Progress in Grid Amplifiers

Chun-Tung Cheung[1], Blythe Deckman[1], James J. Rosenberg[2], David B. Rutledge[1]
[1]Department of Electrical Engineering, California Institute of Technology, Pasadena, CA 91125
[2]Department of Engineering, Harvey Mudd College, Claremont, CA91711

Abstract
In view of the growth in demand in high data rate communications, satellite communications, radar imaging and detection applications and astronomical applications, microwave and millimeter wave power amplifiers capable of providing tens of watts are in need. The recent improvements in III-V solid-state technology provide high yield reliable transistors that can be fabricated in a large quantity. This capability allows the development of grid amplifiers combining power of more than 500 transistors. This paper presents the recent achievements in grid amplifiers. In particular a 5W, 8dB gain, 15% power added efficiency (PAE) monolithic grid amplifier and a 1W monolithic grid oscillator with tuning range from 37.5-41GHz are going to be presented. The associated calibration, measurement and packaging techniques are discussed as well.

I. Introduction

Grid amplifiers are arrays of transistors fabricated and biased such that they coherently amplify an input signal. The input and output are usually separated by polarization and are incident and radiate normal to the plane of amplifiers. They posses several advantages in general. Solid-state amplifier in a grid structure has been shown to have graceful degradation property [1]. This property alleviates maintenance criticality and secondary system necessity. The use of lower operating voltage of transistor allows lower power supply equipment cost and failure rate. Research efforts have been focused on realizing high power grid amplifiers in various configurations and frequency ranges. The power increases in amplifier allows the use of more sophisticated coding schemes such as 16-QAM. In addition, it allows operating the amplifier in non-compression region that maintains linearity but with lower than maximum power output. Typically hybrid and monolithic are the two main different approaches to realize grid amplifiers. For hybrid amplifier, many pre-packaged chips are placed in a grid structure to provide the required spatial power combing. Cheng *et al.* [2] described the design and fabrication of a 60W hybrid amplifier in X-band. Recently Qrtiz *et al.* [3] and Sowers et al. [4] demonstrated a 25W amplifier at 34GHz and a 36W amplifier at V-band. Both of them are hybrid grid amplifiers. The disadvantage of hybrid grid amplifier is the higher labor cost of installing and wire bonding MMIC chips to a circuit board or a supporting substrate. This supporting substrate is usually fabricated with input and output coupling antennas. On the other hand, monolithic grid amplifier is a single chip containing all the transistors and antenna geometry fabricated from GaAs or InP wafer. Deckman *et al.* [5] demonstrated a 5W monolithic grid amplifier at 37GHz. A lot of work in this paper is based on the amplifier in [5]. Monolithic grid amplifier is usually giving less power and may need to be tiled to meet the power specification. Both amplifier configurations make use of spatial power combining as oppose to circuit power combing technique. In the following section, we explain the reasons of using spatial power combining. Then we will show the design of grid amplifiers and oscillators in section III and IV. In section V and VI, the associated measurement and packaging techniques will be discussed. Finally we will discuss about the direction of the future research effort in the conclusion section.

II. Advantage of spatial power combining

Single transistors like FET and HBT deliver power that is frequently too low for power amplifier specifications. One of the solutions to this problem is to employ transmission line splitting and combining circuits such as Wilkinson power combiner. The limit to this approach is the finite loss associated with transmission line and the growth in length of transmission line as the number of devices to be combined increases. In order to overcome this limit, spatial power combining is used that allows every device radiates into a lossless or low loss medium such as free space and coherently add the power. York [6] suggested a calculation based on PAE to determine when a spatial power combiner should be used. One can find that the length of transmission line growth logarithmically while the power increases linearly with respect to the number of devices under combining. This implies the net growth in power output will eventually peak at certain point and start to roll-off as the number of devices increases. On the other hand, in spatial power combining, the loss is linearly proportional to the number of devices.

III. Design of a Ka-band grid amplifier

Fig. 1 shows a common grid amplifier configuration with input and output waves separated by polarization. The design of a grid amplifier usually starts by making an infinite periodic array assumption that allows a single unit cell design approach. The unit cell size is limited by the cutoff frequency of the first higher order mode traveling in the unit cell TEM waveguide and the surface wave excited oscillation with adjacent cells. Each unit cell consists of a differential pair of one or more amplifier stages limited by the unit cell size. The advantage of differential pair is that a virtual ground is available at the center of the unit cell and can readily terminate the source at RF. The radiating antennas of gate and drain are modeled after [7] and are incorporated into circuit simulation to calculate small-signal gain and amplifier stability. Simultaneous input and output conjugate impedance matching is achieved by choosing material of suitable dielectric constant and optimizes the transmission line length using commercially available optimization packages such as Advance Design System (ADS) of Agilent. It is not only the dielectric constant of thermal spreader is important but also the thermal conductivity of the material. Aluminum Nitride, Beryllium oxide and CVD Diamond substrates are potential candidates for heat spreading. Table 1 shows the dielectric constant, typical loss tangent and thermal conductivity of these materials.

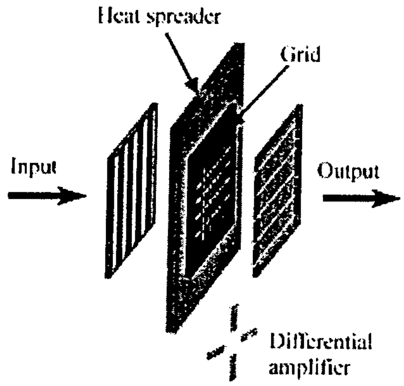

Fig. 1. Schematic of the grid amplifier with heat spreader. The input and output waves are in orthogonal polarizations.

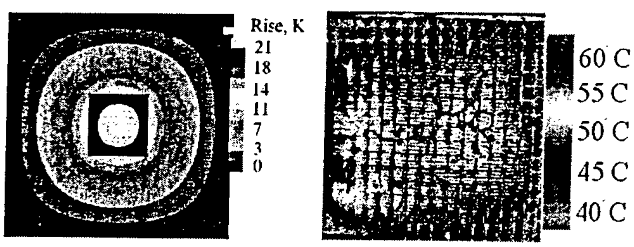

Fig. 2. a. Simulated temperature profile with uniform heat flux in grid region shows 21°C rise in temperature. **b.** Measured temperature profile across the grid using thermal camera. The peak temperature is 60°C.

Table 1

Material	Dielectric constant εr	Loss tangent	Thermal conductivity W/mK
AlN	8.6	0.001	170
BeO	6.5	0.0004	270
Diamond	5.7	0.00002	1800

Based on the thermal conductivity of AlN, and the waste heat power estimated, Fig. 2a shows the simulation result of the temperature rise across the grid region assuming uniform heat flux on the surface of the grid. Adding the ambient room temperature, the estimated operating temperature of the grid is 45°C. A thermal camera image is shown in Fig. 2b and the measurement is in good agreement with the prediction. For grid amplifier of higher density or larger number of elements, we may yet employ BeO or diamond substrates and reduce the temperature rise by a factor of 1.6 and 10.5 respectively.

A Ka-band grid amplifier designed using the method mentioned above has been fabricated and measured in Dickman *et al.* [5]. The size of the grid is $1cm^2$ with 256 $0.625mm^2$ unit cells. It is fabricated by Rockwell Science Center with 0.25μm pHEMT process. Fig. 3 shows the gain and output power as a function of input power at 37GHz. The maximum output power measured was 5W with 15% PAE. The maximum small-signal gain of the grid was 8dB at 37.2GHz with 1.3GHz bandwidth as shown in Fig. 4.

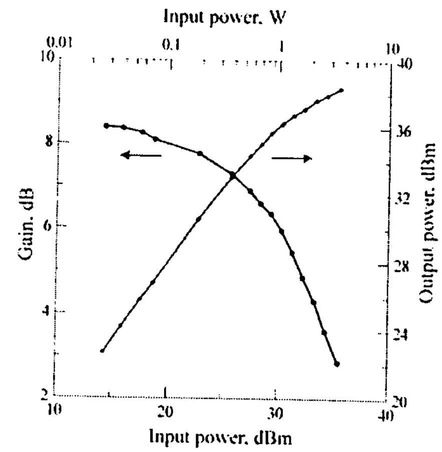

Fig. 3. Output power and gain versus input power.

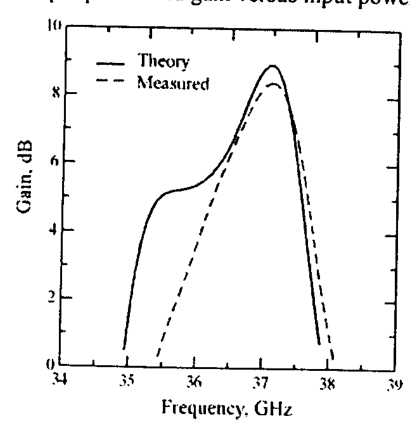

Fig. 4. The theory and measurement of small-signal response of the grid amplifier. They agree with each other except around 35.5GHz.

IV. A 1W Ka-band grid oscillator

For grid amplifiers, polarization separation technique is usually used to avoid strong coupling between input and output antennas. However, if we feedback part of the output energy into input using angled polarizer as shown in Fig. 5, we can make an oscillator running in differential mode. This oscillation, as opposed to common mode oscillation, generates useful boardside radiation beam and can be collected easily by lens, parabolic dish antenna or horn antenna. Deckman *et al.* [8] based on the amplifier described in [5] presented the design and measurement of a grid oscillator using twist reflector as an external feedback element. The output power of the oscillator was 1W at 38GHz with noise of -106dBc/Hz at 1MHz offset. Fig. 6 shows the effective radiated power across the tuned frequency range. By adjusting the back short and re-optimizing the output with the double slug tuner, tuning range from 37.5GHz to 41GHz was achieved.

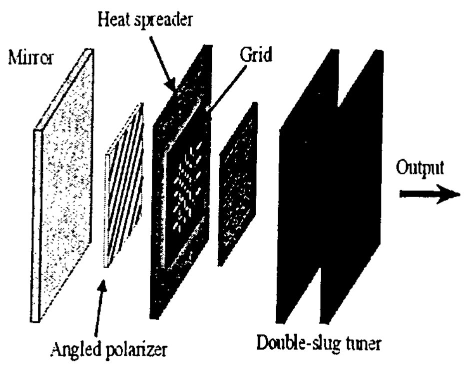

Fig. 5. Schematic of a grid oscillator.

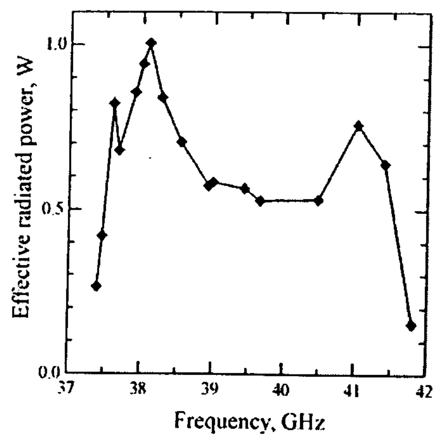

Fig. 6. The effective radiated power across the frequency.

V. Calibration and measurement techniques

Using techniques in gaussian optics, we can focus a radiating field into a region using lenses as shown in Fig. 7. The focused energy at beam waist is of uniform phase distribution in the plane normal to the propagation direction of the incident wave. This is a good environment for grid amplifier excitation provided that the grid size is within the waist diameter. Furthermore, focused beam system avoids the use of empirical estimate of the radiating area and the associated space-loss correction factors. It also ensures that most of the reflected energy from grid amplifier is captured by the conical horn at the input. This capability increases the dynamic range of the measurement and makes input reflection coefficient measurement possible.

Following [9], measurement with device smaller than the beam waist such as grid amplifier, calibration is complicated since the surrounding environment outside the grid has to be the same for the calibration standards and the actual device. The calibration standards of short, delay short and delay match are usually used for calibration because they are usually more readily available and reproducible. The longitudinal and transverse positions of these calibration standards are necessary to be as identical as possible. It is because the surrounding area outside the grid is under substantial illumination of the incident wave and thus the measurement results are sensitive to the accuracy of positioning. Time gating of signals is necessary in order to remove unwanted scatterers other than the grid at reference plane. These scatterers include but not limited to holding fixtures, edge of lenses and optical bench. Fig. 8 shows a reflection measurement comparing with simulation results. They are in fair agreement due to non-uniform reflection of the grid aperture and surrounding area. The amplifier is described in [4] with input polarizer removed.

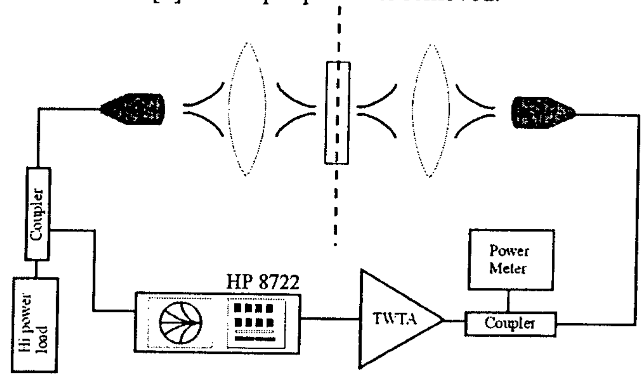

Fig. 7. Focused beam measurement system.

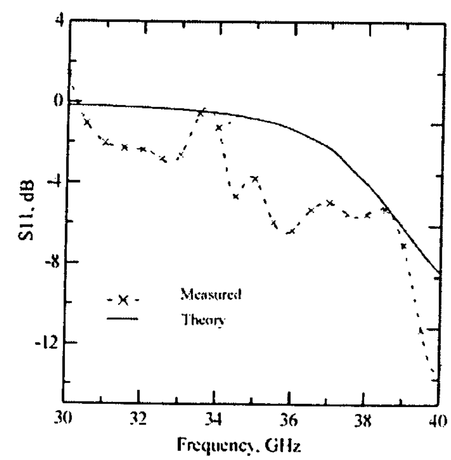

Fig. 8. The measured and theoretical reflection coefficients.

VI. Excitation of grid amplifier

Focused beam system possesses a lot of advantages for measurement and characterization of grid amplifier as shown in the previous section. However, in order to have a more compact setting for commercial applications, traditional waveguide packaging becomes more attractive. The use of over-moded waveguide to excite quasi-optical amplifier has been discussed in Kamei *et al* [10]. The basic idea is to excite TE_{n0} modes in a controlled fashion such that a maximally flat electromagnetic field is presented to the grid. There will be successive number of flat phase planes due to the different phase velocities of modes within the waveguide. A mode converter designed based on 2dB ripple criteria has been fabricated and measured. The simulated and measured field distribution across the waveguide aperture are shown in Fig. 10. Applying this mode converter to a waveguide input, radiating output structure as shown in Fig. 11 has been simulated. In this case, the entire structure's dimensions are treated as variables to minimize the function

$$e = \frac{variance(|E|)}{mean(|E|)^2} + \frac{variance(\angle E)}{mean(\angle E)^2} + |S_{11}|^2 \quad (1)$$

where E is the electric field phasor measured over the grid area and S_{11} is the small-signal s-parameter of the input. In order to maintain good input and output matching, input impedance of the grid has to be included as an impedance sheet over the grid region with impedance obtained from circuit simulation as estimation. e=0.056 has achieved which is corresponding to normalized magnitude variance, phase variance and magnitude of input reflection coefficient of 0.010, 0.012 and 0.184 respectively. The total length of the mode converter and over-moded waveguide section is 12.8mm which is corresponding to 1.5λ at 35GHz. This waveguide feed grid amplifier is undergoing fabrication at the time of paper submission.

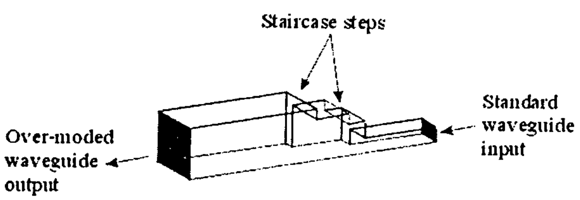

Fig. 9. Wireframe schematic of a mode converter. The staircase steps expand in E- and H-planes simultaneously.

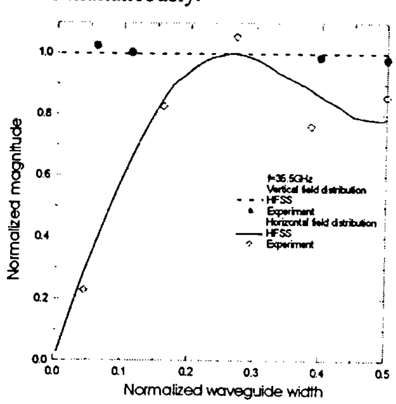

Fig. 10. Measured and theoritical field distribution for mode converter at flat phase plane.

VII. Conclusions

We presented the recent achievement in grid amplifiers and oscillators. As more advanced solid-state technology such as InP becomes mature, frequencies up to W-band or high gain grid amplifiers should be achievable and are now under serious investigations. Nevertheless, the better understanding of characterization of the grid amplifier and the improvements in calibration methods allow us to be able to predict and measure more accurately. In addition, feeding the input and output with waveguide structure is going to allow grid amplifiers to be incorporated with other standard waveguide components. This makes grid amplifiers easily incorporated into commercial applications.

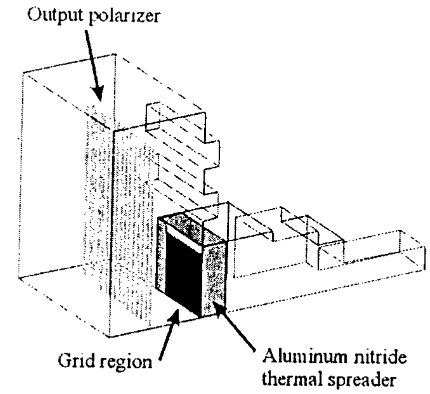

Fig. 11. A quarter sized field simulation for input circuit of grid amplifier and mode converter.

VIII. Acknowledgements

The authors appreciate the support from the Army Research Office through the Caltech Quasi-Optic Power Combining MURI program.

References

[1] D. B. Rutledge, N. Cheng, R. A. York, R. M. Weikle, M. P. De Lisio, "Failures in Power-Combining Arrays," *IEEE Trans. Microwave Theory and Tech.*, Vol. 47, pp. 1077-1082, July 1999.

[2] N. Cheng, T. Dao, M. G. Case, D. B. Rensch, R. A. York, "A 60-Watt Spatially Combined Solid-State Amplifier," *IEEE MTT-S Int. Symp. Dig.*, 1999, pp.539-542.

[3] S. Ortiz, J. Hubert, L. Mirth, E. Schlecht, A. Mortazawi, "A 25Watt and 50Watt Ka-band Quasi-optical Amplifier," *IEEE MTT-S Int. Symp. Dig.*, 2000, pp.797-800.

[4] J. J. Sowers, D. J. Pritchard, A. E. White, W. Kong, O.S.A. Tang, "A 36W, V-band, Solid State Source", *IEEE MTT-S Int Symp. Dig.*, 1999, pp. 235-238.

[5] B. Dickman, D. S. Deakin Jr., E. Sovero, D. Rutledge, "A 5-Watt, 37-GHz Monolithic Grid Amplifier," *IEEE MTT-S Int. Symp. Dig.*,2000, pp. 805-808.

[6] R. York, "Some Considerations for Optimal Efficiency and Low Noise in Large Power Combiners," to be published in *IEEE Trans. Microwave Theory and Tech.*.

[7] P. Preventza, B. C. Dickman, E. A. Sovero, M. P. De Lisio, J. J. Rosenberg, D. B. Rutledge, "Modeling of Quasi-Optical Arrays," *IEEE MTT-S Int. Symp, Dig.*, 1999, pp.563-566.

[8] B. Deckman, J. J. Rosenberg, D. Rutledge, E. Sovero, D. S. Deakin, Jr., "A 1-Watt, 38-GHz Monolithic Grid Oscillator," Submitted to *IEEE MTT-S Int. Symp.* 2001.

[9] B. Deckman, J. J. Rosenberg, D. Rutledge, "Ka-Band Quasi-optical Measurements Using Focused Gaussian Beams," *IEEE MTT-S ARFTG Dig.*, 2000, pp. 43-48.

[10] T. Kamei, C. Cheung, J. J. Rosenberg, D. B. Rutledge, "Design and simulation of a mode converter for the excitation of Quasi-optical Amplifiers," *IEEE Int. AP-S Int. Symp. Dig.*, 1999.