MEASUREMENTS AND MODEL EXTRACTION

At first, RF measurements are performed on single MZM, realized on the generic integration platform [2] in order to validate the already developed equivalent circuit model [3]; scattering parameters are obtained for modulators with different width, length and waveguide structure. Next, these parameters are converted to ABCD parameters in order to be able to extract the characteristic impedance and propagation constant of the device; with these two, it is possible to extract an estimation of the equivalent circuit parameters [5]. These values are later inserted in an equivalent circuit model developed for similar modulators [3] in a circuit simulation tool and an optimization algorithm is used in order to fit the simulations to the measurements and extract the final equivalent circuit parameters. Figure 1 shows the agreement between the measurements and simulations on a COBRA modulator with shallow waveguide structure, contact width of 11 μm and length of 450 μm.

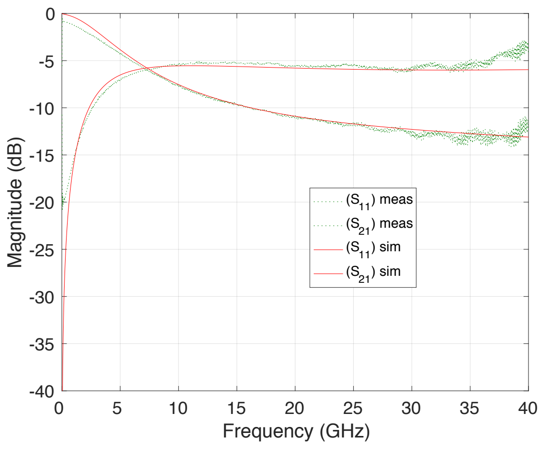

Figure 1: Comparison of the scattering parameters measured and simulated on a COBRA modulator

The broadband behaviour is correctly reproduced by the equivalent circuit model, confirming its validity.

Closely spaced modulators can experience crosstalk through the substrate or through a radiative path. Additional measurements and simulations were carried out on different PICs to measure the substrate crosstalk between RF probing pads and both the radiative and substrate crosstalk between coupled MZMs. In the COBRA platform, the substrate can be modelled with a resistive network where the capacitance between the metal top contact and the substrate needs to be taken into account; moreover, the potential difference and current introduced by the electro-magnetic field of the neighbouring device can be considered by inserting a mutual capacitance and inductance to account for radiative crosstalk.

A sample PIC was used to perform substrate crosstalk measurements by applying an RF signal to a pair of ground-signal-ground (GSG) pads. Considering how the substrate can be modelled, an equivalent circuit was designed in a circuit simulation tool to give a broadband estimation of the magnitude in dB of the S21, measured between the pads. The substrate resistive network was initially evaluated thanks to the substrate resistivity, the distance between the pads and the pad area; then, an optimization algorithm adjusts these values to match with the experimental data.

Next, radiative crosstalk and substrate crosstalk were measured and simulated in the ADS circuit simulator for coupled MZMs with different separation distances. In this case, a 4-port measurement has to be performed and substrate crosstalk has to be considered between each pair of GSG pads but also between the two coupled modulators; for this reason, substrate resistances were added in the model together with a capacitor parallel to the depletion capacitance that models noise injection into the substrate. Electrical crosstalk was included by adding a capacitor between the modulators and a mutual inductance. Figure 2 shows the developed equivalent circuit:

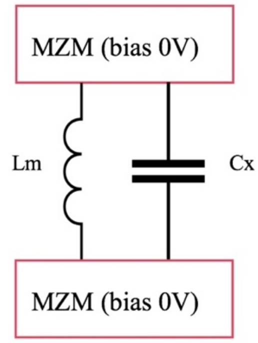

Figure 2: Schematic representation of the equivalent circuit model developed for the description of radiative crosstalk between MZMs

Again, using the same optimization algorithm it was possible to achieve a good broadband estimation of the measured electrical crosstalk level; in Figure 3, the measured and simulated crosstalk for two MZMs separated by a distance of 115 µm is plotted:

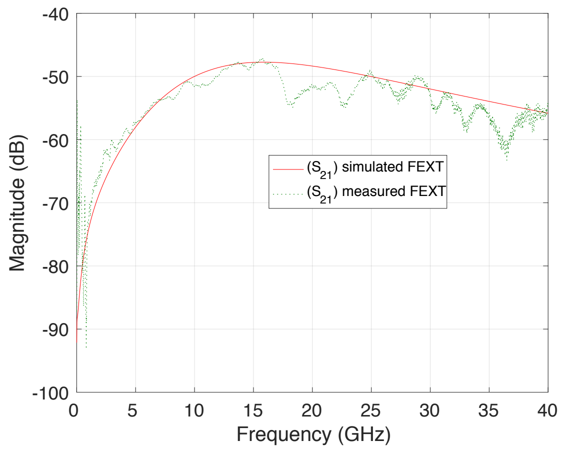

Figure 3: Measured and simulated crosstalk on two coupled modulators separated by a distance of 115 µm

The RF peaks are most probable caused by unwanted reflections experienced by the electrical signal propagating through the electrode. This is not reproduced in the simulator ADS, as we did not account for impedance mismatching. A value of 29.17 fF/mm was found for the mutual capacitance and a coupling factor of 0.02 was found for the mutual inductance, leading to a good broadband match of experiment and simulation.

3. ELECTRO-OPTICAL ANALYSIS

Thanks to the developed equivalent circuit model, it is possible to perform an electro-optical analysis, that relates the optical output pattern to its electrical input signal [3]. In fact, the electrical signal changes its amplitude along the electrode line and suffers from degradation during the propagation due to transmission line losses: its signal quality is best at the start [3]. For this reason, in case of velocity match between the optical and electrical signal the electro-optical output should be better than the electrical signal output and their quality can be compared by the evaluation of an eye diagram. However, it is still reasonable to make a comparison between the two eye diagrams since the two signals co-propagate throughout the modulator and the optical signal can be affected by the electrical signal [3]. This type of analysis can be easily implemented in a circuit simulation tool to estimate the eye diagram at the output and see how the eye opening and jitter are affected by the crosstalk.

A transient simulation involving two coupled modulators was arranged. A thousand bits on each modulator are sent with a bitrate of 6 Gbps; the two sources are fully de-correlated. Velocity mismatch was determined to be around 20 ps and not considered critical since it is much lower than the bit period (200 ps). The electrical eye diagrams at the electrode end and the optical modulated output eye diagrams are plotted for two coupled MZMs with electrical crosstalk up to -50 dB in Fig. 4:

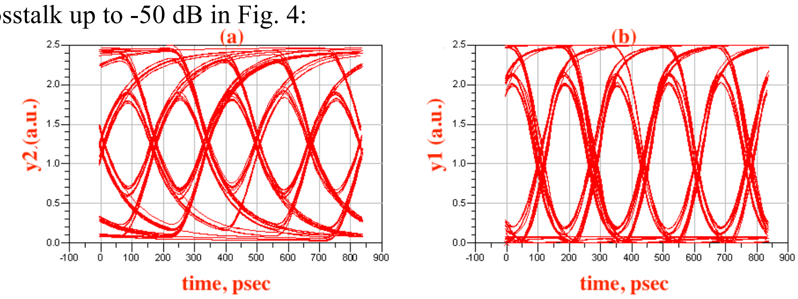

Figure 4: Comparison between electrical eye diagram (a) and electro-optical eye diagram (b) with crosstalk between MZMs up to -50 dB

The two diagrams have similar rise times and jitter. The crosstalk is not affecting the system performance in this case, since it is very low. If the crosstalk is set to -20 dB by changing the radiative crosstalk parameters (Cx set to 21.54 fF/mm and coupling factor between inductors to 0.35), two different eye diagrams can be obtained as shown in Fig. 5:

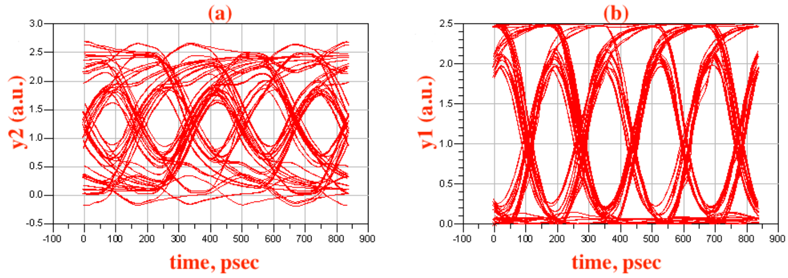

Figure 5: Comparison between electrical eye diagram (a) and electro-optical eye diagram (b) with crosstalk between MZMs up to -20 dB

Comparing Figure 4b to Figure 5b, it can be seen that the electro-optical eye diagram shows more distortion and more jitter in presence of crosstalk. It can be concluded that our model can estimate the time-domain impact of electrical crosstalk using the equivalent circuit approach.

4. CONCLUSIONS

We have measured the electrical crosstalk between modulators and test structures on PICs fabricated in the generic integration platform and developed an equivalent circuit model; the simulations showed good agreement with the measurements, demonstrating that the equivalent circuit allows for a broadband estimation of the level of crosstalk. Moreover, we presented an electro-optical analysis that uses this model to estimate the time-domain performance of two coupled MZMs in presence of electrical crosstalk; A high crosstalk level (-20 dB) clearly limits the modulator performance through increased distortion and jitter.

REFERENCES

[1] S. Choi *et al.*: An Efficient Crosstalk-Included Eye-Diagram Estimation Method for High-Speed Interposer Channel on 2.5-D and 3-D IC, *IEEE Transactions on Electromagnetic Compatibility*, vol. 59, no. 3, pp. 927-939, June 2017.

[2] A. Sathish *et al.*: Crosstalk reduction technique on data-bus in DSM technology, *2011 International Conference on Signal Processing, Communication, Computing and Networking Technologies*, Thuckafay, 2011, pp. 486-489.

[3] Weiming Yao: Towards a High-Capacity Multi-Channel Transmitter in Generic Photonic Integration Technology, PhD thesis, Technische Universiteit Eindhoven, 2016.

[4] Meint Smit *et al.*: An introduction to InP-based generic integration technology, *Semiconductor Science and Technology*, vol. 29, no. 8, June 2014.

[5] S. Irmscher: Design, Fabrication and Analysis of InP-InGaAsP Traveling-Wave Electro-Absorption Modulators, Ph.D. dissertation, Royal Institute of Technology (KTH), 2003.