22 GHZ PERFORMANCE OF THE PERMEABLE BASE TRANSISTOR

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Abstract - Small-signal and power performance of GaAs permeable base transistors (PBTs) at 22 GHz is reported. A small-signal gain of 14.5 dB was demonstrated over a 1 GHz bandwidth from a device having a 3200-Å-periodicity base grating and an 8 x 20 μm^2 active area. A similar device, biased for Class AB operation, achieved 45% power-added efficiency with an output power of 83 mW, and an associated gain of 5.7 dB. We believe this to be the highest reported efficiency of any device operating at this frequency and power level. An output power of 210 mW with 4.7 dB of gain and 37% efficiency were obtained from a larger device having an 8 x 40 μm^2 active area. A pair of these large devices in parallel delivered 370 mW with 3.7 dB gain and 33% efficiency, and 410 mW with 3.1 dB gain and 31% efficiency.

I. INTRODUCTION

In the design of EHF systems, transmitter performance is usually one of the chief design drivers. Transmitter output power limits system performance, while transmitter power consumption, size, and cost often dominate other system components. Currently, most state-of-the-art, solid-state, EHF transmitters employ IMPATT diodes in their output stages, resulting in relatively large, inefficient designs. IMPATTs usually require circulators or couplers to separate input from output signals and to provide interstage isolation. Many low gain, low efficiency devices must be employed, converting much of the system's prime power into heat.

At moderate microwave frequencies, conventional field-effect transistors (FETs) provide efficient power amplification in a relatively small amount of space. Since they are three-terminal devices with inherent input/output isolation, no circulators or couplers are needed. As the operating frequency increases, power FET performance becomes limited by lithographic constraints and by gate voltage distribution problems. In contrast, due to its structure, the permeable base transistor does not encounter these problems until much higher frequencies, allowing it to provide superior power amplification performance.

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This paper reports on the GaAs PBT's performance at 22 GHz. 22 GHz was a convenient operating frequency for these experiments due to the availability of test fixtures and measurement equipment in this band. Additionally, having previously built 22 GHz FET power amplifiers, we had a good benchmark for comparison.

II. DEVICE CHARACTERISTICS

Since the operation of the PBT has been described in detail elsewhere [1]-[5], only a brief description is included here. Figure 1 shows the cross section of the GaAs PBT. The PBT is a vertical device, in which the emitter and collector of the device are separated by a submicrometer-periodicity tungsten grating that forms the base of the transistor. Two large tungsten pads that connect the stripes of the tungsten grating provide the base contact. The collector and emitter contacts are made to the GaAs above and below the base grating.

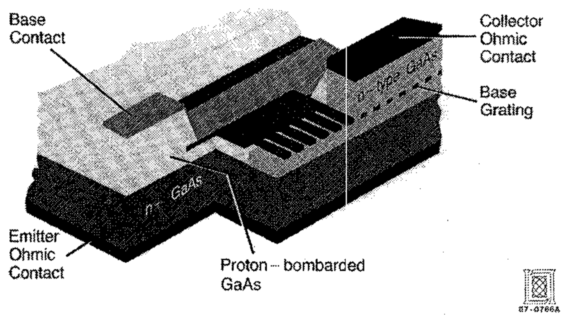

Figure 1 - Cutaway schematic of a GaAs PBT.

The structure of the PBT has several advantages over other devices for millimeter wave operation. It has a very short control region, determined by the base grating thickness and electron concentration, not by lithography. The PBT's physical gatelength is typically 30 nm, compared to 250 nm in state-of-the-art FETs and HEMTs. Additionally, the PBT is a very compact device, due to its vertical geometry. Large effective gatewidths can be achieved in small areas. For example, a PBT with an active area of 8 x 40 μm^2 has the same power handling capacity as a 0.5-mm-gatewidth FET, but the surface area consumed by the PBT is 25 times smaller. Large currents can be controlled by the PBT without gate voltage distribution problems at frequencies well into the EHF range.

III. SMALL-SIGNAL PERFORMANCE

A small-signal model for an 8 x 20 μm^2 GaAs PBT was derived (Figure 2) based on small-signal scattering-parameter measurements from 1 to 25 GHz, 1 MHz capacitance measurements, and dc I-V characteristics. The PBT has a feedback capacitance C_{BC} half that of a typical small-signal, submicrometer gate-length FET with comparable input capacitance C_{BE}. Due to the small amount of feedback presented by the C_{BC}/C_{BE} divider, the PBT is a highly unilateral device. At 22 GHz, $|S_{12}|$ is less than -25 dB. This high input/output isolation greatly simplifies matching network design and tuning.

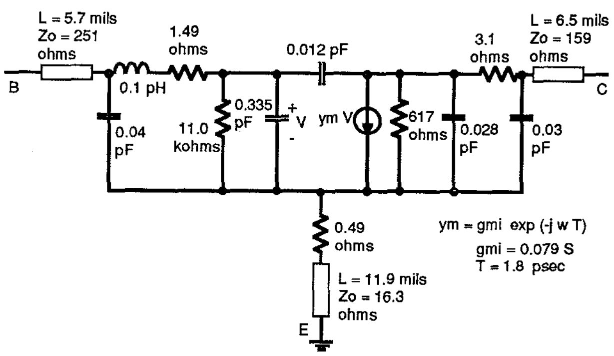

Figure 2 - Small-signal Model of 8 x 20 μm^2 GaAs PBT.

A small-signal 22 GHz amplifier was designed (Figure 3) using the model of Figure 2. From a Smith Chart plot of S_{11} and S_{22}, simple transmission line matching networks were synthesized and then optimized using Super-Compact.[1] The PBT and its input and output matching networks are mounted on a removable, gold-plated, tellurium-copper carrier, 0.25 in. wide and 0.05 in. thick. The microstrip matching networks were fabricated on 10-mil-thick alumina. The PBT is mounted in the center of the carrier on a web, the height of which has been designed to put the top surface of the PBT at the same height as the microstrip. Tapered pieces of gold mesh are used to connect the base and collector contacts to their respective matching networks . DC bias is provided through a pair of bias-tees based on quarter-wavelength low and high impedance transmission lines. Ferrite beads are placed on the bias feedthroughs to improve low frequency stability.

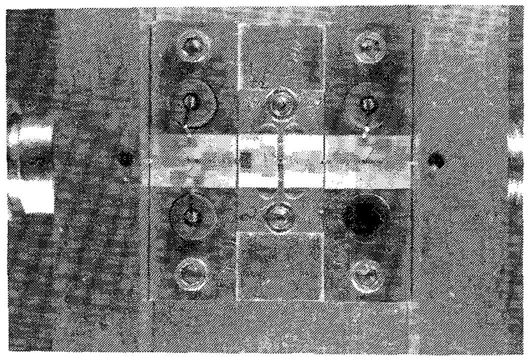

Figure 3 - 22 GHz Small-signal Amplifier

The measured response of this small-signal amplifier is shown in Figure 4. Including the bias network and fixture losses, this amplifier exhibited over 13 dB of gain across the 21.75 to 22.75 GHz operating band. Since the fixture and bias networks have 1.5 dB of loss, the PBT itself has over 14.5 dB of gain. These results were obtained with the PBT biased at V_{CE} = 2V, I_{CE} = 74mA, and V_{BE} = 0.6V. This bias point corresponds to the point of peak transconductance (g_m) for this device. Since the base-emitter junction is almost turned on, this bias point is unsuitable for power operation.

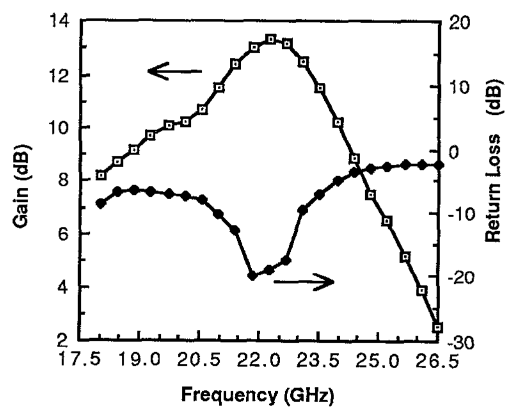

Figure 4 - Measured Response of Small-signal Amplifier.

1. Super-Compact is a trademark of Compact Software, Inc.

IV. POWER RESULTS

For our power amplifier work, the PBTs were again mounted on gold-plated tellurium-copper carriers. The PBT carrier was dropped into a simple through-line test fixture, with dc bias provided by external broadband bias tees. Unlike the small-signal amplifier described above, the input and output microstrip networks consisted of simple 50-ohm through-lines surrounded by arrays of bonding pads. This allowed us to measure the device small-signal scattering parameters from 0.045 to 26.5 GHz before starting the power experiments, and gave us the flexibility to evaluate many different matching networks for the same device.

Scattering-parameter measurements of an 8 x 20 μm^2 PBT show that its input impedance is fairly insensitive to dc bias (Figure 5). Holding V_{CE} constant at 3 V and varying I_{CE} from 1 mA to 60 mA (by varying V_{BE} from -0.6 V to +0.4 V) has only a slight effect on S_{11}. Similarly, holding I_{CE} constant at 20 mA and varying V_{CE} from 1 to 6 V has virtually no effect on S_{11}. This property allows the small-signal input matching network designed earlier to be used for power amplifier designs.

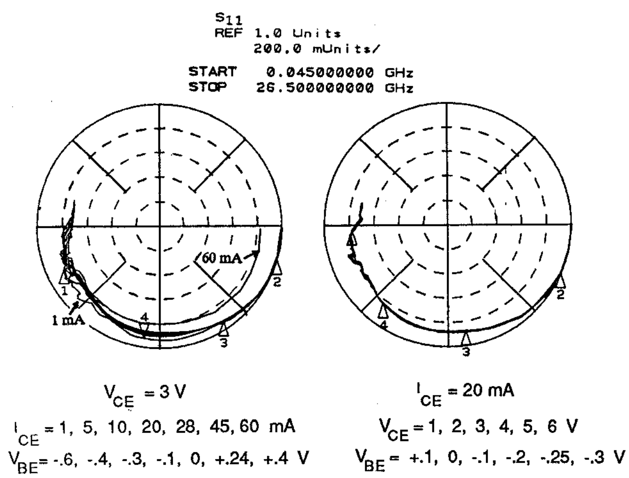

Figure 5 - S_{11} of 8 x 20 μm^2 PBT versus DC Bias.

For power operation, the base must be biased more negative than in the small-signal case, so that large-signal base voltage excursions do not forward bias the base-emitter junction. For these power experiments, the PBT was biased Class A ($I_{CEQ} \simeq I_{CEmax} \div 2$), Class B ($I_{CEQ} \simeq 0$), or Class AB ($0 \leq I_{CEQ} \leq I_{CEmax} \div 2$), where I_{CEQ} is the quiescent collector-emitter current and I_{CEmax} is the maximum collector-emitter current. A first-cut output matching network was designed from the low frequency optimum load resistance as determined from load-line analysis, along with the small-signal output reactances (C_{CE} and the output parasitics). Final output tuning was determined empirically, while observing large-signal gain and input return loss on a high-power scalar network analyzer. The output was re-tuned at each bias point and drive level.

Figure 6 shows the output power, gain, and power-added efficiency as a function of input drive level obtained from an 8 x 20 μm^2 GaAs PBT at 22.25 GHz. Fixture and bias network losses have been removed. This device exhibited a peak power-added efficiency of 45%, which we believe to be the highest reported efficiency of any device operating at this frequency and power level. The PBT was biased Class AB with V_{CE} = 5 V, and had an associated output power of 74 mW and a gain of 6.2 dB. Driving this PBT further into saturation resulted in an output power of 83 mW, with 5.7 dB gain and 45% efficiency. Biased Class B, with V_{CE} = 6 V, this same device delivered 106 mW with 5 dB of gain and 44% power-added efficiency.

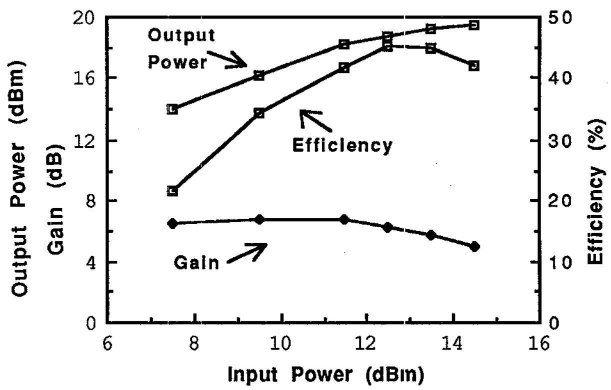

Figure 6 - 22.25 GHz Power Performance of 8 x 20 μm^2 PBT.

Using similar methods, an 8 x 40 μm^2 GaAs PBT, biased Class AB, achieved 37% power-added efficiency at an output power of 210 mW with an associated gain of 4.7 dB (again, at 22.25 GHz). The gain and power-added efficiency of this device were somewhat lower than that obtained from the smaller device, possibly due to heating. Although the 8 x 40 μm^2 device has twice the active area of the 8 x 20 μm^2 device, its thermal resistance is not half that of the smaller device, so it runs hotter (since it dissipates twice the power).

Mounting two 8 x 40 μm^2 devices from the same wafer in parallel on a single carrier resulted in 370 mW of output power and 3.7 dB of gain. At this operating point, this device pair had a 58% collector efficiency, but had a power-added efficiency of only 33% due to its low gain. Driven harder, this device delivered 410 mW of power with 3.1 dB gain and 31% power-added efficiency. Table 1 summarizes the 22.25 GHz power performance obtained from the various PBTs at different bias points and drive levels.

Device	Amplifier Class	V_{CE}	Output Power	Gain	Collector Efficiency	Power-added Efficiency
8x20μm^2	AB	5.0V	74mW	6.2dB	59%	45%
	AB	5.0V	83mW	5.7dB	61%	45%
	B	6.0V	106mW	5.0dB	64%	44%
8x40μm^2	AB	6.0V	210mW	4.7dB	56%	37%
	AB	6.5V	245mW	3.9dB	57%	34%
	B	6.0V	186mW	3.7dB	61%	35%
Double	AB	5.0V	370mW	3.7dB	58%	33%
8x40μm^2	AB	5.0V	410mW	3.1dB	60%	31%

Table 1 - GaAs PBT Power Performance at 22.25 GHz.

All of the above results have been obtained from relatively thick (6-7 mils) devices that have not been optimized for power. The thermal resistance of the 8 x 40 μm^2 PBT is approximately 600 °C/W, resulting in about a 140 °C temperature rise. To combat this thermal problem, new PBTs have been designed, employing both a much thinner wafer (less than 2 mils thick) and a new device layout [6]. In contrast to the present PBT design in which most of the heat must flow out through the emitter, the new design incorporates larger bonding pads to distribute the heat over a larger effective area. The thermal resistance of these new power PBTs is expected to be much less than half that of the current design. Gains and efficiencies should improve due to decreased heating. In addition, the reduction in chip thickness will decrease the emitter inductance of the PBT, resulting in further performance improvement.

V. CONCLUSIONS

The GaAs PBT shows great potential as both a small-signal and power device at microwave and millimeter-wave frequencies. At 22 GHz, 14.5 dB of gain was obtained in small-signal operation, while 5.7 dB gain, 45% power-added efficiency, and 83 mW were achieved in power operation from an 8 x 20 μm^2 PBT. Larger devices delivered 210 mW and 370 mW at power-added efficiencies of 37% and 33%, respectively. Even better results are expected from a new PBT power design, incorporating a much thinner wafer and a new device layout.

Sometime in the not-too-distant future, EHF transmitters may be able to replace part or all of their large, inefficient IMPATT output stages with much smaller, more efficient three-terminal devices. In the interim, efficient three-terminal devices driving high-power, high-efficiency varactor doublers [7] may be an attractive approach. While power FETs are limited by lithography and distributed gate effects at higher microwave frequencies, the PBT is free from these problems and may prove to be the three-terminal power device most suited for millimeter-wave operation.

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