A new, compact model for high-speed electro-optic modulators fully integrated within a microwave CAD environment

Paolo Zandano, Marco Pirola and Giovanni Ghione,
Dipartimento di Elettronica, Politecnico di Torino Corso Duca degli Abruzzi 24, 10129 Torino, Italy

Abstract— **A compact model is presented for high-speed electro-optic modulators fully integrated within the framework of a microwave circuit design suite (MWOFFICE of AWR). Starting from geometrical and layout parameters, the model allows both simple (travelling wave) and complex (phase reversal, periodically loaded) structures to be analyzed and optimized from the standpoint of the electro-optic response both in small-signal (analog) operation and in large-signal (digital) operation exploiting standard simulator tools, including the Monte Carlo statistical analysis of device yield and sensitivity. Finally, the new model allows the designer to include, at no additional effort, parasitic and passive elements (such as optical or electrical delay paths) in the modulator model to account for the effect of tapered transitions and packaging. Comparisons with literature data and design examples are presented to validate the approach and stress its potential in the design of high-speed structures on $LiNbO_3$ substrates.**

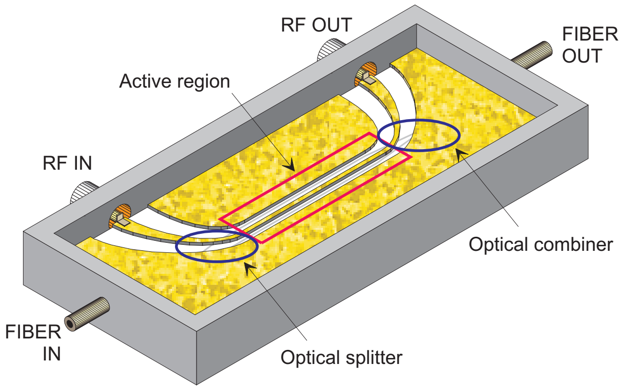

Fig. 1. Packaged electro-optic Mach-Zehnder amplitude modulator structure.

I. INTRODUCTION

High-speed fiber transmission systems are now moving towards the 40 Gbps goal; at the same time, new narrowband RF-on-fiber approaches are being investigated with centerband frequencies in the microwave and mm-wave range. In such systems, the analog and/or digital RF modulation of the optical signal plays a crucial role. At present, external modulation through electro-optic or electro-absorption modulators (EAM) seems to be the most effective solution in terms of modulation bandwidth and other system requirements. Although EAMs are appealing in terms of device size, cost and integration, electro-optic modulators still are considered superior, e.g. from the standpoint of chirping. The present paper will therefore focus on the modelling of electro-optical (e.g. lithium niobate) amplitude modulators.

High-speed electro-optic modulators are distributed structures, wherein a microwave signal travels along a transmission line interacting with an optical waveguide. The microwave field modifies the optical refractive index through the electro-optic effect, and two phase modulated optical beams can be made interfere, thus achieving amplitude modulation. An example of the resulting Mach-Zehnder amplitude modulator in packaged form is sketched in Fig. 1.

The microwave design of the active interaction region affects the modulator performances both in terms of modulation bandwidth and of driving voltage amplitude (on-off voltage or V_π). Moreover, optimization of the modulator cross-section alone, which can be obtained through electromagnetic analysis tools based on quasi-static or full-wave approaches (see e.g. [1] and references therein), does not completely solve the overall design problem. In fact, even in simple travelling-wave modulators, parasitic effects arise due to transitions, bends, tapers, real loads, and other package-related features. The situation is much worse when complex, non-uniform modulators are to be designed, such as *phase-reversal* modulators [3], wherein the optical-microwave interaction has to be modulated in each modulator section according to a global requirement concerning the frequency response, or *periodically loaded* [4] modulator structures, wherein modulating line sections are periodically sandwiched between delay blocks, such as transmission line stubs, so as to achieve narrowband synchronous coupling. Although approximate design strategies have been suggested for phase-reversal or periodically loaded modulators, and *ad hoc*, stand-alone models have been proposed for simple travelling-wave structures [2] there is a complete lack, as far as the authors' knowledge goes, of a global CAD modulator model fully integrated within an integrated microwave circuit design environment and able to carry out the analysis (small-signal or large-signal, for analog and digital applications, respectively) and geometrical optimization of arbitrarily complex modulator structures.

In the present paper, we propose a new CAD modulator model able to predict the device response starting from the layout and line geometry. The model has been implemented as a user-defined component within the framework of the MWOFFICE *design suite* produced by AWR Inc. The model structure, discussed in Sec. II, allows for frequency-domain small-signal and large-signal (HB) analysis, tuning, optimization, coupling with internal or external EM models for transitions or other critical features, yield and sensitivity analysis with respect to geometrical parameters. After a few details concerning the implementation (Sec. III), the model capabilities are investigated in Sec. IV, where several design examples taken from the literature are easily reproduced within the CAD environment.

0-7803-6540-2/01/$10.00 (C) 2001 IEEE

II. THE MODEL

The theory of electro-optical interaction within a distributed structure is well established. The microwave signal guided by a coplanar transmission line interacts with the optical signal, causing it to be phase-delayed. The phase achieved by a line section depends on the line voltage (i.e. the microwave field), the line length, and the relative velocities of the microwave and optical signals. Interference between phase-delayed signals, obtained through an optical combiner, leads to amplitude modulation. In small-signal conditions (i.e. superposing a microwave modulating signal to a DC bias) the amplitude modulation index $m(f)$ depends on the modulation frequency, yielding the modulator frequency response, which can be shown to be equal to the phase modulation frequency response. However, as a whole the amplitude modulator response is non-linear, since optical interference leads to a raised cosine law with respect to the normalized input modulator voltage V/V_π. Analog modulators are polarized at $V_\pi/2$ to work with optimum linearity in small-signal conditions.

Although analytical expressions for the small-signal frequency response of an uniform modulator line with known load and generator impedances are easily derived as a combination of two sinc functions of frequency, and are widely exploited for modulator *ad hoc* optimization, the development of a general model must start from a more general standpoint, since a basic difficulty has to be solved: the fact that interferometric modulators are *both* nonlinear and dispersive in the electro-optic response. Moreover, the modulator model must be local, i.e. it must depend on the input and output total voltages rather than on generator and load conditions, which have to be imposed at a network level. Finally, a suitable pseudo-electrical model has to be investigated for the optical line, since this component does not exist as such in microwave CAD environments.

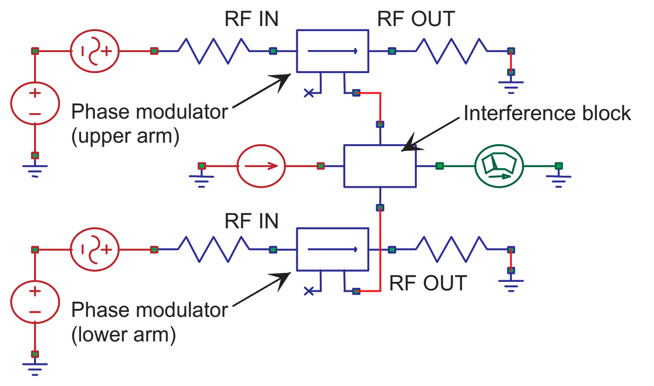

Fig. 2. Schematic of a generic Mach-Zehnder amplitude modulator with two phase modulating paths showing the phase modulation and interference blocks.

The above issues have been solved as follows in the present approach. The global amplitude modulator is simulated by two separate devices:

• The first device is a four-port (two electrical, two pseudo-optical) driven by the port electrical voltages, which provides, at the output pseudo-optical port, the total *phase* optical modulation of the optical signal resulting from the phase modulation of the input signal and of the phase modulation of the modulator section. The output optical phase modulation results in terms of a phase-modulated pseudo-RF current signal having the same frequency as the input RF signal but propagating at the velocity of the optical signal. Phase modulators can be cascaded and/or intermixed with other circuit elements (delay lines, stubs, transitions etc.) thus generating a global phase modulation according to an optical signal path. This first device will be referred to as *phase-modulation block* (PM block).

• The second device is a four-port, having as inputs two pseudo-electrical signals carrying the information of phase delay according to two different paths and a pseudo-electrical DC signal carrying information on the input optical power; the output is a pseudo-electrical amplitude-modulated DC signal describing the optical output power resulting from interference. This second device will be referred to as *interference block*.

The two blocks (PM and interference) can be exploited to simulate a simple amplitude modulator with two different phase modulation paths according to Fig. 2. If the modulator is symmetric, only one path is simulated and the interference block automatically assumes as the second input the first, but with opposite phase difference.

Concerning the PM block, this basically is a transmission line section from the standpoint of the microwave circuit. It can be readily shown that phase modulation can be directly expressed as a function of the driving voltages in closed form starting from the transmission line parameters, the section length and the optical signal velocity; the detailed expressions are omitted here for brevity. The resulting device is *linear* but *frequency dispersive*, i.e. with memory. The equivalent circuit of the PM block also includes a delay line, as sketched in Fig. 3, whose purpose is to simulate the delay introduced by the optical path on the optical signal even without the effect of phase modulation. Cascaded active regions therefore see a progressively delayed optical signal, associated to a pseudo-electrical RF signal.

The interference block implements a simple raised cosine transfer curve and is therefore *nonlinear* but *memoryless*. Notice that the input optical power is simply associated, in the interference block, to a DC electrical signal which is amplitude-modulated at the output.

Globally, therefore, the amplitude modulator is modelled as a cascade of modulating and/or non-phase modulating PM sections along two paths, and a device performing beam interference. If the modulator is symmetric, as often occurs, only one phase modulation path has to be modelled. Notice that optical, nonmodulating delay sections can be easily introduced without additional complexity. A schematic representation of the phase modulation and interference section is shown in Fig. 1 (right), together with the schematic of a simple uniform amplitude modulator resulting from the combination of two phase modulator paths and an interference block.

III. IMPLEMENTATION

The modulator elements (PM and interference blocks) have been implemented within the MWOFFICE design suite. Once linked as user-defined components, the new element can be directly linked to other RF components or even EM models. For the RF modulator coplanar line, an accurate closed-form analytical model has been implemented according to [1] based on

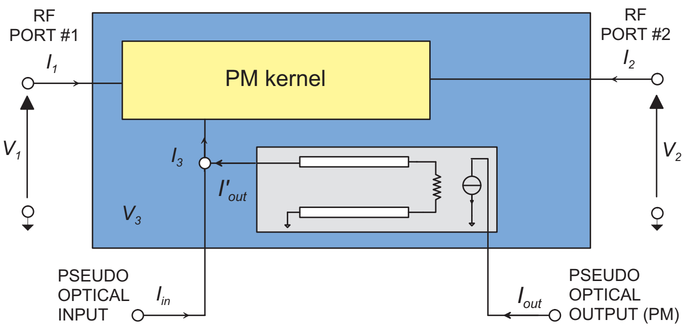

Fig. 3. Phase modulation block; the optical inputs and phase-modulated outputs are associated to proper RF currents so as to allow the block to work as a single frequency linear device.

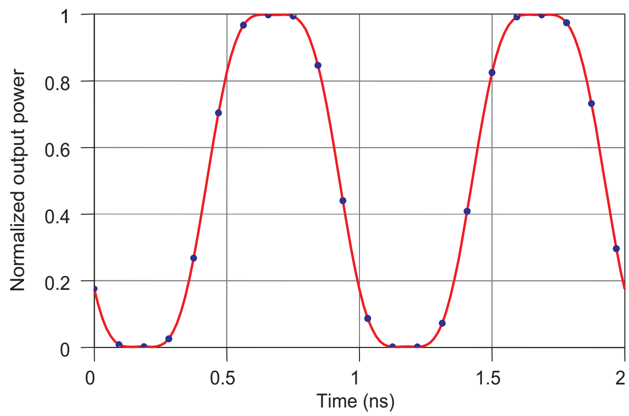

Fig. 4. Mach-Zehnder optical output power as a function of time. Analytical ideal results: markers, our approach with MWOFFICE: continuous line.

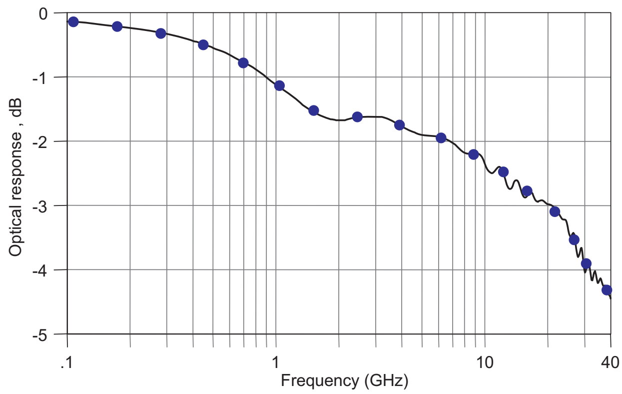

Fig. 5. Electro-optic response of the uniform modulator proposed by [2] and accounting for the package. Continuos line: this model, markers: Burns results.

a quasi-TEM approach, which allows optimization to be performed directly on the basis of physical parameters, at least for electrodes having rectangular shape. In the present version, the superposition integral between the optical and microwave fields has to be given as an input parameter, rather than evaluated from the RF line geometry and optical waveguide position; the development of a closed-form model is in progress.

The splitting of the modulator model in two parts, a linear but frequency dispersive and a nonlinear but memoryless allows the simulations to be easily performed within the MWOFFICE environment, both in small-signal conditions around a user specified bias and in nonlinear (large-signal) periodic regime, thus allowing distortion and intermodulation performances to be directly simulated together with system-oriented features like eye diagrams.

As a simple example, a travelling-wave modulator was designed for small-signal operation with a modulation bandwidth in excess of 10 GHz. Then, the modulator was biased at half V_π voltage and driven with a sine signal able to lead the modulator from the off to the on state. Since the signal frequency is 1 GHz, no low-pass effect is detected and the sine input signal is only distorted at the power output as the effect of the raised cosine interferometer characteristic. The result obtained from the simulator is reported in Fig. 4 under the form of the time evolution of the modulator output optical power. The result obtained analytically by filtering a sine curve through a raised cosine characteristic (dots) are in complete agreement.

Concerning the environment for the model development, MWOFFICE was chosen for its full integration into the Windows OS, since this package makes use of the Component Object Model (COM) architecture for interfacing with other ones. Specifically, for the generation of the model Dynamic Linked Library (DLL), to be used within the MWOFFICE executable kernel, COM resources were exploited to interface the high level C++ description finally implemented with the help of the MWOFFICE wizard tool. It should be noticed that, however, implementations of the model strategy within other design environments are also possible.

IV. Examples

Starting from the modelling approach presented, a virtually unlimited class of electro-optic modulators can be analyzed and designed within a single CAD environment, regardless of structure complexity, thus avoiding the development of *ad hoc* models and allowing parasitic elements or other layout features to be incorporated at no additional cost. Results relative to the analysis and optimization of some structures already documented in literature will now be presented; these are (1) a uniform in-package travelling-wave modulator analyzed by Burns [2]; (2) the phase reversal modulator proposed by Hui [3]; (3) the periodically loaded modulator proposed by Schaffner [4].

Concerning the travelling-wave modulator, the response as simulated by Burns [2] and the one obtained by the present approach, exploiting the same nominal parameters as in [2], are shown in Fig. 5; the agreement obtained is excellent for all the frequency range.

Several phase reversal modulator structures with a different number of section [3] were then simulated with the same parameters as in [3]; the comparison between the present approach and Hui's result is shown in Fig. 6; again, the agreement is excellent. An independent optimization of the response was then carried out with MWOFFICE (the optimization parameters were the superposition integrals of each section) in order to improve the response flatness; the result, in Fig. 7, shows improved performances with respect to the original one [3]. A Monte Carlo analysis was then performed with MWOFFICE to assess the sensitivity of the response with respect to a random variation of the section V_π; the result is reported in Fig. 8.

0-7803-6540-2/01/$10.00 (C) 2001 IEEE

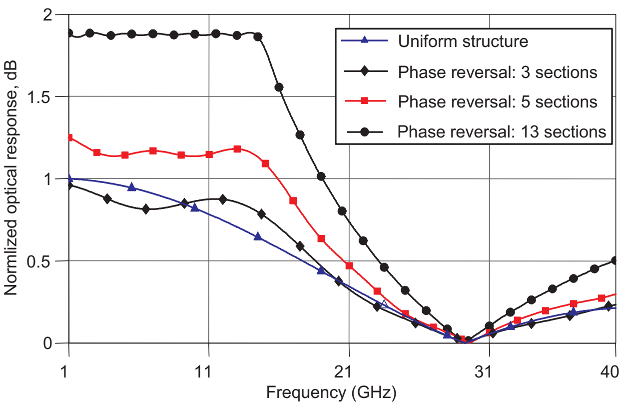

Fig. 6. Electro-optic response, normalized to the uniform structure low frequency response, of the phase reversal modulator proposed by Hui [3] for several section numbers. Lines: this model, markers: Hui results.

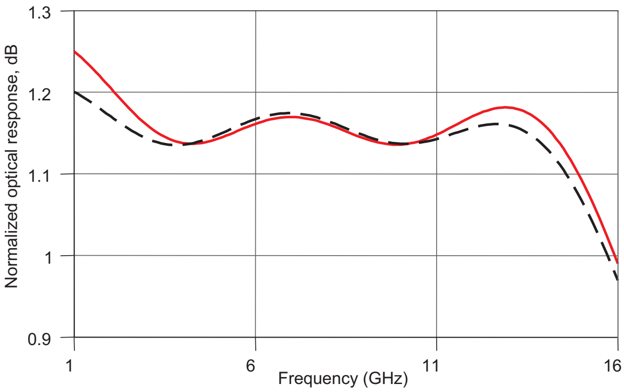

Fig. 7. Electro-optic optimization of the 5 section phase reversal modulator [3]. Continuos curve: Hui result, dashed curve: present approach.

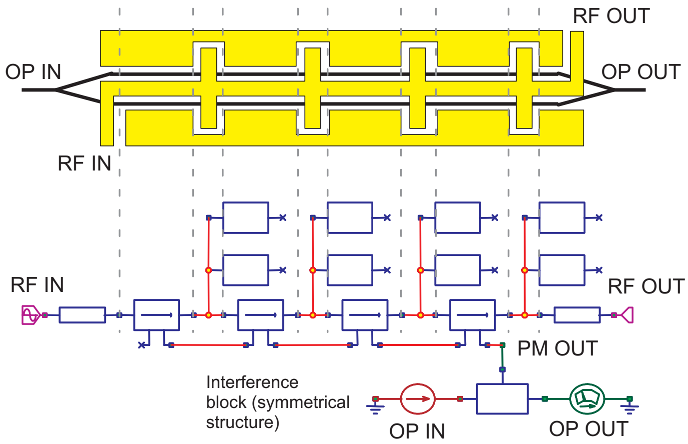

Fig. 9. Periodically loaded modulator [4] and its schematic representation.

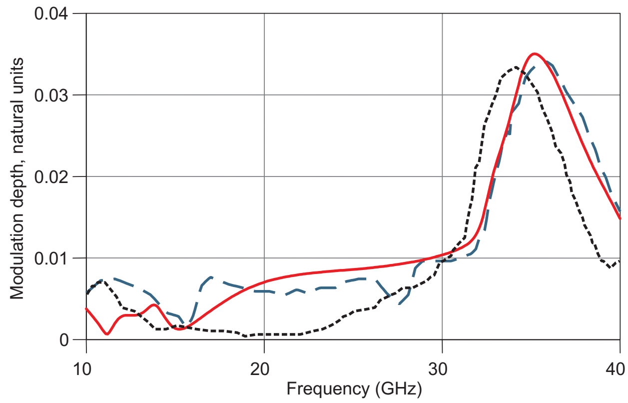

Fig. 10. Response of the six-section periodically loaded modulator reported in [4]. Continuous line: this work, Dotted curve: Schaffner simulated response, dashed curve: measurements.

The last structure considered is the periodically loaded modulator reported in [4], reported in Fig. 9 with the schematic. The frequency response simulated with MWOFFICE is compared in Fig. 10 with the experimental and simulated data from [4], with good agreement. The modulator was simulated from the geometrical parameters in [4] and exploiting the CPW model in [1].

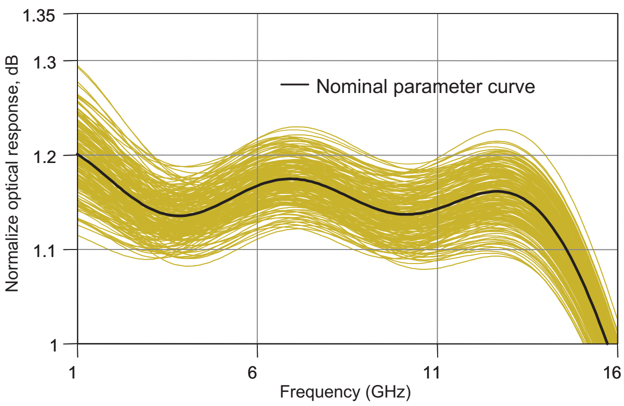

Fig. 8. Monte Carlo simulation the 5-section phase reversal modulator [3], changing V_π ($\pm$ 5%) for each section around its nominal value.

V. Conclusions

A full small- and large-signal model for electrooptic modulators running within a CAD environment for circuit analysis and optimization has been presented, together with a few examples of application. Future work will concern model refinements (e.g. the evaluation of frequency chirping and the closed-form implementation of the overlap integral) and the extension to the EAM case.

Acknowledgements. This research was partly supported by the CNR project MADESS II. The technical support from the AWR staff is kindly acknowledged.

References

[1] G. Ghione et al., "Microwave Modeling and Characterization of Thick Coplanar Waveguides on Oxide-Coated Lithium Niobate Substrates for Electrooptical Applications", *IEEE Transactions on Microwave Theory and Techniques*, pp. 2287-2293, Vol. 47, NO. 12, December 1999.
[2] W.K. Burns et al., "Modeling of Broad-Band Traveling-Wave Optical-Intensity Modulators", *IEEE Transactions on Microwave Theory and Techniques*, pp. 860-864, Vol. 48, NO. 5, May 2000.
[3] K.W. Hui et al., "Electrode Optimization for High-Speed Traveling-Wave Integrated Optic Modulators", *Journal of Lightwave Technology* pp. 232-238, Vol. 16, NO. 2, February 1998.
[4] J.H. Schaffner et al., "Velocity-Matching in Millimiter Wave Integrated Optic Modulators With Periodic Electrodes", *Journal of Lightwave Technology*, pp. 503-511, Vol. 12, NO. 3, March 1994.