Monolithic 40-GHz 670-mW HBT Grid Amplifier

Cheh-Ming Liu, Emilio A. Sovero, Wu Jing Ho, J. A. Higgins, Michael P. De Lisio, and David B. Rutledge

Abstract—**A 36-element monolithic grid amplifier has been fabricated. The active elements are pairs of heterojunction-bipolar-transistors. Measurements show a peak gain of 5 dB at 40 GHz with a 3-dB bandwidth of 1.8 GHz(4.5%). Here we also report comparisons of patterns and tuning curves between the measurements and theory. The grid includes base stabilizing capacitors which result in a highly stable grid. The maximum saturated output power is 670 mW at 40 GHz with a peak power-added efficiency of 4%. This is the first report of power measurements on the monolithic quasi-optical amplifier.**

I. Introduction

A grid amplifier is a spatial power-combining device that amplifies a microwave beam and combines the outputs of many transistors, making it possible to greatly increase power [1-3]. Combining the power in free space, grid amplifiers eliminate losses associated with waveguides and transmission-line networks. Grid amplifiers have demonstrated gains of 10 and 11 dB at 10 GHz with HBT's [1,2], and 12 dB at 9 GHz with pHEMT's [3]. Other spatial-power combining approaches are actively being pursued [4-9]. Recently, Higgins, Sovero and Ho demonstrated a monolithic Q-band plane-wave amplifier using slot and patch antennas [10]. Based on the gain and stability models of the hybrid grid amplifiers [2,3], we reported monolithic HBT and pHEMT grid amplifiers [11,12]. In this paper, we report additional measurements on the monolithic HBT grid amplifier, including gain, tuning curves, patterns, and power measurements. The grid has a 5-dB gain and 670-mW saturated output power at 40 GHz.

The monolithic grid amplifier, shown in Fig. 1, is composed of 36 unit cells on a 565-μm thick GaAs substrate. There are 6 elements on each side. The length is 12 mm on one side. The grid was fabricated with the HBT process established at Rockwell International [13]. The maximum available gain of an individual transistor at 40 GHz is 9 dB.

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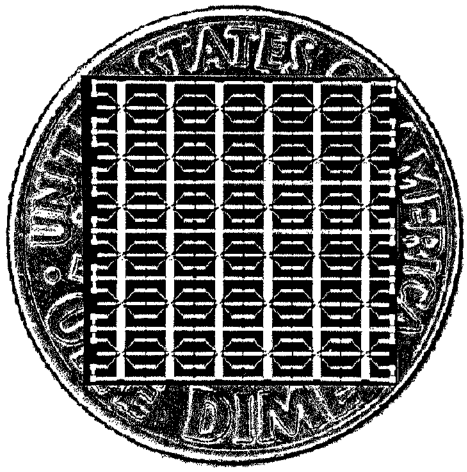

Fig. 1. Photograph of the 36-element monolithic grid amplifier compared with a dime. The chip is 12 mm on each side.

II. Design

The unit cell is shown in Fig. 2. The period of the unit cell is 1.9 mm. In the unit cell, the input leads receive the horizontally-polarized input beam. The input matching capacitor cancels the inductive reactance of the input lead. The stabilizing capacitor prevents common-mode oscillations. The output leads radiate the output beam with vertical polarization.

The grid-amplifier system(Fig. 3a), can be represented by an equivalent-circuit model(Fig. 3b) [2]. The input beam is on the left-hand side with horizontal polarization. The input beam is received by the amplifier grid, amplified, and then reradiated with vertical polarization, as the output beam to the right. The unit cell links the input and output. The polarizers confine the signal path from the left, input with horizontal polarization, to the right, output with vertical polarization. The matching conditions are determined by the polarizers and tuning slabs.

At 40 GHz, the HBT input impedance for the maximum available gain is $8 + j5.5\ \Omega$. It is important to match the input because the resistive part of the corresponding input impedance is much lower than the free-space impedance. To match the input, the GaAs substrate acts as a quarter-wavelength transformer.

In previous grid amplifiers, common-mode oscillations were observed [2,3]. Hence stability is an important issue in the design. Based on the stability analysis in [2], if stabilizing capacitors are not included, we predict the grid

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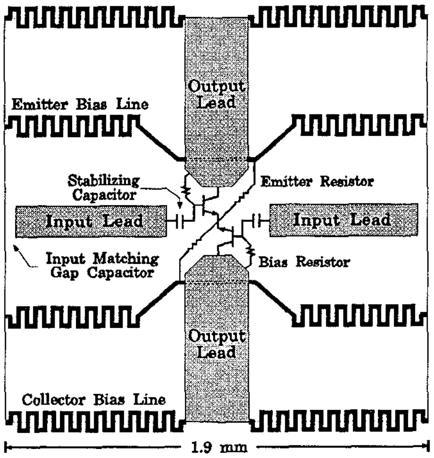

Fig. 2 The unit cell. The input leads are 120 μm wide and the output leads are 300 μm wide. The width of the input matching gap is 30 μm. The stabilizing capacitor is 27 fF. The bias resistors are 4 kΩ and the emitter resistors are 150 Ω. The width of the meandering bias line is 20 μm.

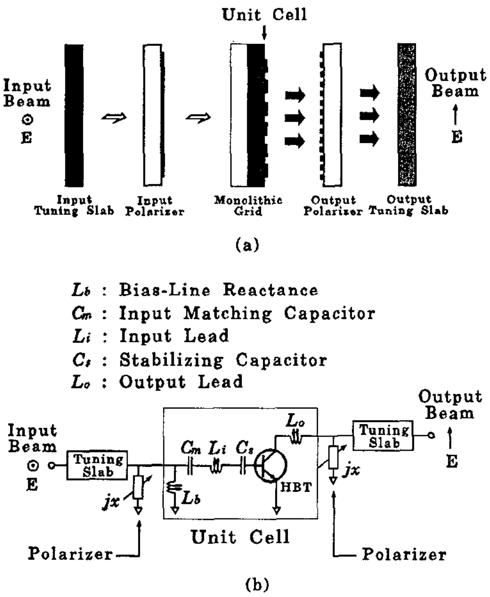

Fig. 3 (a) Cross-section of the grid amplifier. The input beam, with horizontal polarization, is fed from the left. The output beam, with vertical polarization, is measured on the right. (b) Equivalent-circuit model.

will oscillate at 22 GHz. With the stabilizing capacitors, the grid is stable with a phase margin of 58 degrees and a gain margin of 6.6 dB [11].

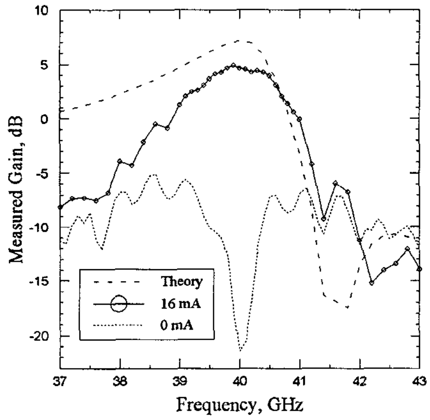

Fig. 4 Gain measurements. The peak gain is 5 dB at 40 GHz. The 3-dB bandwidth is 1.8 GHz(4.5%). The theory is calculated from the transmission-line equivalent-circuit model [2].

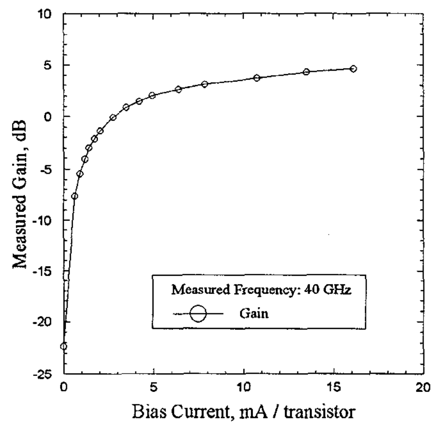

Fig. 5 Gain versus bias current at 40 GHz. The peak gain is 5 dB at 16 mA per transistor. The on-off ratio is 27 dB.

III. Gain

The gain is measured in the far-field [1]. Due to the high DC dissipation, the grid was biased for only 0.6 seconds at a time to avoid thermal damage. The gain response, from 37 to 43 GHz as shown in Fig. 4, has a peak gain of 5 dB at 40 GHz and 3-dB bandwidth of 1.8 GHz(4.5 %). Fig. 5 shows the gain versus the bias current at 40 GHz. The gain inceases monotonically from −22 dB to 5 dB as the bias current increases from 0 to 16 mA per transistor. The difference between biased and zero-biased gains is 27 dB at 40 GHz. No oscillation was observed—the grid is highly stable.

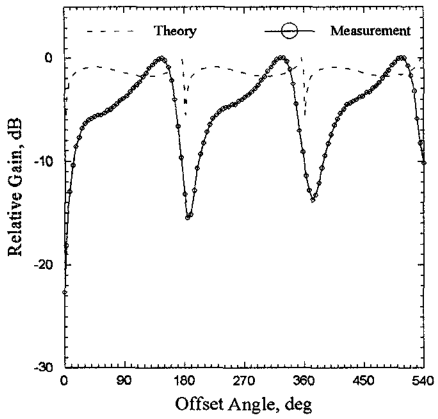

Fig. 6 Relative gain at 40 GHz as a function of output polarizer position.

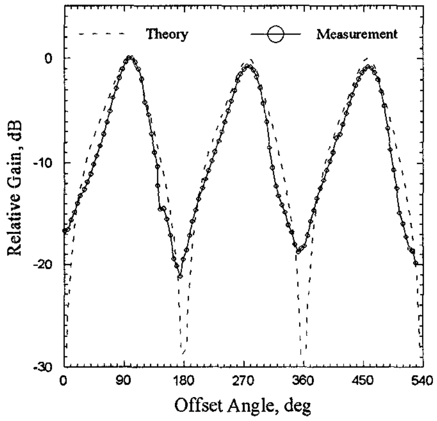

Fig. 7 Relative gain at 40 GHz as a function of input polarizer position.

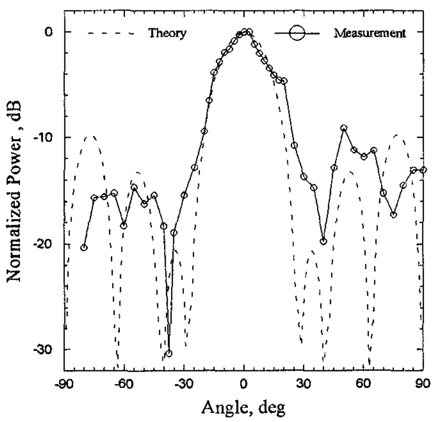

Fig. 8 Output H-plane radiation pattern at 40 GHz.

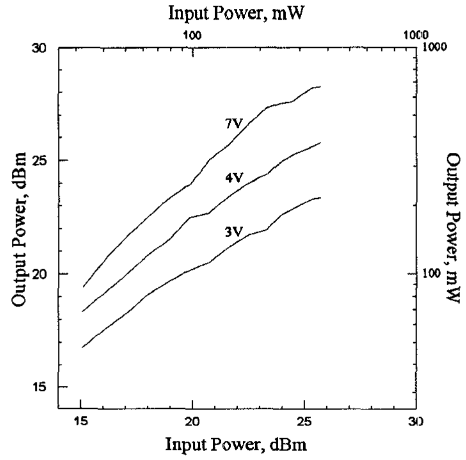

Fig. 9 Output power versus input power at 40 GHz. The peak output power is 670 mW at 7 V.

IV. Tuning and Pattern

Fig. 6 and Fig. 7 show input and output tuning curves at 40 GHz. The tuning curves are plots of the gains versus the polarizer positions. The measured input-tuning curve is different from the theoretical one. This may be due to the critical matching condition at the input. However, the measured output-tuning curve matches to the theory well.

The output H-plane radiation pattern is shown in Fig. 8. This pattern is measured by fixing the grid amplifier and the input antenna, and rotating the output antenna. The theoretical pattern of six elementary dipoles with a mirror 8.5-mm behind is also shown in Fig. 8. The measurement shows reasonable match to the theory in the main lobe.

V. Power

In the power measurement, we used a 10-W Ka-band Traveling-Wave Tube(TWT) amplifier as the source. The power was measured in the far field at 40 GHz. Fig. 9 shows the output power versus the input power of the grid amplifier at three bias levels. The peak output power is 670 mW at 7 V with the bias current of 16 mA per transistor. Fig. 10 shows the gain and power-added efficiency versus the input power. The gain drops to 2.5 dB at the maximum output power. The peak efficiency is 4% with 500-mW output power. At 7 V, 70% of the DC power is actually dissipated in the bias lines and emitter resistors.

IV. Conclusion

We have demonstrated a 36-element monolithic HBT grid amplifier. Based on the gain and stability models, the result is a highly stable grid amplifier. The grid has a 5-dB gain at 40 GHz with 4.5% 3-dB bandwidth. The

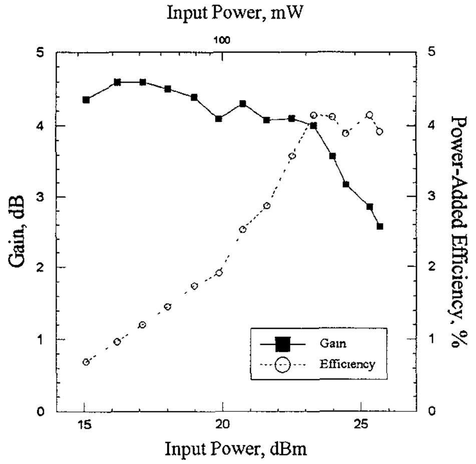

Fig. 10 Gain and power-added efficiencies versus input power at 40 GHz. The gain at maximum output power is 2.5 dB. The peak grid efficiency is 4%.

maximum measured output power is 670 mW with 4% power-added efficiency at 40 GHz.

V. References

[1] M. Kim, E. Sovero, J. Hacker, M. De Lisio, J.-C. Chiao, S. Li, D. Gagnon, J. Rosenberg, and B. Rutledge, "A 100-Element Grid Amplifier," *IEEE Trans. Microwave Theory Tech.*, MTT-41, pp. 1762–1771, October 1993.

[2] C.-M. Liu, E. Sovero, M. De Lisio, A. Moussessian, J. Rosenberg, and D. Rutledge, "Gain and Stability Models for HBT Grid Amplifiers," *1995 IEEE AP-S Int. Symp. Dig.*, pp.1292–1295, 1995.

[3] M. De Lisio, S.W. Duncan, D.-W. Tu, C.-M Liu, A. Moussessian, J. Rosenberg, and D. Rutledge, "Modelling and Performance of a 100-Element pHEMT Grid Amplifier," submitted to *IEEE Trans. Microwave Theory Tech*, 1995.

[4] H.-S. Tsai, M.J.W. Rodwell, and R.A. York "Planar Amplifier Array with Improved Bandwidth Using Folded-Slots," *IEEE Microwave and Guided Wave Letters*, MGWL-4, pp. 899–901, May 1994.

[5] J. Benet, A. Perkons, S. Wong, and A. Zaman, "Spatial Power Combining for Millimeter-wave Solid State Amplifier," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 619–622, 1993.

[6] T. Mader, J. Schoenberg, L. Harmon, and Z. Popović, "Planar MESFET Transmission Wave Amplifier," *Electronic Lett.*, vol. 29, pp 1699–1701, September 1993

[7] N Sheth, T Ivanov, A Balasubramaniyan, and A. Mortazawi, "A Nine HEMT Spatial Amplifier," *IEEE MTT-S Int. Microwave Symp. Dig.*, 1994, pp. 1239–1242.

[8] "Quasi-Optical Power Combining Techniques," Robert York, in *Millimeter and Microwave Engineering for Communications and Radar,* J.Wiltse, editor, *Critical Reviews of Optical Science and Technology,* vol. 54, pp. 63–97, 1994.

[9] J. Hubert, J. Schoenberg, and Z. Popović, "High-Power Hybrid Quasi-Optical Ka-Band Amplifier Design," *IEEE MTT-S Int. Microwave Symp. Dig.*, 1995, pp. 585–588.

[10] J.A. Higgins, E.A. Sovero, and W.J. Ho, "44-GHz Monolithic Plane Wave Amplifiers," *IEEE Microwave Guided Wave Lett.*, MGWL-5, pp. 347–348, October 1995.

[11] C.-M. Liu, E. Sovero, W.-J. Ho, J.A. Higgins, and D. Rutledge, "A Millimeter-Wave Monolithic Grid Amplifier," *Int. Journal of Infrared and Millimeter Waves*, pp. 1901-1910, Vol. 16, November 1995.

[12] M. De Lisio, S.W. Duncan, D.-W. Tu, S. Weinreb, C.-M. Liu, and D Rutledge, "A 44-60 GHz Monolithic pHEMT Grid Amplifier," to be presented in the *1996 IEEE MTT-S Int. Microwave Symposium.*

[13] P. Asbeck, F. Chang, K.-C. Wang, G. Sullivan, D. Cheung, "GaAs-Based Heterojunction Bipolar Transistors for Very High Performance Electronic Circuits," *Proceedings of the IEEE,* vol. 18, pp. 1709–1726, December 1993.