# AN INTEGRATED ELECTROMAGNETIC AND NONLINEAR CIRCUIT SIMULATION ENVIRONMENT FOR SPATIAL POWER COMBINING SYSTEMS

M. A. Summers, C. E. Christoffersen, A. I. Khalil, S. Nakazawa, T. W. Nuteson†, M. B. Steer and J. W. Mink
Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC 27695-7914.
† T. W. Nuteson, the Aerospace Corporation.

ABSTRACT

An integrated electromagnetic and circuit simulation environment is developed for the simulation of spatial power combining systems. The analysis incorporates surface modes, nonuniform excitation and full nonlinear effects. The simulation tools are used to predict the performance of a 2 by 2 quasi-optical grid amplifier

## INTRODUCTION

Quasi-optical systems combine the power of numerous solid state devices in free space. A typical quasi-optical system is the grid system shown in Fig. 1 where a large number of active device are distributed on the grid surface. The grid is excited by a horn and lens system which concentrates the incident field on the grid and polarizers are used to isolate the input and output.

Electromagnetic models are required to design these spatially distributed systems. Past efforts have used electric and magnetic walls to reduce the grid structure to a single unit cell for modeling purposes. The unit cell model is a good starting point in a design, but consideration of nonuniform illumination and edge effects dictate that the entire grid structure be modeled. Recent work has lead to the development of a method of moment simulator [1] which does not require the unit cell approximations. The simulator can model finite-sized grids with the inclusion of all mutual coupling between cells, surface waves, nonuniform excitation, and gain and phase variations of the unit amplifiers.

This work was supported in part by the Defense Advanced Research Projects Agency (DARPA) through the MAFET Thrust III program as DARPA agreement number DAAL01-96-K-3619.

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. The multiport admittance matrix, along with a nonlinear active device model are used in a nonlinear circuit simulator to model the performance of the spatial power combining system.



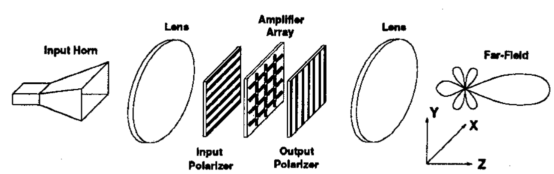


Fig. 1. Quasi-optical lens system configuration with a grid amplifier array and polarizers.

In a more general context this paper is a development in the area of device-circuit-field interaction with the transformation of an electromagnetic simulation of a distributed structure into a circuit element. Since the part of the structure that is modeled electromagnetically is linear, it only needs to be simulated (modeled) once even though it is part of the larger nonlinear system. The electromagnetic model is reduced to terminal characteristics at defined ports and represented as a port-based nodal admittance matrix.

## Strategy

A typical spatial power combining system is shown in Fig. 1. The system contains components which are spread over several wavelengths and the active surface contains numerous nonlinear devices connected to input and output radiators. The system presents some challenging problems: components are spatially distributed, power is radiated through the system, and nonlinear devices are present in the system. The first two problems dictate that electromagnetic models be used, however the nonlinear devices are naturally handled in a circuit simulator. The solution is to divide the system into electromagnetic components and circuit components as shown in Fig. 2. The spatially distributed elements are handled using electromagnetic simulation and the nonlinear devices are handled using harmonic balance circuit simulation techniques. The electromagnetic simulator models finite-sized grids with all mutual coupling between elements considered. The circuit simulator accounts for nonlinearities in the active device, incorporates lumped parasitics, and handles the interconnectivity of the entire network. The interfaces between the two simulators must be clearly defined with self consistency established between the electromagnetic view and the steady-state harmonic balance view. In particular the circuit simulator requires the impedance network seen by the active devices. The simulator also requires any excitation currents or voltages generated by incident fields. The electromagnetic simulator requires the voltages at the ports of the active devices to calculate the current distribution and radiated fields.

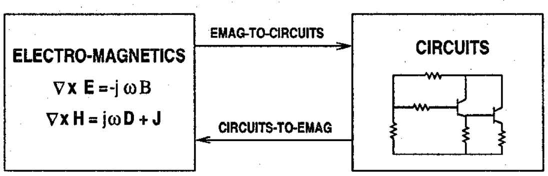


Fig. 2. Division of system into fields and circuits.

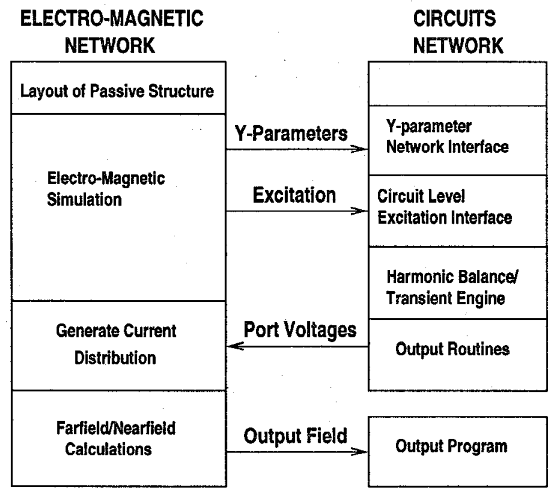


Fig. 3. The general flow for the simulation of a quasi-optical system.

The general CAE flow is documented in Fig. 3. 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. 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.

## Simulation Results

The simulation tools were used to model the nonlinear performance of a 2 by 2 quasi-optical grid amplifier system. 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. The construction and measurement of the grid amplifier as well as the simulation results are discussed below.

### *A. Construction and Measurement of the Grid Amplifier System*

The 2 by 2 grid amplifier system is constructed and measured as shown in Fig. 4. The horns are kept at a distance of 31 cm from the grid surface, and captured only a fraction of the power radiated by the system. This is a consequence of the small size of the system. The input and output horns are also rotated 90° with respect to each other to account for the polarization difference between the input and output fields. The grid layout and bias network are shown in Fig. 5. The grid amplifier is constructed on a 0.762 mm thick duroid dielectric substrate with $\epsilon_r$ of 2.33. The bias is provided to the grid through Microwave Components Inc. 11 nH air coil inductors which act as RF chokes and remove the bias network from the circuit at high frequencies. Dummy inductors are also attached to the input leads of the grid to maintain RF symmetry. This was required to maintain a centered beam with low side-lobes. The resistor marked $R_T$ was used to prevent thermal runaway. The active devices are Mini-Circuits ERA-6 amplifiers used in a differential pair configuration.

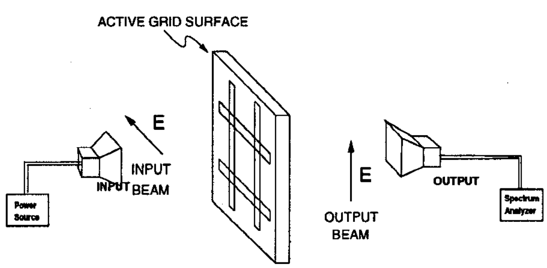


Fig. 4. Setup for measurement characterization of the quasi-optical amplifier system.

The output power of the grid amplifier system was characterized over a frequency range of 4 GHz to 8 GHz.

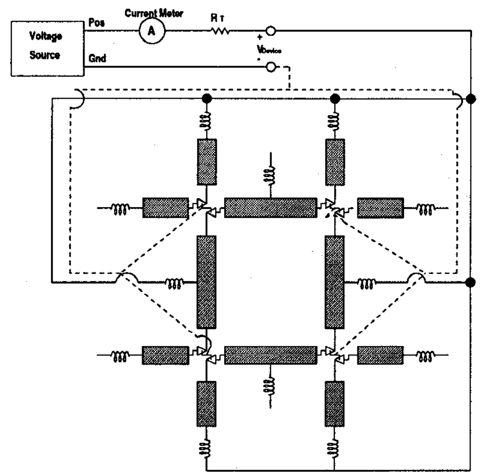


Fig. 5. Layout for 2x2 quasi-optical grid amplifier with bias inductors shown.

### *B. Simulation of the Grid Amplifier System*

A horn-to-horn simulation of the grid amplifier system described above was performed. A layout of the passive grid structure was constructed in Virtuoso$^{TM}$, from Cadence Design Systems. The CIF generated from the layout tool is used by the MOM simulator [1], [2], [3] to generate the multiport admittance matrix and excitation currents for the grid structure. A nonlinear circuit simulation is used to calculate the voltages at the ports of the grid. The port voltages along with the admittance matrix for the complete grid structure can be used to generate the current distribution on the grid. The radiated field can be calculated given the current distribution on the grid structure. The horns are included in the simulation by modeling the horns using their far-field gain. This is admittedly a crude model, but is being used pending a theoretical model under development. The gain of the horns is used to calculate the field incident on the grid and the power received from the field radiated by the grid amplifier. The model however does not include interaction of the horns.

The simulation results are compared with measurements as shown in Fig. 6. The simulation follows the basic pattern of the measured power output of the grid amplifier. It was determined experimentally that the horn-to-horn interactions were the main reason for the rapidly varying ripple in the measured response. An improved horn model should account for these significant interactions. The far-field radiation pattern of the grid

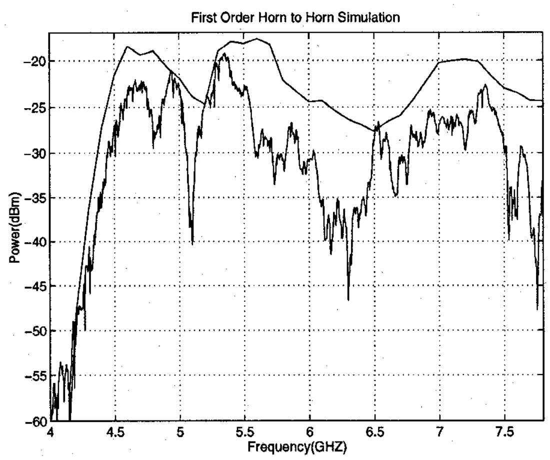


Fig. 6. Power output for 2x2 grid amplifier system: solid line, measurement; dashed line, simulation.

amplifier system at 5.4 GHz is shown in Fig. 7. A simulated plot of $P_{OUT}$ versus $P_{IN}$ is shown in Fig. 8 where the input power is the power delivered to the input horn, and the output power is the power collected by the output horn. The simulation shows that as the input power to the grid is increased the output power begins to saturate and the grid amplifier is operating in saturation.

## Conclusions

A simulation environment capable of simulating spatial power combining systems has been presented. The analysis incorporates surface modes, nonuniform excitation, and full nonlinear effects. The simulation environment was used to predict the output power of a 2 by 2 grid amplifier system. The simulations agreed favorably with measurements. Far-field radiation and power saturation plots were also presented.

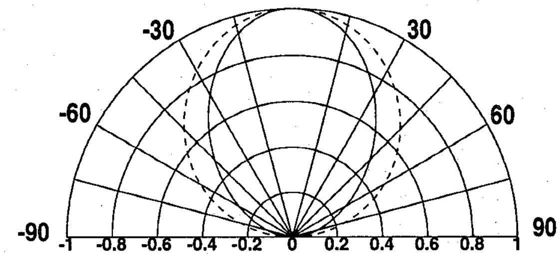

Fig. 7. Radiation pattern at 5.4 GHz as a function of $\Theta$ solid line, $E_\phi$ in the plane $\phi = 0°$; dashed line, $E_\Theta$ in the plane $\phi = 90°$.

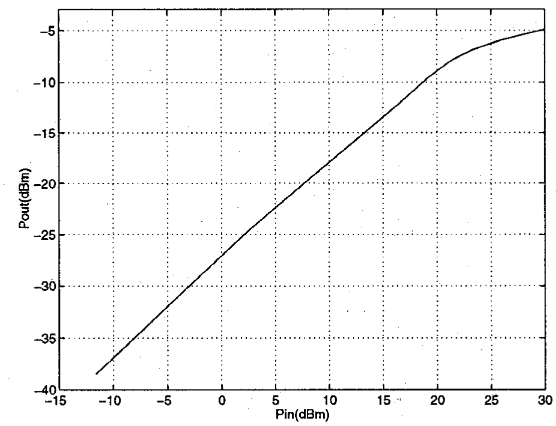


Fig. 8. Output power of the 2x2 grid amplifier system at 5.4 GHz.

## References

[1] T. W. Nuteson, G. P. Monahan, M. B. Steer, K. Naishadham, J. W. Mink, K. K. Kojucharow, and James Harvey, "Full-wave analysis of quasi-optical structures," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-44, pp. 701-710, May 1996.

[2] T. W. Nuteson, H. Hwang, M. B. Steer, K. Naishadham, J. Harvey, and J. W. Mink, "Analysis of finite grid structures with lenses in quasi-optical systems," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-45, pp. 666-672, May 1997.

[3] F. Nusseibeh, T. W. Nuteson, J. Patwardhan, M. A. Summers, C. E. Christoffersen, J. Kreskovsky, and M. B. Steer, "Computer Aided Engineering Environment for Spatial Power Combining Systems," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1073-1076, June 1997.