COMPUTER-AIDED DESIGN AND ANALYSIS OF LIGHTWAVE/MICROWAVE SYSTEMS

Tianrong Zhang, Ross Hicks
Compact Software Inc.
483 Mclean Blvd & Corner of 18th Avenue, Paterson, N.J. 07504

Rodney S. Tucker
Dept. of Electrical and Electronic Engineering
University of Melbourne, Parkville Vic 3052, Australia

Abstract

This paper describes algorithms and techniques for the computer-aided design and analysis of optoelectronic circuits for microwave applications. Linear and non-linear analysis methods for hierarchically structured multiport microwave circuits with arbitrary topology have been extended to include optoelectronic device models. Ideal control sources are often used in modelling optoelectronic and optical components, and sometimes introduce problems to nodal analysis and harmonic balance methods. The paper will show how these difficulties can be overcome and how lightwave/microwave circuits can be efficiently analyzed. As an example, a novel lightwave/microwave transceiver module has been analyzed and optimized for large-signal operation at microwave frequencies.

Introduction

Optical links are finding increasing application in microwave systems. As lightwave device technology matures and operation in the microwave region becomes possible, there is an increasing need for computer-aided design tools to design lightwave/microwave systems [1]. A variety of modelling techniques for laser diodes [2,3], light emitting diodes [4], optical fibers [5 - 8], and photodetectors [9] have been reported for a number of years. The large-signal modelling of some active optoelectronic devices and non-linear analysis methods for the equivalent circuit of laser diode have been investigated [10,11,12]. Commercial microwave CAD tools such as SuperCompact and Touchstone have also been used as an aid to the design of linear optoelectronic systems [13,14].

The representation of 'optical power' by 'electrical voltage' [3] enables equivalent circuits to be derived from the optical rate equations, and it has opened up the opportunity to develop general purpose CAD tools for hierarchically structured multiport lightwave/microwave systems with arbitrary topology. In this paper, we discuss some algorithms and techniques used to implement optical models and analysis methods into a CAD microwave program based on nodal formulation and the harmonic balance method.

Optoelectronic Models in Nodal Analysis

The nodal admittance formulation is a widely used method for the analysis of electrical linear circuits and networks due to its effectiveness and convenience. Since this method is based on an easily filled admittance matrix representation and leads to sets of linear algebraic equations in the case of frequency domain analysis of linear networks, it is best suited to computer-aided design applications of electrical circuits and networks. In addition, in nodal formulation, the noise analysis of a linear multiport microwave network with arbitrary topology can be simultaneously carried out with the conventional analysis of the circuit.

However, the models of optoelectronic components and the transducers between optical power and the electrical signal usually include ideal control sources. Admittance representations do not exist for these two-ports ideal sources. More generally speaking, since there is no analog to 'current' at the optical side, the nodal admittance analysis will break down during analysis of any subcircuit with optical external ports.

In order to overcome this difficulty, a small resistance can be added to the optical part of the equivalent circuit. However, this introduces the unnecessary numerical error to the analysis. The error will be amplified in a complicated CAD program and can become significant in some cases. For instance, inaccurately calculated currents from linear analysis will affect the convergence of nonlinear analysis of the microwave/lightwave system.

A method combining a hybrid matrix description with the modified nodal admittance analysis [15] to deal with these non-existing admittance situations has been used [16] for CAD of microwave circuits. We follow this method and implement it into the program for simulations of lightwave/microwave systems. An (n x n) dimensional hybrid matrix is used to describe n-port optoelectronic component (or subcircuit) and will be converted to generalized ((n+m) x (n+m)) dimensional admittance matrices during analysis. Here m is the number of extra internal nodes introduced to describe the non-existing admittance representation subcircuit and will be reduced during analysis [15]. After filling up these generalized admittance matrices with regular admittance matrices of other elements into a consolidation admittance matrix, the regular nodal analysis and noise analysis can be performed to obtain final results for lightwave/microwave systems. The optical power represented by voltages in optical side can be calculated from these hybrid matrices.

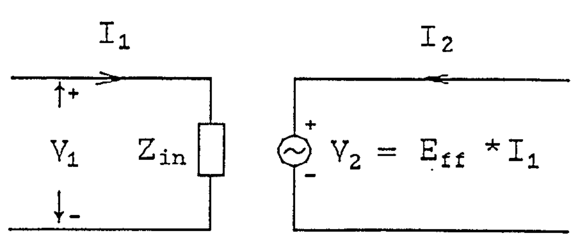

Figure 1 : Simplified Model of Laser Diode

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For example, a simplified linear model of the laser diode is shown in Fig. 1. This two-port component can be described by a hybrid matrix P:

$$P = \begin{bmatrix} 1/Z_{in} & 0 \\ E_{ff}/Z_{in} & 0 \end{bmatrix} \quad (1)$$

which is defined by

$$\begin{bmatrix} I_1 \\ V_2 \end{bmatrix} = P * \begin{bmatrix} V_1 \\ I_2 \end{bmatrix} \quad (2)$$

Here Z_{in} is the input impedance of laser diode and E_{ff} is the frequency dependent external quantum efficiency from microwave current to optical power. The variables I_1 and V_1 are current and voltage respectively at the electrical input of the laser diode. The voltage V_2 represents the output optical power from the laser diode. The current I_2 is meaningless to the optical domain. It is easy to see from (1) and (2) that there are no physical quantities of the laser diode which depend on I_2. We keep to use this notation only for mathematical purpose.

Hybrid matrix P in (1) will be converted to a 3 x 3 generalized admittance matrix Y :

$$Y = \begin{bmatrix} 1/Z_{in} & 0 & 0 \\ 0 & 0 & 1 \\ E_{ff}/Z_{in} & -1 & 0 \end{bmatrix}, \quad (3)$$

which is defined by

$$\begin{bmatrix} I_1 \\ I_2 \\ 0 \end{bmatrix} = Y * \begin{bmatrix} V_1 \\ V_2 \\ I_2 \end{bmatrix}, \quad (4)$$

Then matrix Y can be used for nodal formulation and the last dimension will be reduced after analysis.

Non-linear Analysis of a Complicated Optical Link

In previous works [10,11,12], the harmonic balance technique has been used only to analyze the equivalent circuits of laser diodes. The analysis has not included optical transmission components such as optical fibers and optical attenuators. The large-signal equivalent circuits of photodetectors have also been excluded in these analyses. In the present paper, we will show how the harmonic balance technique can be used for nonlinear analysis of a complete lightwave/microwave system with several nonlinear optoelectronic devices. For example, we consider the optoelectronic link as shown in Fig. 2, consisting of a nonlinear laser diode, optical fiber, and a nonlinear PIN photodiode.

Note that there are coupling losses between the laser and the fiber and the fiber and the PIN photodiode. These losses are modeled as the optical attenuators. In Fig. 2, optical fiber and optical attenuators are modeled by ideal voltage controlled voltage sources. The circuit has been partitioned into a linear subcircuit and a nonlinear subcircuit. There are three ports connecting linear and nonlinear subcircuits. The satisfaction of Kirchhoff's current laws requires that the currents into the linear subcircuit should be equal to the currents from the nonlinear subcircuit at three connected ports, i.e. using the notations and labels in Fig. 2, the following equations must be satisfied: $I_1=-\bar{I}_1$, $I_2=-\bar{I}_2$, and $I_3=-\bar{I}_3$. The linear current vector can be calculated from

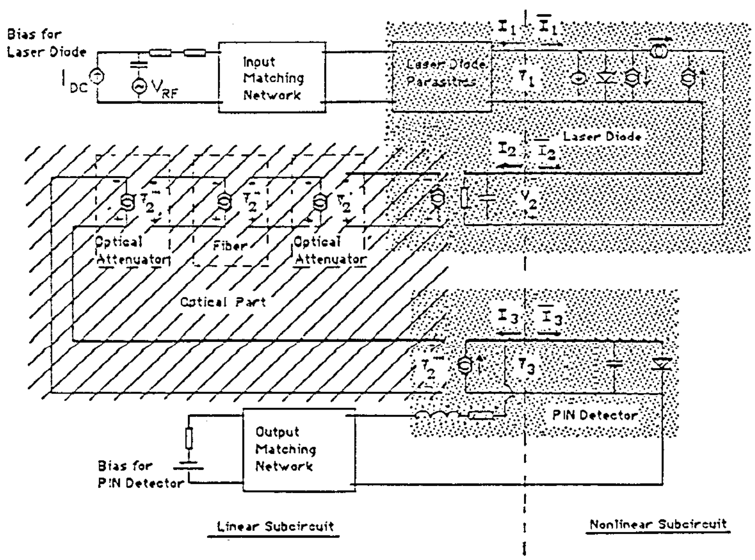

Figure 2: Equivalent circuit of a complete lightwave/microwave system with nonlinear laser diode and nonlinear PIN detector.

the port voltage vector, that has components V_1, V_2 and V_3, by multiplying an admittance matrix Y, which can usually be obtained from linear analysis.

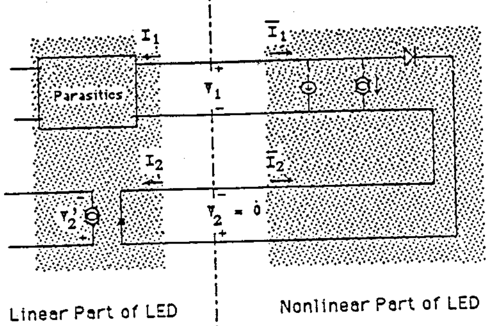

Figure 3: Equivalent circuit of nonlinear light-emitting diode.

It is obvious from Fig. 2 that the linear subcircuit of equivalent circuit for the microwave/lightwave system includes several ideal control sources with non-existent admittance representations. Linear analysis can be carried out by using modified nodal analysis method we discussed in previous section. As long as the overall admittance matrix Y exists, the conventional harmonic balance method can be used to analyze the system.

However, when the harmonic balance method is used for analyzing a complete optical link including at least a light-emitting diode, the admittance description of the linear subcircuit does not exist in this case. A hybrid representation for the linear part is obtained from a modified nodal analysis instead of admittance matrix which is necessary to calculate currents on the linear side in order to use harmonic balence technique.

For example, we consider an optoelectronic link modified from Fig. 2 by replacing the equivalent circuit of the laser diode by the equivalent circuit of LED, which has been shown in Fig. 3, consisting a nonlinear LED, optical fiber, and a nonlinear PIN detector. Since voltage V_2 is always zero in LED circuit, the Y matrix of linear subcircuit does not exist. This problem can be solved if we replace port voltage V_2 by voltage V_2', that is the 'analog' of output optical power of LED, and redefine the admittance matrix Y as:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = Y * \begin{bmatrix} V_1 \\ V_2' \\ V_3 \end{bmatrix} \qquad (5)$$

Analysis, Synthesis and Optimization of an Optical Link (An Example)

Finally, as an example, we analyze and design a novel directly modulated lightwave/microwave transceiver operating over the frequency range 3 to 6 GHz. The schematic of the link is shown in Fig. 2.

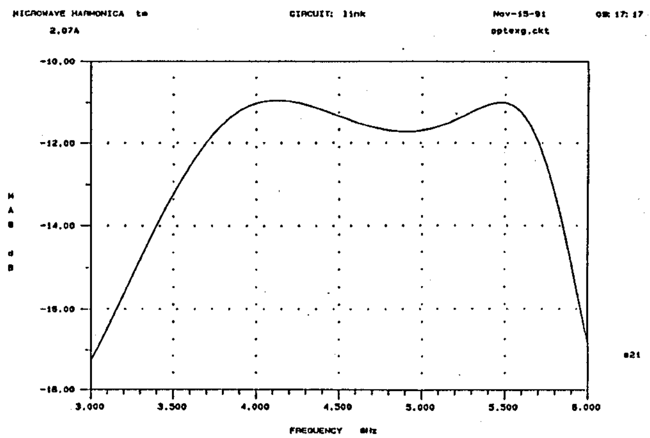

Figure 4 : Minimized RF to RF insertion loss after linear optimization of the optoelectronic transceiver operating over the frequency range 3 to 6GHz.

As we stated above, the coupling losses between the laser and the fiber and the fiber and the PIN photodiode are modeled as the optical attenuators. A 50mA dc current source forward-biases the laser, and a 10V dc voltage source reverse-biases the PIN photodiode. The input and output transmission-line impedance matching networks have been designed and optimized to yield the minimum insertion loss for the link. The result is shown in Fig. 4. A large signal analysis has been performed on the system at 4.5GHz using the harmonic balance technique. Fig. 5 shows the frequency spectrum (sine wave) of drive current to the laser diode. The frequency spectrum and output waveform at the optical output port of the laser diode and at the microwave external port are shown in Fig. 6 and Fig. 7, respectively. These results indicate the effect of nonlinear distortion caused by nonlinearities of the laser diode and PIN detector.

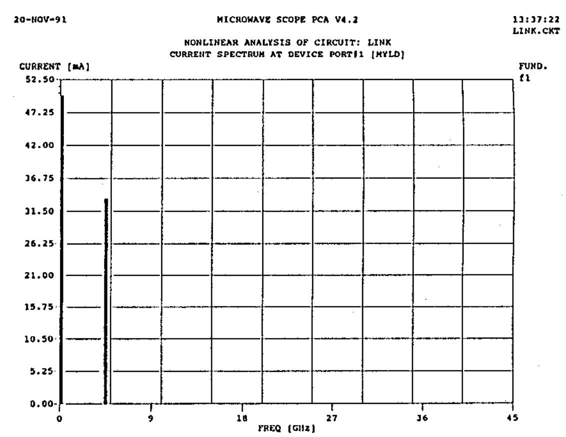

Figure 5 : Frequency spectrum of driven current of the laser diode.

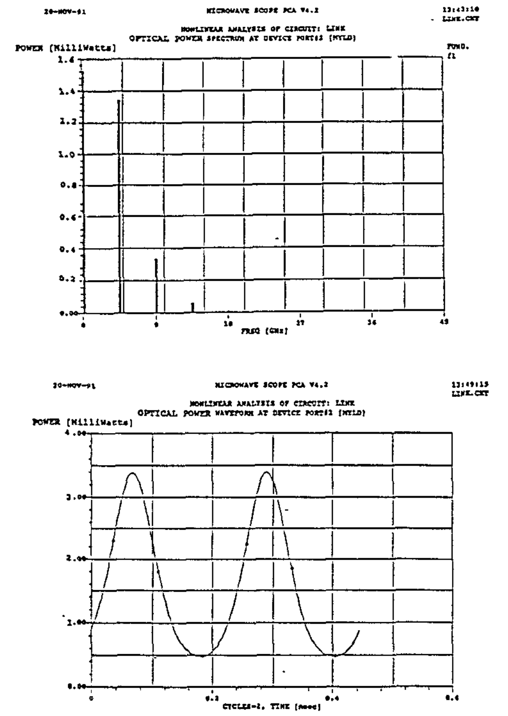

Figure 6 : Frequency spectrum and output waveform at the optical output port of the laser diode.

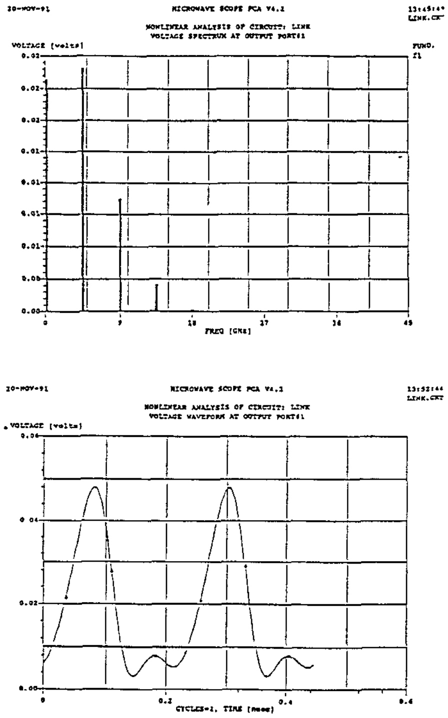

Figure 7 : The frequency spectrum and output waveform at the microwave output of the link.

Conclusions

We have discussed several techniques for computer-aided analysis and design of hierarchically structured multiport microwave/lightwave systems. The method presented in this paper, using modified nodal formulation for linear analysis and harmonic balance for nonlinear analysis, has already been included in convenient, easy to use, fast and accurate software.

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