Highest Efficiency, Linear X-Band Performance Using InP DHBTs–48% PAE at 30 dB C/IM3

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***Abstract*—InP single heterojunction bipolar transistors have previously demonstrated 5–10 dB lower third-order intermodulation products (IM3) compared to GaAs heterojunction bipolar transistors (HBTs) under low voltage (2 V) operation [1]. This paper reports excellent single-tone and two-tone X-band operation, including high two-tone power-added efficiency (PAE), on linear InP double heterojunction bipolar transistors (DHBTs) operated at $V_{\rm ce} = 4$ V. The InP DHBT demonstrated a 30 dB carrier to third-order intermodulation product (C/IM3) output power ratio simultaneously with 48% two-tone PAE. This is the highest known efficiency of an X-band device under linear (30 dB C/IM3) operation. This is especially significant for microwave power amplifiers for satellite communication transmitters, where lower intermodulation distortion is normally accomplished by backing off in RF drive and output power, thus sacrificing PAE performance.**

***Index Terms*—InP DHBT, intermodulation distortion, linear efficiency, linear HBT, linear power amplifier.**

I. Introduction

The advantages of single-supply and low–voltage operation, as well as the need for efficient linear power amplifiers for commercial wireless communication applications, are well documented. Nonlinearities in power amplifiers for communication transmitters result in higher intermodulation distortion and raise the bit error rate. GaAs heterojunction bipolar transistor (HBT)-based power amplifiers are a possible efficient, microwave power amplifier solution toward achieving linear performance. Common emitter (CE) AlGaAs/GaAs HBTs have shown 7 GHz performance of -20 dBc IM3 and 12% PAE per tone at the 1 dB gain compression point, with IM3 dropping to -30 dBc at 1.5 dB output power backoff [2].

Previous work on InP HBTs [1] demonstrated the superior third-order intermodulation distortion and fifth-order intermodulation distortion (IM5) characteristics of low-voltage, commercial wireless communication GaAs, and InP HBT power amplifiers and suggested that InP HBT power amplifiers could achieve 5–10 dB lower IM3 and IM5 compared to GaAs HBTs under low voltage (2 V) operation. In lower power and lower power density applications, InP DHBTs provide an even greater advantage over GaAs HBTs in achieving linear performance [high, 30 dB carrier to third-order intermodulation product (C/IM3)] simultaneously with high power-added efficiency (PAE) (48% two-tone PAE), without requiring as much backoff in RF drive and output power.

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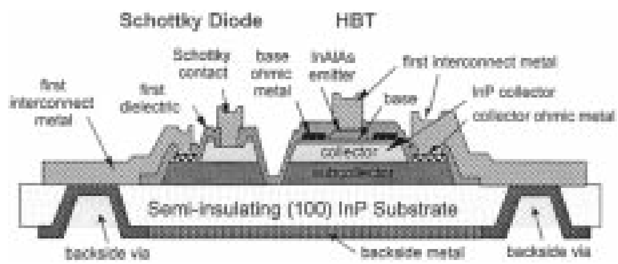


Fig. 1. InP HBT device and IC technology.

II. HBT and InP DHBT Linearity

It has been previously reported [3] that III–V based HBTs inherently possess an advantage in voltage immunity $C_{\rm cb}$ characteristics, which can result in less output distortion. HBTs can provide a fixed linear $C_{\rm cb}$ capacitance at a low-voltage bias in a region where the collector is fully depleted of carriers. This constant $C_{\rm cb}$ can be achieved by using a lightly doped collector region. During low voltage reverse bias operation, the collector-base junction behaves like a reversed-bias p-i-n diode whose microwave linearity characteristics improve the output linearity of the HBT device.

As shown in Fig. 1, the InP DHBT consists of InAlAs/InGaAlAs/InP emitter-base-collector layers. The wide bandgap InP collector forms a base-collector heterojunction, resulting in high breakdown voltage and high cut-off frequency. The double heterojunction further reduces the offset voltage of the bipolar transistor, providing near-ideal I-V characteristics [1]. The $1.5\times 30\ \mu{\rm m}^2\times$ two- finger InP DHBT which was evaluated for linearity and efficiency had a $V_{\rm knee} < 1$ V @ 53 kA/cm^2 and a $V_{\rm offset} < 50$ mV.

The HBTs constant $C_{\rm cb}$ at low voltage bias, combined with the high breakdown voltage (and cut-off frequency) associated with the InP collector and the reduced offset voltage resulting from the double heterojunction, result in a InP DHBT with excellent linearity and efficiency. The measured single-tone and

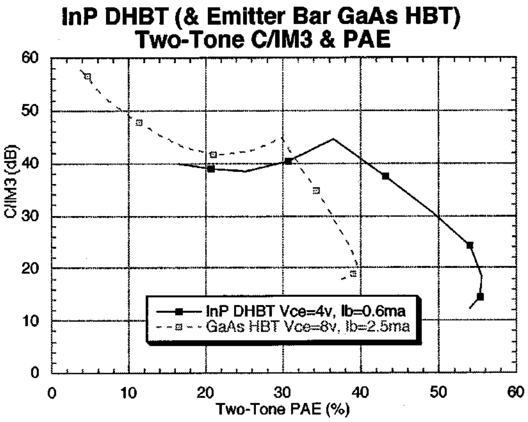


Fig. 2. C/IM3 ratio (carrier to third-order intermodulation product output power ratio) versus two-tone power-added efficiencies for the InP DHBT and the GaAs HBT.

TABLE I
InP DHBT UNDER RF BACKOFF TEST CONDITIONS (1 dB GAIN COMPRESSION)

(10 GHz)					
Single-tone:	Pin avail	Pout	Gt	PAE	
	4.0 dBm	15.8 dBm	11.8 dB	50.1%	
	(f1 + f2)	(f1 + f2)			
Two-tone:	Pin avail	Pout	Gt	PAE	C/IM3
	4.0 dBm	15.3 dBm	11.3 dB	48.2%	30.2 dB

two-tone results for InP DHBTs in the following section highlight the saturated (and backed-off) efficient C/IM3 advantage of these devices.

III. TWO-TONE VERSUS SINGLE-TONE RESULTS FOR THE InP DHBT AND THE GaAs HBT

The single-tone (10 GHz) and the two-tone (100 kHz tone-spacing) measurements were performed with a Maury microwave automated tuner system on two-finger InP DHBT cells with 1.5-μm emitter widths, 30-μm emitter lengths, and total emitter area of 90 μm^2. Measurements were also performed on similarly sized CE AlGaAs/GaAs HBTs which were two-finger cells with 2-μm emitter widths, 25-μm emitter lengths, and having total emitter area of approximately 100 μm^2. The InP DHBT had an $f_t = 80$ GHz and an $f_{\max} = 160$ GHz. The lower frequency, higher operating voltage, higher power GaAs HBT had an f_t and an $f_{\max}$ approximately half the InP DHBT values. The device inputs were conjugately matched to deliver optimum input power ($P_{\text{in\_deliv}}$) to the device. The output was matched for maximum PAE. The two-tone HBT measurements were accomplished at high RF drive levels to determine linearity in saturation, C/IM3, rather than linearity based on the third-order intercept point or a linearity figure of merit.

RF drive levels and output power (P_{out}) for two-tone measurements refer to the total power with both tones (f_1 and f_2) present. As shown in Fig. 2 and the summarized data in Table I, the result was extremely high C/IM3 ratios simultaneously with high PAE performance, 30 dB and 48%, respectively, for the InP DHBT. This was achieved at a dc bias of $V_{\text{ce}} = 4$ V and $I_b = 0.6$ mA. The C/IM3 results reflect third-order intermodulation product nulls, typical in HBTs.

The bias-dependent data in Fig. 3 also confirms high ($> 50\%$) PAE simultaneously with > 26 dB C/IM3 ratios for various InP DHBT dc biases. Of further significance, and shown in Fig. 4, is that the InP DHBT two-tone saturated power performance

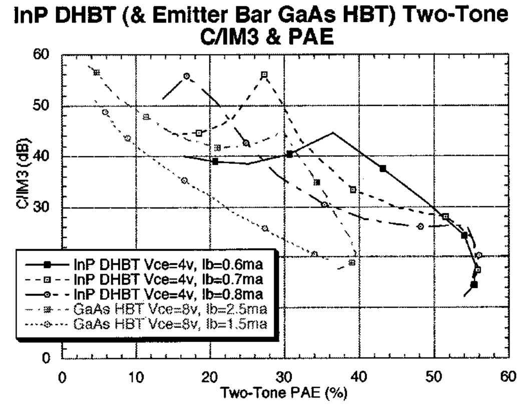


Fig. 3. Bias-dependent C/IM3 ratio (carrier to third-order intermodulation product output power ratio) versus two-tone power-added efficiencies for the InP DHBT and the GaAs HBT.

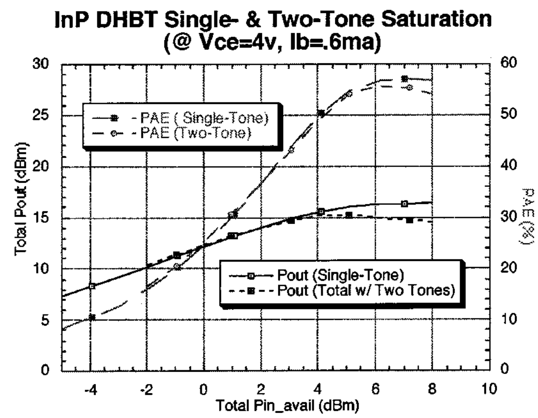
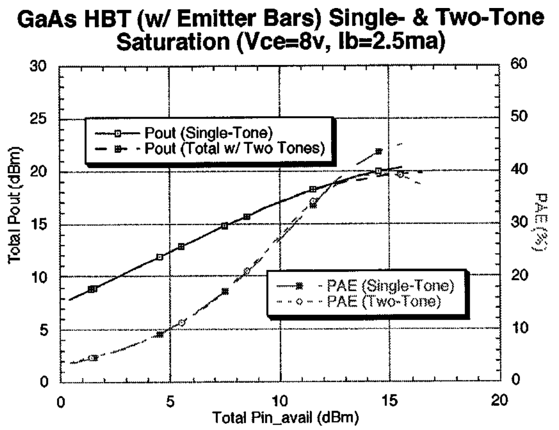


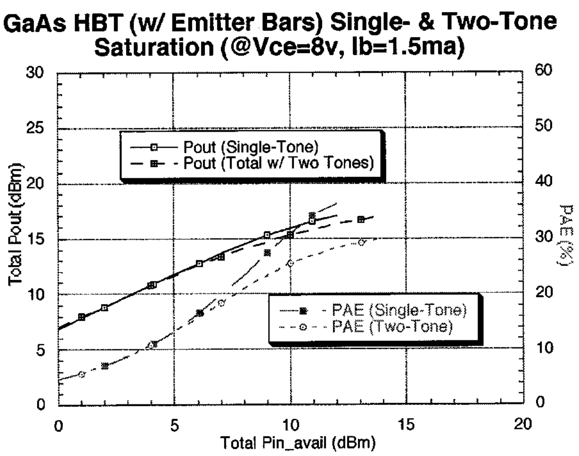
Fig. 4. Single-tone output power (as well as total two-tone output power) and single-tone power-added efficiency (as well as two-tone power-added efficiency) versus $P_{\text{in\_avail}}$ (power available at the device input). The InP DHBT demonstrated $> 55\%$ single-tone (10 GHz) and two-tone peak PAEs.

TABLE II
GaAs HBT UNDER RF BACKOFF TEST CONDITIONS (1 dB GAIN COMPRESSION)

(10 GHz)					
Single-tone:	Pin avail	Pout	Gt	PAE	
	12.5 dBm	18.9 dBm	6.4 dB	38%	
	(f1 + f2)	(f1 + f2)			
Two-tone:	Pin avail	Pout	Gt	PAE	C/IM3
	12.5 dBm	18.7 dBm	6.2 dB	37%	27.5 dB



(a)



(b)

Fig. 5. GaAs HBT single-tone output power (as well as total two-tone output power) and single-tone power-added efficiency (as well as two-tone power-added efficiency) versus $P_{\mathrm{in\_avail}}$ (power available at the device input): (a) $I_b = 2.5$ mA, (b) $I_b = 1.5$ mA.

is only slightly reduced in comparison to single-tone saturated performance, with two-tone peak PAE remaining $> 55\%$.

Similar single-tone and two-tone evaluation was also performed on the 100 μm^2 GaAs HBTs described above, while they were biased and matched for optimum PAE. As shown in Fig. 2 and in Table II, C/IM3 ratios of 27.5 dB were achieved simultaneously with 37% PAE with the GaAs HBT. Further, Figs. 5(a) and (b) illustrate that the degradation in the GaAs HBTs two-tone peak PAE, as compared to its single-tone peak PAE value, was greater than in the case of the InP DHBT.

Another measure of comparison is Class-A IM3 results on a CE HBT as reported in [2]. The CE HBT single-tone test resulted in 23.8 dBm output power at 1 dB gain compression, with PAE of 41.8%. In the two-tone test, 19.63 dBm output power per tone was achieved at 1 dB compression, which was 4.2 dB lower than the single-tone $P_{-1\ \mathrm{dB}}$. This implies a total two-tone output power approximately 1.2 dB lower than the single-tone $P_{-1\ \mathrm{dB}}$ output power. Further, the CE HBT reported PAE for each tone reached only 12.4% at the 1 dB compression point.

IV. Conclusion

InP DHBTs can meet stringent performance requirements in transmit applications involving low-voltage microwave power components for lightweight satellite communications systems. These reported InP DHBTs linearity and power results demonstrate that this advancing device technology is a critical material system and device structure for linear, efficient microwave power applications. Of significance is that the measured InP DHBTs, unlike the measured GaAs HBTs, maintained extremely high PAEs (48%) under two-tone operation, while simultaneously displaying C/IM3 performance of 30 dB. Further, under two-tone saturated power conditions, the InP DHBTs two-tone peak PAE remained $> 55\%$, which was only slightly reduced in comparison to its 10 GHz single-tone peak PAE.

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