# 44 GHZ HYBRID HEMT POWER AMPLIFIERS

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## ABSTRACT

Doped Channel 0.25µm gate length InGaAs Pseudomorphic HEMTs developed in our laboratory have exhibited state-of-the-art power performance at millimeter wave frequencies, including output power density of 0.93 W/mm and power added efficiency of 41% at 44 GHz. Using these devices, two Q-Band hybrid power amplifiers have been developed. A two-stage design has produced 108 mW output power gain with 9.5dB and 26.5% power added efficiency. A three-stage design produced 251mW output power with 13.6dB of gain and 26.8% power added efficiency. The peak efficiency of the three stage amplifier was 31.3% when biased differently. The linear gain of these amplifiers was 12 and 20 dB respectively. These results clearly show the potential of these devices for millimeter wave transmitters.

## INTRODUCTION

Three-terminal devices have recently demonstrated potentially useful power amplifier performance at 44 GHz [1]-[3]. These devices promise the potential for high reliability and high efficiency power amplifiers at this frequency, a condition not easily obtainable with the more conventional approaches of tubes and IMPATT devices. However, the previously reported transistor amplifiers [1]-[3] have not produced the kind of output powers and efficiencies necessary for most transmitter applications. output powers of 60-100mW are typical and efficiencies are unreported.

High Electron Mobility Transistors (HEMTs) have demonstrated excellent transistor power performance in recent years, simultaneously providing high power density and high efficiency [4]. In this paper we report the development of 44 GHz multi-stage power amplifiers based on 0.25µm gate length InGaAs pseudomorphic HEMTs developed in our laboratory. The circuits were designed with standard CAD techniques and software using approximations based upon small signal models and DC parameters. To our knowledge, these amplifiers have delivered the highest output power and efficiency to date at this frequency.

| Gate Width (µm) | Output Power (mW) | Power Density (W/mm) | Power-Added Efficiency (%) | Power Gain (dB) |
|---|---|---|---|---|
| 150 | 119 | 0.79 | 41.2* | 5.1 |
| 75 | 65.9 | 0.93* | 31.5 | 4.8 |

*Biased and Impedance-Matched to Maximize this Parameter

Table 1. 44 GHz Power Performance of Doped Channel Pseudomorphic Device Structures.

## DEVICE DESCRIPTION

The devices used were based on an AlGaAs/InGaAs/GaAs pseudomorphic layer structure which offers several advantages over conventional HEMT materials for power applications. These advantages include a true quantum well structure between the AlGaAs and GaAs and a larger conduction band energy discontinuity at the heterojunction, allowing higher currents and less substrate injection [5]-[6]. For this project additional dopants were added to the channel layer. The doped channel structure offers further improvements in current density, confinement, and breakdown voltage when compared to the basic pseudomorphic HEMT structure. As can be seen in Table 1, this device has demonstrated state-of-the-art performance at 44 GHz.

## AMPLIFIER DESIGN

Two amplifiers, one two-stage and one three-stage design, were fabricated. Generalized schematics showing the basic circuit topology of the two and three stage amplifiers are shown in Figure 1. DC blocking was accomplished using $\lambda/4$ coupled line sections between each stage and before each waveguide transition. The two-stage amplifier was designed first and utilized a simpler circuit with only one size of device (150µm gate periphery). The three-stage circuit was slightly more complicated and used a progressive chain of increasing gate periphery in order to maximize the efficiency of the amplifier. The three stage circuit topology was optimized to improve bandwidth and decrease sensitivity to amplifier fabrication variations.

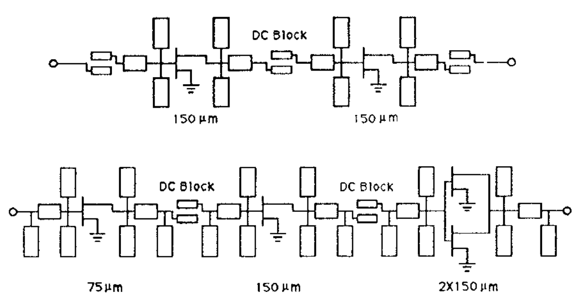


Figure 1. Generalized Amplifier Schematics.





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The circuits were fabricated on 0.010 inch thick quartz and used basic microstrip circuit elements such as open stubs, high and low impedance sections, and $\lambda/4$ coupled line sections as shown in the schematics in Figure 1. Not shown in the schematics are the bond wire inductances, which are sensitive tuning elements in all hybrid circuits. In this design, the bond wire inductances were minimized in order to reduce their total effect on the circuit, although their values were calculated based on the number of wires used and their length. Matching element values were then determined using standard matching techniques on a linear CAD system.

The complete three-stage amplifier (without housing cover) is shown in Figure 2. Both amplifiers used a stepped ridge waveguide to microstrip transition that was designed in our laboratory using an internally developed CAD program. A fixture consisting of back-to-back transitions has been tested from 40-50 GHz and has demonstrated 0.8 dB +/- 0.1dB loss over that band.

Due to the approximations involved, all circuits were designed to allow for tuning. This is one of the advantages of the hybrid approach, which not only allows for the selection of optimum devices, but also allows for the empirical tuning of circuits after fabrication. Tuning can be accomplished by the use of gold wires or ribbon bonded to pads provided in the circuit design.

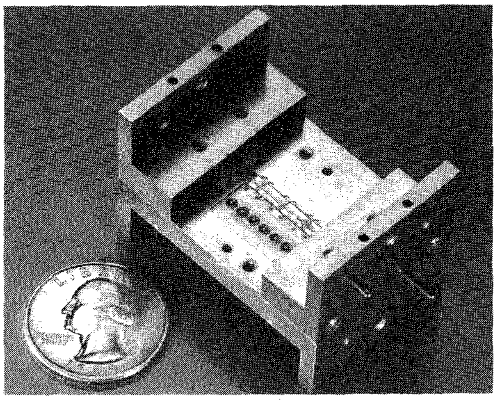

Figure 2. Three Stage Amplifier Housing and Circuit.

For our design method we utilized linear CAD techniques to approach the nonlinear problem by way of approximation [7]-[8]. Using a small signal model derived from 2-20 GHz S-Parameter measurements and a load line derived from DC I-V characteristics, a new linear model was defined by changing the values of some of the elements and inserted into the CAD system. This new model approximated the necessary impedances required in order to force the full voltage and current swings of which the device is capable while at the same time absorbing the parasitics of the device. Impedances derived in this manner have produced good large signal responses in our single stage circuits.

## AMPLIFIER PERFORMANCE

The amplifiers were tuned for power performance at 44 GHz using a klystron source with an automated power measurement system which automatically sweeps the input power and calculates the performance. The two-stage amplifier performance versus input power is shown in Figure 3. Peak power was 108mW with 9.5 dB gain and 26.5% power added efficiency. Linear gain was approximately 12 dB.

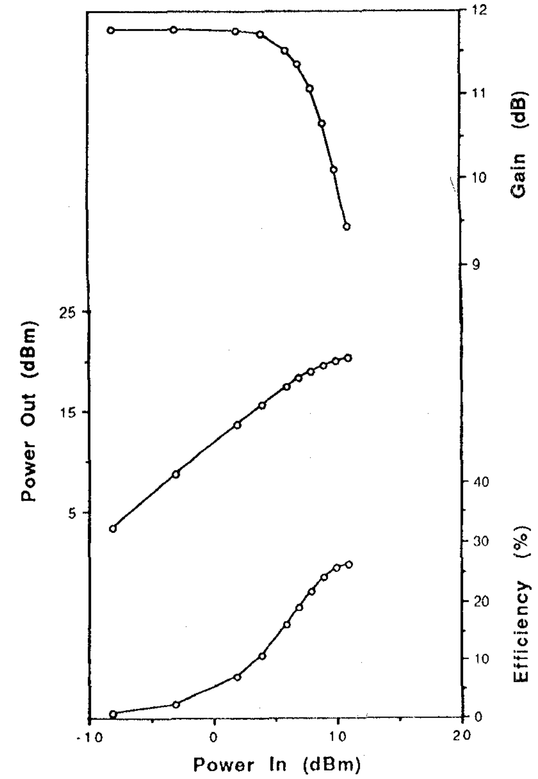


Figure 3. Power Performance vs Power In for Tuned 2-Stage Amplifier.

| Number of Stages | Output Power (mW) | Power-Added Efficiency (%) | Power Gain (dB) | Linear Gain (dB) | DC Power (mW) |
|---|---|---|---|---|---|
| 2 | 108 | 26.5 | 9.5 | 11.8 | 363 |
| 3 | 251 | 26.8 | 13.6 | 19.8 | 896 |
| 3 | 202 | 31.3 | 13.5 | 19.7 | 616 |

Table 2. 44 GHz Power Performance of Multi-stage Hybrid HEMT Amplifiers.

The three-stage amplifier in its untuned state produced 11-13 dB of gain over a fairly broad band (see Figure 4). Center band return loss was 15 dB. The tuned power performance is shown in Figure 5. Peak power was 251mW with 13.6 dB of gain and 26.8% power added efficiency with a linear gain of approximately 20 dB. The three-stage amplifier produced higher efficiencies when the stages were biased at slightly lower drain voltages. Power added efficiency peaked at 31.3% with 13.5 dB gain and 202 mW output power. The amplifier performance and DC power consumption of the two amplifiers is shown in Table 2.

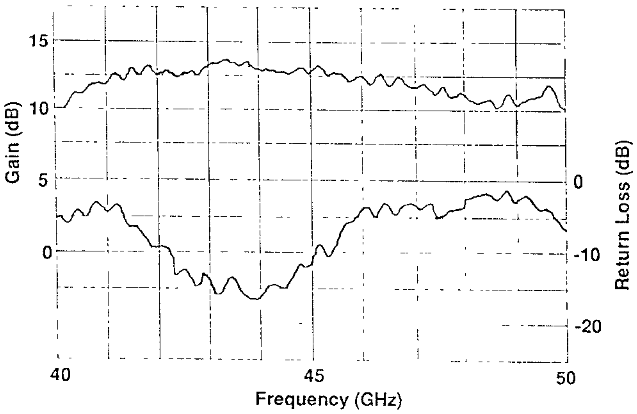


Figure 4. Small Signal Gain and Return Loss of Untuned 3-Stage Amplifier Circuits.

## FUTURE IMPROVEMENTS

Although these results are promising, there is always a demand for more power and better efficiency. That demand will be met through further device development. Larger gate width devices should be capable of generating more than 0 5W at 44 GHz in a single device. We have also developed shorter gate length devices (0.1-0.15µm) which have demonstrated improved gain and efficiency in comparison with similar 0.25µm devices [9]. Through further layer structure optimization and gate length reduction we will improve gain and efficiency performance of these HEMTs. We believe power densities already demonstrated by these devices are high enough; any higher densities would begin to degrade device reliability due to the increase in channel temperature.

In addition to improving device performance, our amplifier design methods can also be improved. Present designs are based on small signal measurements from 2-20 GHz extrapolated to the design frequency. By using coaxial network analyzers now available we can measure S-Parameters up to 40 GHz, which will reduce our extrapolation error. New nonlinear modeling software is now more accurate and can more easily be used in circuit design to replace our approximation methods, although they still fall short at modeling HEMT nonlinearities. Inaccuracies of microstrip models and nonlinear models can be partially compensated for through experience in tuning which indicates empirical adjustments to circuit designs. Through improved design methods it should be possible to develop hybrid power amplifiers that exhibit better performance and require minimal tuning.

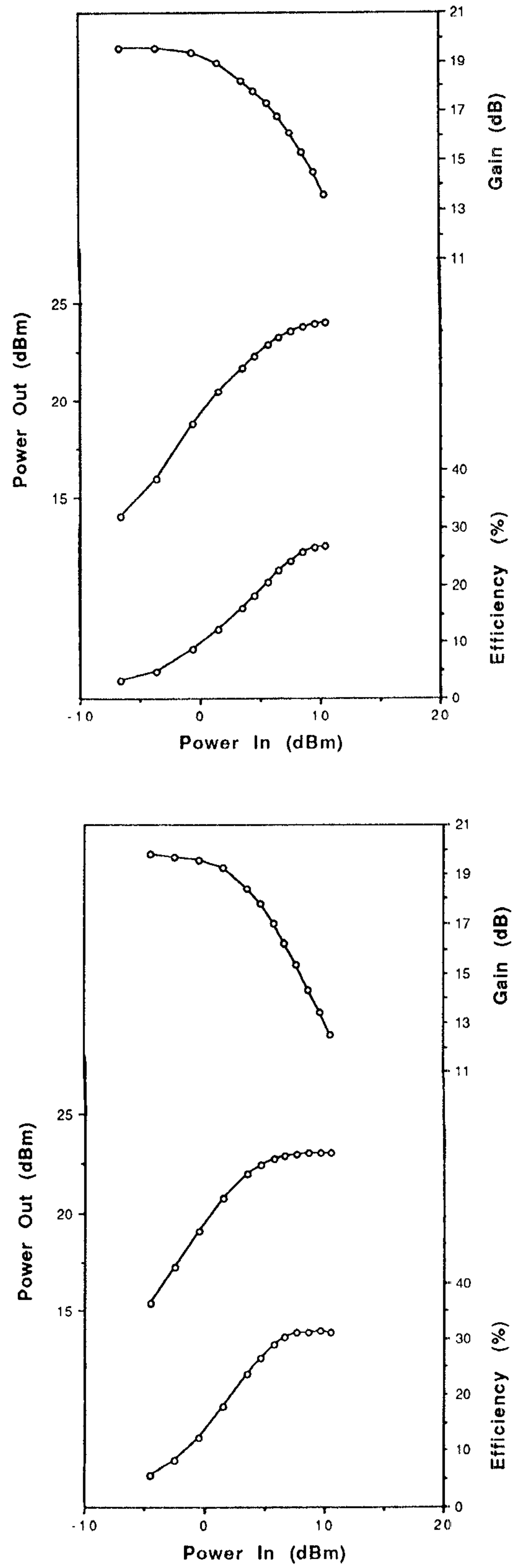


Figure 5. Power Performance vs Power In for 3-Stage Amplifier Tuned for Power (top) and Efficiency (bottom).

## SUMMARY

Two state-of-the-art hybrid power amplifiers based on pseudomorphic HEMTs have been demonstrated at 44 GHz. A preliminary two-stage design yielded 108mW output power and 26.5% power added efficiency. A three stage design has produced a peak power of 0.25 Watt and a peak efficiency of 31.3% To our knowledge, these results represent the highest output powers and efficiencies yet reported from a GaAs transistor-based amplifier at this frequency. Through further device optimization and increase in gate width, a 1 watt amplifier with comparable efficiency is feasible. These hybrid power amplifiers based upon pseudomorphic HEMTs are an attractive alternative for designers of future millimeter-wave transmitters.


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