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# Modeling of Quasi-Optical Arrays

Polly Preventza,[1] Blythe Dickman,[1] Emilio Sovero,[2] Michael P. De Lisio,[3] James J. Rosenberg,[4] David B. Rutledge[1]

[1]Department of Electrical Engineering, California Institute of Technology, Pasadena, CA 91125
[2]Rockwell International Science Center, Thousand Oaks, CA 91358
[3]Department of Electrical Engineering, University of Hawai'i at Mānoa, Honolulu, HI 96822
[4]Department of Engineering, Harvey Mudd College, Claremont, CA 91711

*Abstract* **A model for analyzing quasi-optical grid amplifiers based on a finite-element electromagnetic simulator is presented. This model is deduced from the simulation of the whole unit cell and takes into account mutual coupling effects. By using this model, the gain of a $10 \times 10$ grid amplifier has been accurately predicted. To further test the validity of the model three passive structures with different loads have been fabricated and tested using a new focused-beam network analyzer that we developed.**

## I. INTRODUCTION

Two techniques have been reported for the modeling of quasi-optical systems. The first technique assumes an infinite array, allowing the grid to be analyzed with a single unit cell with symmetry planes [1]. The unit cell of an amplifier grid is shown in Fig. 1. De Lisio *et al.* [1] developed a transmission-line model for this unit cell where the metal strips are analyzed by the method of moments. The model is shown in Fig. 2 and it overpredicts the gain by 3 dB. Mutual coupling between the lines is neglected.

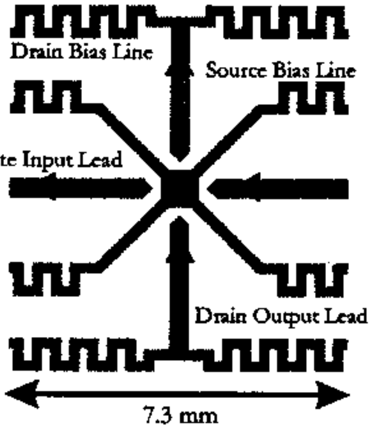


Fig. 1. Unit cell of a 100-element, 10-GHz grid amplifier [1]. The input beam is coupled to the gates of the transistor through the horizontal gate leads. The output beam is reradiated from the vertical drain leads. The thin meandering lines provide bias to the drain and source.

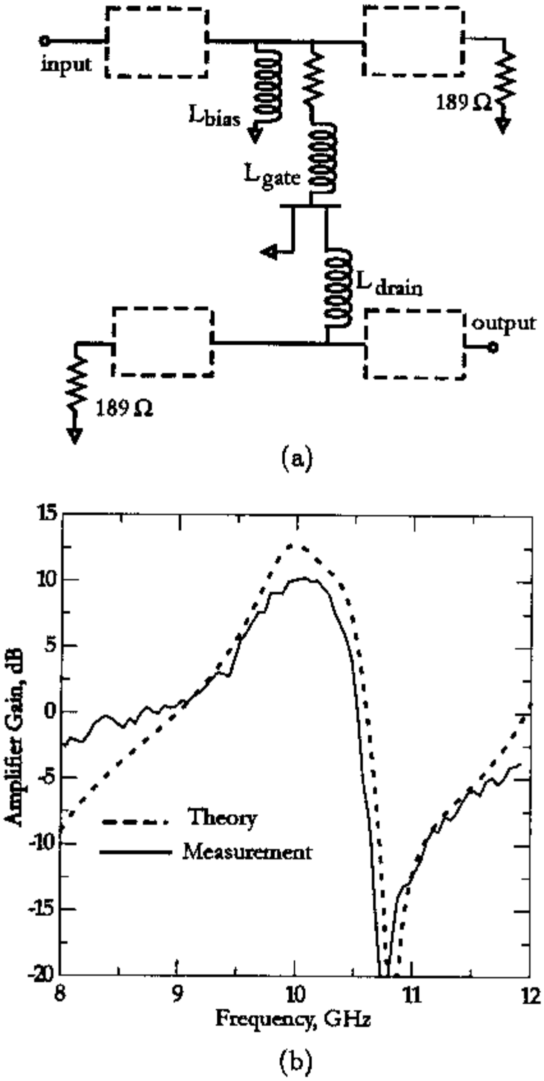


Fig. 2. (a) The unit-cell transmission-line model. The input, output leads and the bias lines are modelled as inductors. (b) Grid amplifier gain versus frequency.

The second technique [2], uses the method of moments to simulate the full grid and includes the edge effects of the array. This model uses a simplified grid layout without complicated metal shapes like meandering lines. It also overpredicts the gain by as much as 3 dB.

Advancement in finite-element analysis techniques, such as Ansoft's High Frequency Structure Simulator (HFSS), allow an accurate and fast solution for the electromagnetic modeling of arbitrarily-shaped, passive, three-dimensional structures. Two new models that are an extension of the unit-cell transmission-line model and include mutual coupling effects are developed based on HFSS simulations. The first model is a lumped-element equivalent circuit of the unit cell. The second model finds the full scattering parameters in an approach that is similar to the calibration of a vector network analyzer. In this paper, we show that the new models agree very well with previously published measurements [1]. Comparison between measurements of passive arrays and simulations further validate the new models.

## II. MODELING OF THE UNIT CELL

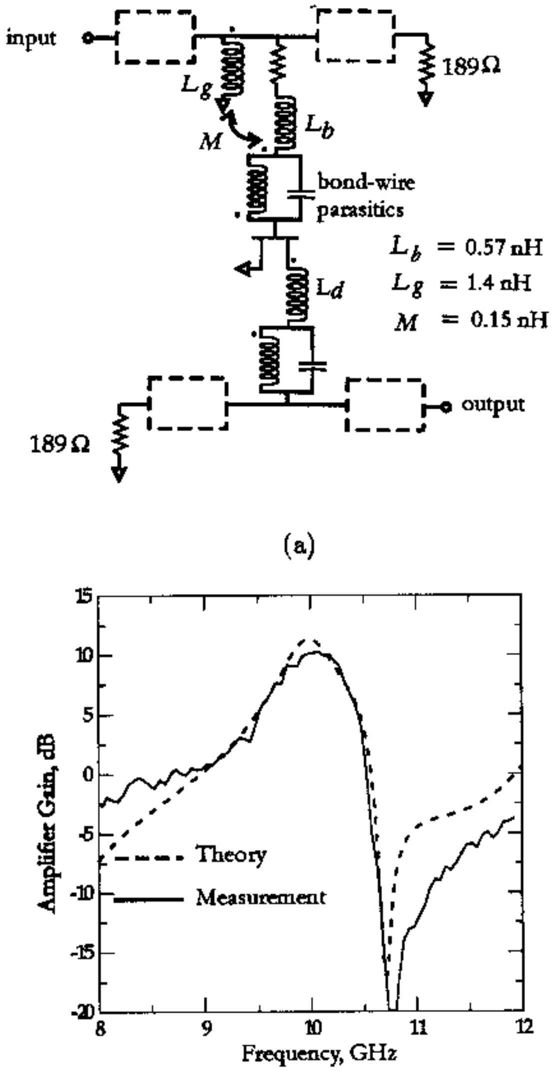
The empirical transmission-line equivalent circuit used in [1] to model the unit cell is shown in Fig. 2(a). The input and output leads of the grid are modelled as inductors. The meandering bias lines are modelled as a shunt inductance. The numerical values of these reactive elements are computed by first using the method of moments to approximate the surface-current distribution and then the induced emf method [3] to calculate the impedances of the elements. This technique analyzes single elements of the unit cell, thereby neglecting coupling effects between these elements.

Two new models have been developed based on HFSS simulations of the whole unit cell. The first model, shown in Fig. 3, accounts for the coupling between the gate lead and the bias lines and predicts a gain that is only 0.5 dB higher than measured. Other parasitic elements such as the inductance of the bond wires and the finite conductivity of the metal are also included in the simulation. The second technique, analogous to the calibration of a network analyzer, directly utilizes data obtained from HFSS two-port simulations. Simulations of the unit cell are carried out for matched, short and open terminations placed at the active device location. These three two-port $s$-parameter files, $\tilde{e}_m$, $\tilde{e}_s$, $\tilde{e}o$ can then be used to find the three-port $s$-parameter matrix of the grid,

$$s = \begin{pmatrix} e_{11m} & e_{12m} & s_{13} \\ e_{21m} & e_{22m} & s_{23} \\ s_{31} & s_{32} & s_{33} \end{pmatrix} \tag{1}$$

where

$$s_{33} = \frac{e_{21s} + e_{21o} - 2e_{21m}}{e_{21o} - e_{21s}} \tag{2}$$



(a)

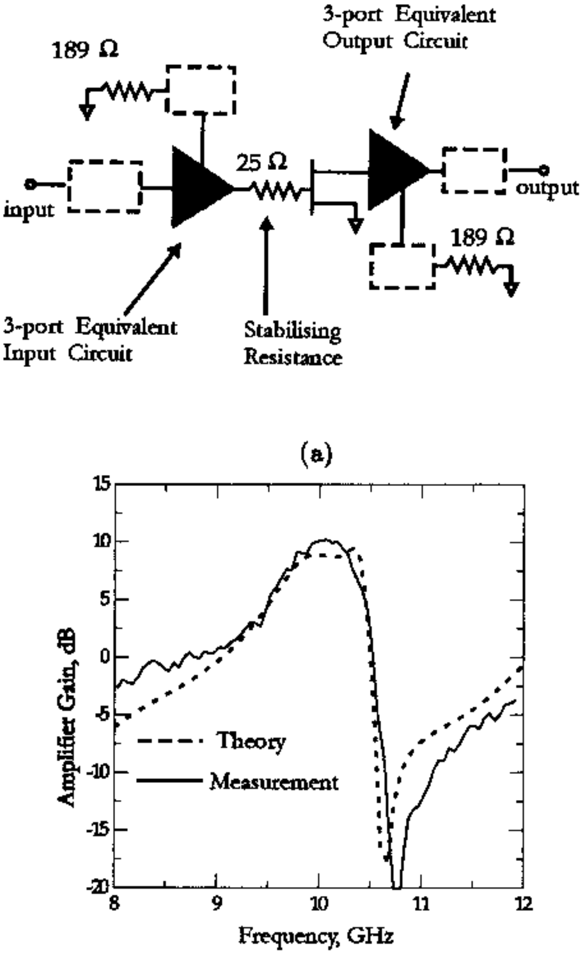
(b)

**Fig. 3.** (a) Lumped-element equivalent circuit deduced from HFSS. $L_b$ and $L_g$ are the inductances of bias lines and gate radiating lead, respectively, and $M$ is the mutual inductance between them. (b) The measured amplifier gain is within 0.5 dB of the theoretical prediction.

$$s_{13} = s_{31} = \sqrt{(e_{11m} - e_{11s})(1 + s_{33})} \tag{3}$$

$$s_{23} = s_{32} = \sqrt{(e_{22m} - e_{22s})(1 + s_{33})} \tag{4}$$

This procedure is done twice, once for each polarization. The resulting pair of $s$-matrices is incorporated into the overall amplifier model as shown in Fig. 4(a).



(a)

(b)

**Fig. 4.** (a) The scattering-parameter model. (b) The measured amplifier gain compared with theory.

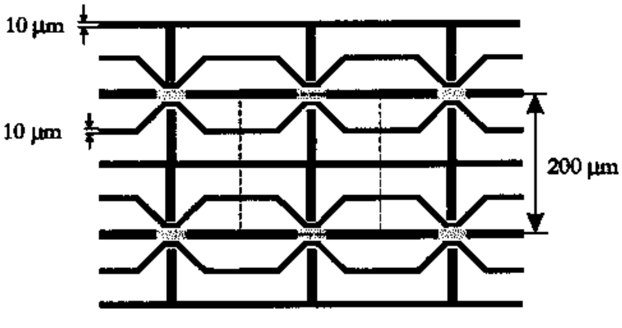


**Fig. 5.** Passive array. The black lines are metal and the shaded area is the location of the devices and the various terminations.

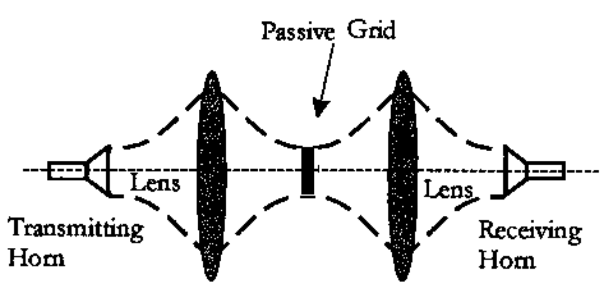


**Fig. 6.** Quasi-optical measurement network analyzer.

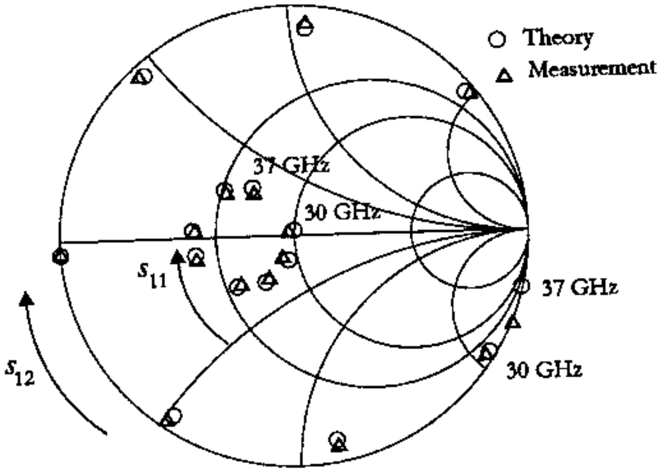


**Fig. 7.** Transmission and reflection measurements of a 2.5-cm polysterene slab ($\epsilon_r$=2.45).

## III. Passive Structures

To validate the use of HFSS in the design of the grid amplifers, three 23 × 23-element passive structures with short circuits, open circuits and 75-Ω terminations have been modelled and tested (Fig. 5). The layout is very similar to the topology of a grid amplifier. The arrays were fabricated by Rockwell International Science Center. The substrate used is a 0.635-mm thick, 75-mm diameter GaAs wafer. The size of the array is chosen to be larger than the beamwaist.

## IV. Measurements

We extended the lens-focused reflectometer, developed by Gagnon [4], to a full two-port system. The apparatus is shown in Fig. 6. It uses two bi-convex lenses with a 30-cm diameter and focal length to focus the beam to a spot at the measurement plane. Two corrugated feed horns driven by an HP8722D vector network analyzer are used to transmit and receive the gaussian beam. The calibration standards for the network analyzer were a short (a large sheet of aluminum at the measurement plane), an offset short and a match (a large section of absorber at some distance from the measurement plane). To check the calibration, measurements were made on a polysterene slab. Fig. 7 shows excellent agreement between simulation

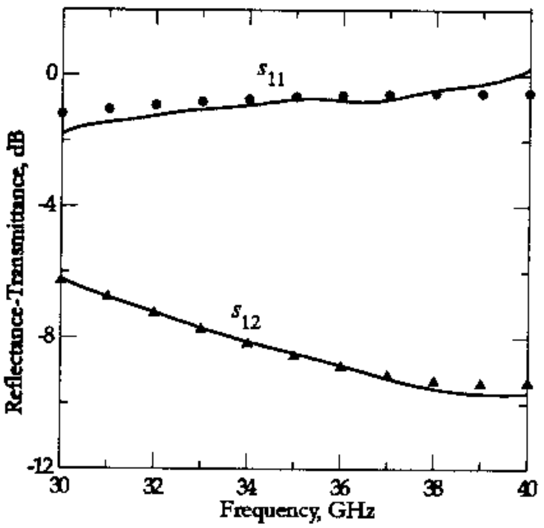


**Fig. 8.** Simulated and measured scattering parameters of the passive array with short-circuit terminations. The solid line shows the measurement.

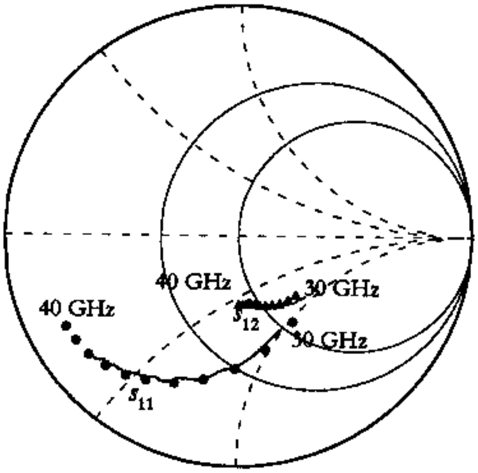


**Fig. 9.** Simulated and measured scattering parameters of the passive array with 75 Ω terminations. The solid line shows the measurement.

and measurement. Gating has been used to eliminate multiple reflections from the lenses and horns.

Comparison between the scattering parameter model and measurements for the passive arrays are shown in Fig. 8, 9 and 10. Agreement is good.

## V. CONCLUSION

We have presented two new models for the design of quasi-optical grid amplifiers based on Ansoft's HFSS. These models account for mutual coupling between the lines of the grid and for parasitic inductances. The models were used to accurately predict the gain of a 10 × 10 grid amplifier. Finally, the scattering parameter model was validated by measuring the scattering parameters of three passive arrays with different terminations.

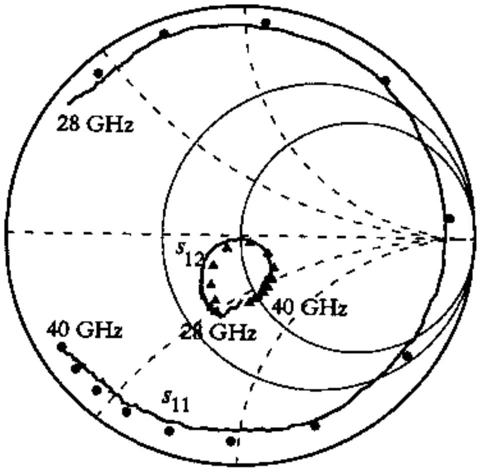


**Fig. 10.** Simulated and measured scattering parameters of the passive array with open-circuit terminations. The solid line shows the measurement.

## VI. REFERENCES

[1] Michael P. DeLisio, Scott W. Duncan, Der-Wei Tu, Cheng-Ming Liu, Alina Moussessian, James J. Rosenberg and David B. Rutledge, "Modeling and Performance of a 100-Element pHEMT Grid Amplifier," *IEEE Trans. on Microwave Theory and Tech.*, (*44*), No. 12, pp. 2136-2144, Dec. 1996.

[2] M.A. Summers, C.E. Christoffersen, A.I. Khalil, S. Nakazawa, T.W. Nuteson, M.B. Steer and J.W. Mink, "An Integrated Electromagnetic and Nonlinear Circuit Simulation Environment for Spatial Power Combining Systems," *1998 IEEE MTT S Int. Microwave Symp. Dig.* (*2*), pp. 168-176.

[3] Z.B. Popović, R.M. Weikle, M.Kim, D.B. Rutledge, "A 100-MESFET Planar Grid Oscillator," *Ieee Trans. on Microwave Theory and Tech.*, (*39*), pp. 823-826, 1994.

[4] D.R. Gagnon, "Highly Sensitive Measurements With a Lens-Focused Reflectometer," *IEEE Trans. on Microwave Theory and Tech.*, (*39*), pp. 2237-2240, Dec. 1991.