Integrated Electromagnetic and Circuit Modeling of Large Microwave and Millimeter-Wave Structures

Michael B. Steer*, Mostafa N. Abdulla, Carlos Christofersen, Mark Summers, Satoshi Nakazawa, Ahmed Khalil and James Harvey

Department of Electrical and Computer Engineering,
North Carolina State University, Raleigh, NC 27695-7911.

Abstract

A strategy integrating electromagnetic, nonlinear circuit and thermal analysis is presented for the modeling of large microwave and millimeter-wave systems. The work is applied to the modeling of a spatial power combining amplifier.

I. Introduction

Modeling of large microwave and millimeter-wave structures using integrated electromagnetic, circuit, mechanical and thermal analyses is now within reach. This results from the convergence of available desktop computing resources and theoretical developments. One key ingredient is that the level of abstraction that microwave engineers are comfortable with has risen rather quickly over the last half decade. In this paper we present one scenario for achieving total system modeling. This work is motivated by the need to model spatial power combining systems. A spatial (or quasi-optical) power combining system is a potential solid-state source of high power at millimeter-wave frequencies. These systems combine the power of numerous solid state devices in free space. A typical quasi-optical system is the antenna array system shown in Figure 1 where a large number of active device are distributed on the array surface.

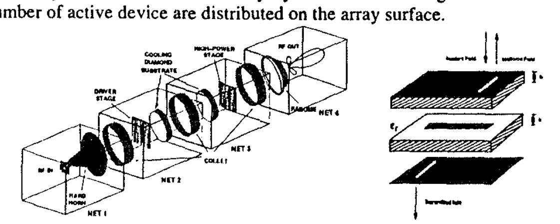

Figure 1: A spatial power combining system with unit cell on the right (a MMIC is placed on the stripline). (After [5].)

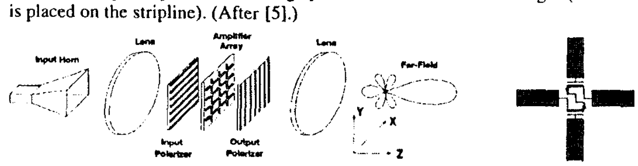

Figure 2 Quasi-optical grid amplifier system with a unit cell shown on the left.

In the grid amplifier system of Figure 2, polarizers separate the oppositely polarized input and output beams. These systems are several wavelengths in each dimension so that electromagnetic modeling is essential. The systems also have hundreds of active devices and significant thermal effects resulting not only from the fact that this is a power amplifying system but also because the active devices are not all seeing the same thermal environment. The phase and amplitude variations across the array, the optimum placement of cells and perhaps different cell design, prediction of side lobe levels and squint, all important issues that require holistic modeling.

II. The Rise of Abstractionism

Electrical engineers are very familiar with the circuit level of abstraction and arguably the ability to work with physical systems at this level of abstraction is fundamental to electrical and computer engineering. In electromagnetic modeling, abstractionism is alive and well with many different "reduced" techniques used to take advantage of special symmetries or other geometric characteristics, in developing an electromagnetic model. However it is difficult to interface different solution domains. The partitioning depicted in Figure 3 is a self consistent way to integrate electromagnetic, circuit and thermal analyses.

There have been a few attempts to model systems with interacting fields and circuit elements. In transient analysis of distributed microwave structures lumped circuit elements can be embedded in the mesh of a time discretized electromagnetic field solver such as a finite difference time domain (FDTD) field modeler. The lumped elements have been incorporated as equivalent current and voltage sources [2], [8], [9], [10] or the field mesh has been merged with the mesh of an active device simulator [1]. There are also commercial products that allow the interfacing of a electromagnetic derived models with circuits but for now only fairly simple systems with a few ports can be handled.

III. Partitioning

The work used here is a progression of three separate developments. First, in [3] a technology for integrating port-based electromagnetic field models with nonlinear devices was introduced. Second in [4] a multiport network was used to enable electromagnetic models of individual interconnects to be assembled in a larger structure. This assemblage accounted for the interactions of the structures through the use of electromagnetic ports with electric and magnetic currents. Third a network model of a large quasi-optical structure was developed in [6] and [7]. The work currently being undertaken develops a network based model of the electromagnetic environment, whereby sections of the large electromagnetic structure are interfaced to each other at "electromagnetic terminals" and to the conventional nodal-based circuit at the ports. The electromagnetic simulator produces the multi-port admittance matrix of the passive grid structure for inclusion in a microwave circuit simulation program. The admittance matrix produced is port based due to the lack of a global reference node in the spatially distributed structure.

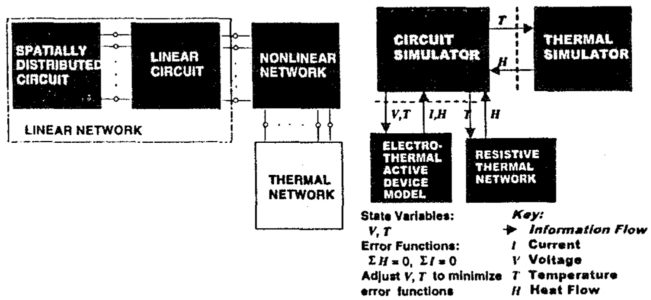

Figure 3: Partitioning of system for analysis: (a) incorporation of an electromagnetically defined model in a circuit simulator, (b) global system partition; and (c) greater detail of circuit-thermal interaction

The first step in the simulation process is to specify the physical characteristics of the passive grid structure. A standard VLSI layout editor is used to generate a CIF formated file which describes the grid structure. Any layout editor capable of generating a CIF may be used. The CIF file is parsed to extract the geometric information required by the electromagnetic simulator. The electromagnetic simulator generates the port-based admittance matrix of the grid structure as well as the excitation currents for a given field profile. The EM simulator output is imported to a nonlinear circuit simulator which performs a state-variable based harmonic balance simulation. The nonlinear effects of the active devices are included in the simulation. The port voltages calculated by the circuit simulator can be used to find the current distribution on the grid. The current distribution is then used to find the fields radiated by the grid.

IV. Modeling Results

The simulation tools were used to model the nonlinear performance of a 2 by 2 quasi-optical grid amplifier system with the results shown in Figure 4. The purpose of this system was to provide experimental verification data, and so compromises were made in the complexity of the system. Furthermore the small size of the system does not efficiently launch a tightly focused quasi-optical beam. However, this does not affect the quality of the modeling.

V Acknowledgements

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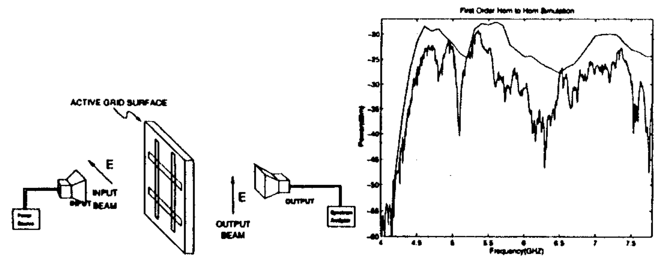

Figure 4: A 2x2 quasi-optical grid amplifier: (a) measurement setup; and (b) output power — solid line is measured, and dashed line is simulated.

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