Measurement-based models of a 40 Gb/s modulator and its electrical driver for joint transmitter design

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***Abstract* — A measurements-based model of Mach-Zehnder electrooptic modulator and of its electrical driver are proposed. These models are essential for concurrent design of the two devices, and allow careful optimisation of the overall performance of the 40 Gb/s transmitter. The design of a travelling wave driver amplifier for a given fabricated modulator has been performed by using the proposed models. An improvement of about 6 dB has been obtained for the extinction ratio with respect to a previously designed 7 Vpp driver.**

I. INTRODUCTION

$LiNbO_3$ Mach-Zehnder modulators (MZM) are widely used in long-haul optical transmission systems operating at λ = 1.55 μm for their capability of controlling the frequency chirping [1]. III-V technologies are used for MZM driver amplifiers [2]-[4] due to the challenging requirements in terms of frequency response and output swing. Therefore, even if some attempts to fabricate HBT devices and EAM on the same substrate are being investigated [5], the cores of 40 Gb/s transmitters (i.e. the optical modulator and its electrical driver) are currently designed in different technologies. The design of the two devices has to be performed concurrently in order to optimise the performance of the overall transmitter. However, the driver is usually designed for a 50 Ω load, whereas lower values of the input impedance are often found for the MZM: a degradation of the extinction ratio (ER) can result because of the mismatch between the two devices, even if high output dynamic values are found at 50 Ω termination.

Several MZM models have been developed in recent years, based on geometrical and technological parameters [6]-[7] and on finite-elements approaches for quasi-static analysis or full-wave analysis of coplanar waveguides. Empirical equivalent models have been also developed to permit straightforward implementation within commercially available CAD tools [8]-[10]. However, to the best of our knowledge no joint model suitable to be used for analysis and design of the driver and the modulator within commercial CAD tools has been proposed. In this paper, we propose measurement-based models of the MZM and of the driver which allows their concurrent design. The models can be used to design each of the two devices when the simulated or measured performance of the other is available, as well as to simulate the performance of the overall transmitter in terms of eye-diagram at each section and ER. Here, the design of a distributed driver amplifier is presented, based on the model of a 40 Gb/s MZM fabricated in Corning-OTI laboratories. The proposed models are also used to simulate the overall performance.

II. THE DRIVER AMPLIFIER MODEL

The model of the driver amplifier is based on both non-linear frequency-domain measurements (or simulations) of the driver itself, and input impedance characterisation of the MZM. In this work, the model has been validated for NRZ pseudo-random bit sequence up to 40 Gb/s. The output response to an input bit sequence is determined by evaluating the Fourier coefficients of the fundamental frequency f_0 contained in the bit stream, and of k harmonics 2 f_0, 3 f_0, ..., k f_0. The fundamental frequency of the bit sequence f_0 is the ratio of the bit-rate to the pattern length. The evaluation of the Fourier coefficients is performed by means of a Harmonic Balance (HB) simulation of a block containing the measured or simulated large-signal S-parameters of the driver. The structure of the model is shown in Fig. 1. The overall response is found by summing the single harmonic contributions through ideal Voltage Controlled Voltage Sources (VCVS´s), the ideal amplifiers A_V at the output side in Fig. 1. The input impedance $Z_{in}(f)$ of the modulator is used as a load for each of the blocks. The bit-sequence source model contains its internal impedance Z_S. Ideal VCVS´s are also used at the input side to decouple each of the blocks which evaluate the Fourier coefficients from the pattern generator, and the impedance Z_S is considered as at the source impedance of each block.

III. THE MODULATOR MODEL

The non-linear dispersive model of the MZ modulator has been proposed in [11] and is reported in Fig. 2. S-parameter matrices are provided to model each of the three parts of the modulator:

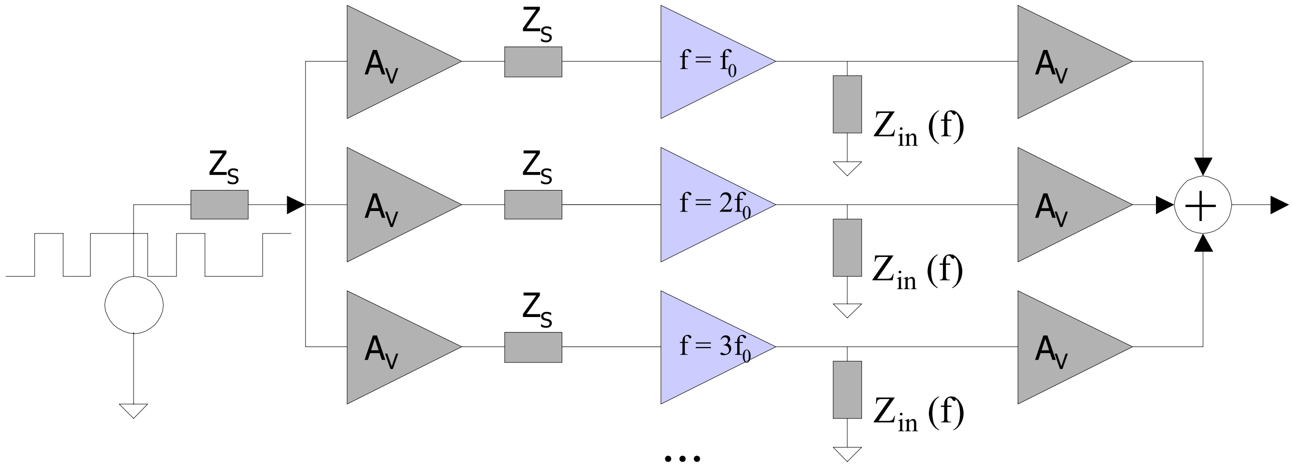

Fig. 1. Block scheme of the driver amplifier model.

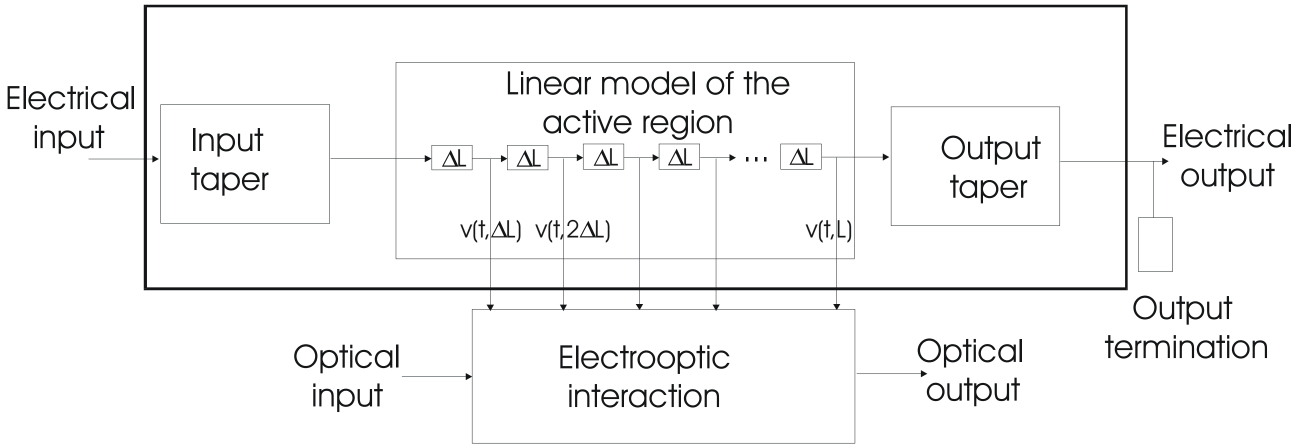

Fig. 2. Block scheme of the modulator model.

the input taper which matches the 50 Ω electrical coplanar input to the lower impedance active region, the active L-length coplanar region where the electrooptic interaction occurs, the output taper with load termination. An empirical measurement-based model has been used to describe the propagation of the electric field E(t,y) within the three sections of the modulator: the time-domain voltage $v_{1,2}(t,y)$ at the position y of each of the two branches at each section is computed by means of the pulse response evaluated from measured S-parameters. The optical field $E_{out}(t)$ at the output of the modulator is evaluated as follows:

$$E_{out}(t) = E_{in}(t-\tau_g)\cdot e^{j\omega_0\cdot(\tau_g-\tau_f)}\cdot\frac{e^{-j\omega_0\cdot\delta\tau_1}+e^{-j\omega_0\cdot\delta\tau_2}}{2} \quad (1)$$

where ideal 3 dB power splitting/combining is considered at the input and the output of the modulator, τ_f and τ_g are the phase and the group delay, respectively. $E_{in}(t)$ is the optical field at the input of the modulator, for which the spectral density width of both the amplitude function $A_{in}(t)$ and the phase function $\varphi_{in}(t)$ are much lower than ω_0.

The phase shift $\delta\tau_{1,2}$ in a ΔL-length coplanar section is evaluated as a function of the voltage $v_{1,2}(t,y)$ of the electrodes 1,2 as:

$$\delta\tau_{1,2}(t) = -\frac{\pi}{LV_\pi}\sum_{m=1}^{L/\Delta L} v_{1,2}\left(t-\frac{L-m\cdot\Delta L}{c}n_e, m\cdot\Delta L\right)\Delta L \quad (2)$$

where V_π is the half-wave voltage at DC which can be measured, and n_e is the effective index of the guided mode. ΔL is chosen much shorter than the line attenuation parameter α, so that the voltage $v_{1,2}(t,y)$ can be considered as a constant within each ΔL-length coplanar section. A single-mode propagation regime and a transmission line model have been assumed for the L-length coplanar section. The S-parameters matrix of a L-length coplanar line modelled as a transmission line, can be expressed in terms of α, β, and the reflection coefficient ρ which takes into account the mismatch between the line impedance Z_c and the input/output probe tips (impedance Z_0). The attenuation and the propagation constants α and β are evaluated at each frequency by means of measurements performed on two structures with identical input and output tapers and different lengths as proposed in [12].

	G_{DC} (dB)	f_{-3dB} (GHz)	S_{11} (dB)	S_{22} (dB)	ER (dB)
50Ω Driver	16.2	35	<-9 up to 29 GHz	<-9 up to 57 GHz	16.6
Redesigned Driver	17.0	41	<-9 up to 28 GHz	<-15 up to 42 GHz	22.5

TABLE I

SIMULATED PERFORMANCE OF THE TWO DESIGNED MODULATOR DRIVERS

IV. CAD IMPLEMENTATION AND SIMULATION

The models of both the modulator and the electrical driver have been implemented in the Agilent - Advanced Design System tool. In the driver model, the block which evaluates the single Fourier coefficients has been implemented by means of the block *AmplifierP2D*. This predefined block calculates the output power of an amplifier at a prespecified frequency, by using the measured or simulated large-signal S-parameters stored in a file. A file containing the input impedance of the modulator is also needed to determine the driver model.

A file containing the small-signal S-parameters of each of the tree sections, the values of V_π and n_e, are required to compose the modulator model. For time-domain or HB simulations of the modulator model, the pulse response of the ΔL-length sections is evaluated from frequency-domain models based on S-parameter tables determined as described above.

V. DESIGN OF A 40 GB/S DRIVER

The model of a z-cut Mach-Zehnder modulator with V_π=5V, designed and fabricated at Corning-OTI laboratories, has been extracted and used to design a driver amplifier for NRZ 40Gb/s systems, in the D01AH P-HEMT process from OMMIC. A minimal 20 dB ER has been set as the design goal. A first driver was originally designed to match a standard 50 Ω load. The driver is composed of two 5-stage TWA´s sharing a common drain line, and an active divider that provides two identical input signals for the two TWA´s. The TWA is composed of 30 µm FET cascode cells with a RC network for the biasing of the upper FET gate. The active divider consists of two source follower stages for each gate line of the two TWA´s, thus providing decoupling and current gain.

All signal interconnections were realised as coplanar lines. Simulation results for this circuit were presented in [13]. The complete circuit, fitting on 3x1 mm^2, has been fabricated as a prototype and is currently being measured in our laboratories. A model of the driver has been extracted in order to simulate the overall transmitter. In Fig. 3 the simulated time-domain waveforms at the driver-modulator interface are shown for both the model and the circuit, denoting excellent accordance. Simulation of the transmitter with a jitter-free pseudo-random 40 Gb/s input signal (see the normalised optical eye-diagram in Fig. 4) has highlighted sub-optimal modulation capability in spite of the high output voltage, due to the mismatch between the two devices: an ER of 16.6 dB has been found in spite of more than 7 Vpp output swing measured for 50 Ω termination load. Therefore, a re-design of the driver has been performed by using the modulator model. Some S-parameters of the driver and the ER at the output of the modulator are reported in Tab. 1 for both the original and the re-designed driver amplifiers.

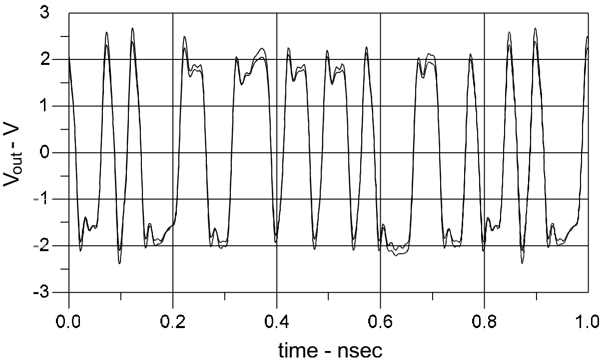

Fig. 3. Simulated time-domain waveforms (with driver model and circuit) at the driver-modulator interface.

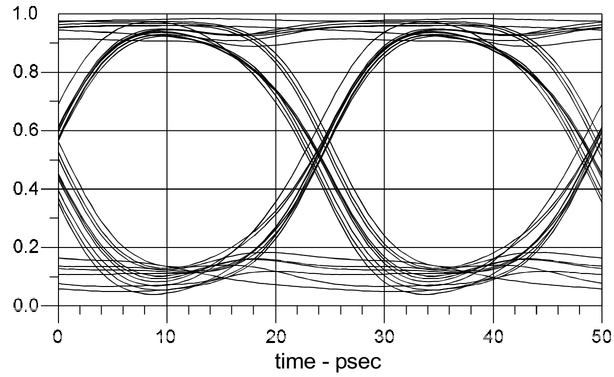

Fig. 4. Normalized optical eye-diagram at the output of the original transmitter.

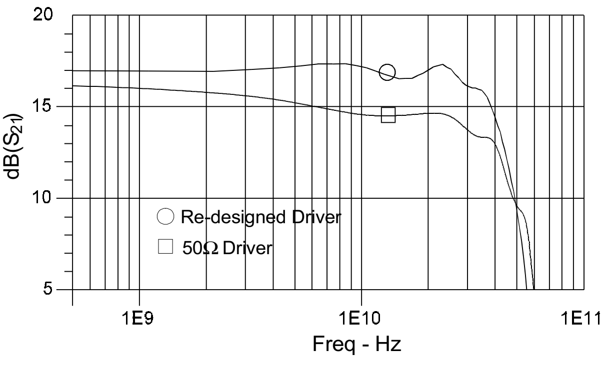

Fig. 5. S_{21} of both the original and the re-designed drivers.

The S-parameters have been evaluated on a 50 Ω termination at the input, and on the input impedance of the modulator at the output. In Fig. 5 the magnitude of S_{21} of both the original and the re-designed drivers are shown: an improvement of 1 dB in the low-frequency gain, and of 6 GHz in the f_{-3dB} bandwidth have been found. In Fig. 6 the normalised optical eye-diagram at the output of the transmitter is reported, denoting 22.5 dB of ER.

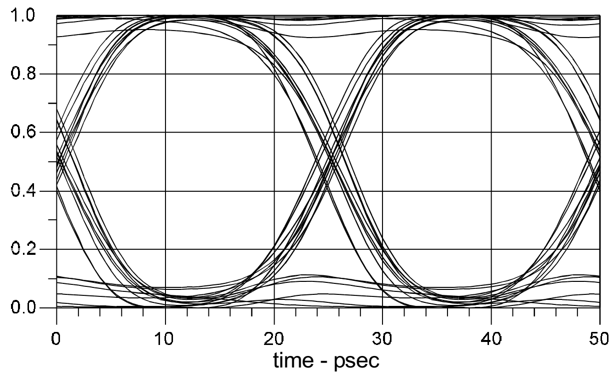

Fig. 6. Normalized optical eye-diagram at the output of the re-designed transmitter.

VI. Conclusion

A measurement-based model of a Mach-Zehnder modulator and the driver for 40 Gb/s optical transmission systems has been proposed and implemented in Agilent - Advanced Design System tool. The models have been used to design a driver in GaAs P-HEMT technology. The driver is composed of an active divider and a dual-input travelling wave amplifier. The model has proven to be essential for the optimization of the performance of the overall transmitter which shows 22.5 dB of simulated Extinction Ratio for a jitter-free pseudo-random 40 Gb/s input signal.

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