HVHBT Doherty and Envelope Tracking PAs for High Efficiency WCDMA and WiMAX Basestation Applications

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Abstract **— HVHBT GaAs technology has been shown to be suitable for use in two leading power amplifier efficiency enhancement solutions: (1) Doherty and (2) Envelope Tracking. Each solution demonstrates the unique high efficiency characteristic of HVHBT GaAs technology. In both of these cases HVHBT GaAs has demonstrated highest efficiency among all evaluated technologies.**

In this paper we will compare Doherty and Envelope Tracking solutions utilizing HVHBT technology. HVHBT results achieved in 2-way symmetric and asymmetric Doherty configurations are compared with recent Envelope Tracking (ET) results reported by researchers at UCSD. Although HVHBT/Doherty is very simple to implement, the advantages offered by HVHBT/ET including very high overall average-power PAE, increased available peak power, very low correction gain, wider tunable bandwidth, and improved thermal management together make HVHBT/ET solution a compelling alternative for high efficiency Power Amplifiers.

Index Terms **— GaAs HVHBT, Doherty, Envelope Tracking, efficiency, WCDMA, WiMAX, digital pre-distortion, power amplifier.**

I. INTRODUCTION

On-going developments in High Voltage Heterojunction Bipolar Transistor (HVHBT) GaAs technology continue to enable significant advancement in WCDMA basestation RF power amplifier efficiency.

High power-added-efficiency (PAE) is a key enabler for modern basestation power amplifiers as system requirements drive toward use of higher peak to average ratio (PAR) signals in conjunction with limited available cooling and lower DC power consumption requirements. Achieving high average-power PAE, while maintaining tight error vector magnitude (EVM) and ACLR specifications, is a challenge for high peak to average ratio WCDMA, WiMAX, and LTE signals.

For the output stage, two leading efficiency enhancement solutions under evaluation are Doherty and Envelope Tracking (ET). HVHBT technology is shown to be compatible with both efficiency enhancement solutions achieving very high efficiency, with HVHBT/ET showing the best overall PAE. GaAs HVHBTs are especially well suited for ET application since they can provide both high efficiency and gain over a wide dynamic range signal.

In previous work [1] we presented a 2-way symmetrical 250W_{pk} HVHBT Doherty that exhibits 57% collector efficiency (53% PAE) at 6dB backoff from P1dB and 62% collector efficiency (56% PAE) at 6dB backoff from Psat. Exceeding efficiency reported for LDMOS[2] and GaN[3].

Recently we developed a 200W_{pk} HVHBT 2-way Asymmetric Doherty that shows 55% collector efficiency (49% PAE) at 9dB backoff from Psat surpassing results reported for a LDMOS Asymmetric Doherty [4] and a GaN symmetric Doherty with asymmetric drain bias [5] and much easier to implement compared to the novel 3-way mixed-signal Doherty proposed in [6]. The efficiency level of our asymmetric Doherty does not include mixed-signal techniques as used in [6] or asymmetric drain biasing as used in [5] and therefore could be further improved, in an actual basestation system, if baseband control of drive levels or asymmetric collector bias voltages is available.

In our previous work [7], GaAs HVHBTs were evaluated in an Envelope Tracking amplifier configuration by researchers at UCSD, surpassing results reported for LDMOS[8][9][10] and GaN[11]. Measurements reported show that the overall system exceeds the linearity requirements for WCDMA and WiMAX and achieves excellent overall efficiency (accounting for power dissipated by both the RF amplifier and the envelope amplifier).

In this paper we will compare Doherty and Envelope Tracking solutions implemented with HVHBT technology. HVHBT 2-way symmetric and Asymmetric Doherty configurations are compared with recent HVHBT Envelope Tracking results reported by researchers at UCSD. The 2-way HVHBT/Doherty is very simple to implement, however the advantages offered by HVHBT/ET including very high average power PAE, increased available peak power, very low correction gain, wider tunable bandwidth, and improved thermal management together make HVHBT/ET solution a compelling alternative for high efficiency power amplifiers.

II. 2-WAY DOHERTY AMPLIFIER

The 2-way Doherty amplifier is widely used in the industry today because it is very easy to implement, it is a drop-in replacement for class AB amplifier, and it is compatible with standard DPD techniques with no need for additional complex circuitry. However, since the efficiency boost of a Doherty amplifier is due to load modulation of the carrier amplifier [1], the efficiency boost occurs across a relatively narrow band and is sensitive to variation in phase offsets. In addition, the RF load modulation is optimized to boost efficiency at a specific level of backoff. Operating beyond this backoff level efficiency decreases rapidly. For example a 2-way symmetric Doherty is optimized for operation through 6dB backoff while a 2-way 3dB-Asymmetric Doherty is designed to be operated a 9dB backoff.

HVHBT technology is well suited for Doherty operation due to very high efficiency at 2*Zopt for symmetric and 3*Zopt for 3dB-asymmetric load conditions where P1dB efficiency exceeds 75%, making a highly efficient carrier amplifier. In addition, the off-state impedance is very high, permitting the peaking amplifier to present a near ideal open at the combiner TEE for power levels at and below the target backoff. To explore the advantages of HVHBT technology, we developed a 2-way symmetric and a 2-way asymmetric Doherty amplifier using HVHBT-GEN1 technology.

A. 2-Way Symmetric HVHBT/Doherty Amplifier

A 2-way symmetric Doherty amplifier was designed to boost efficiency at 6dB Output-Back-Off from P1dB (OBO) [1]. The Doherty amplifier is composed of a main amplifier and a peaking amplifier, where a 100W HVHBT module is used for each shown in Figure 1.

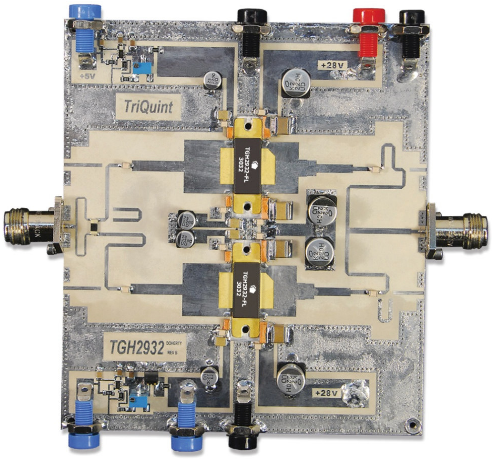

Fig. 1. 2-Way Symmetric Doherty (6dB Backoff Boost).

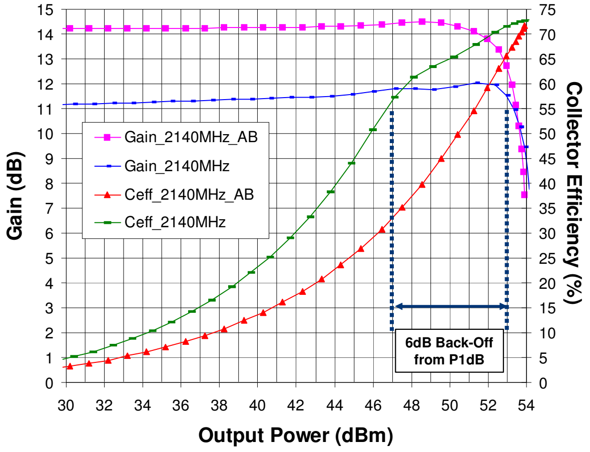

Fig. 2. 2-Way Symmetric Doherty CW Pin/Pout

Figure 2 shows CW performance. CW saturated output power is 54dBm (250W) and P1dB at 53dBm (200W). At 6dB OBO, output power is 47dBm (50W) and corresponding Doherty efficiency is greater than 57%.

WCDMA linearity was characterized with a 2-carrier side-by-side WCDMA signal with 6.5dB PAR. Linearization was accomplished using a PALADIN®15 adaptive DPD test system, provided by PMC Sierra. Greater than 57% collector efficiency at 47dBm (50W) average output power has been demonstrated while achieving –55dBc linearized ACPR at 5MHz offset. At this condition correction gain is near 3dB.

B. 2-Way Asymmetric HVHBT/Doherty Amplifier

A 2-way asymmetric Doherty amplifier was developed to boost efficiency at 9dB backoff form P1dB [12]. The Doherty amplifier consists of a 50W amplifier for the carrier amplifier and a 100W amplifier for the peaking amplifier shown in Figure 3. CW saturated power is greater than 200W (53dBm) and P1dB near 160W (52dBm). At 9dB backoff from P1dB, power is near 20W (43dBm) with collector efficiency near 55% (48% PAE) at 2140MHz as shown in Figure 4.

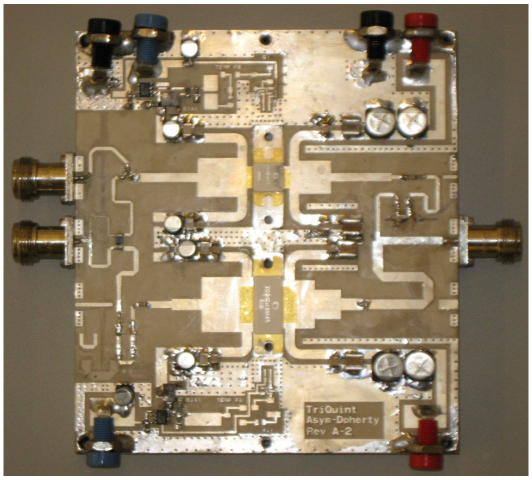

Fig. 3. 2-Way Asymmetric Doherty (9dB Backoff Boost) bed.

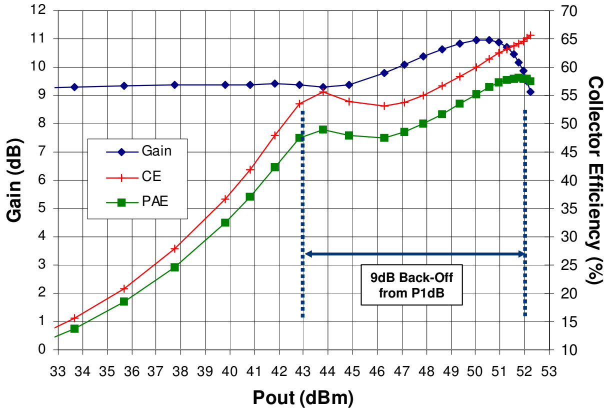

Fig. 4. 2-Way Asymmetric Doherty CW Pin/Pout

III. ENVELOPE TRACKING AMPLIFIER

Figure 5 shows a block diagram for an envelope tracking (ET) basestation amplifier. For envelope tracking (ET), the efficiency boost is achieved with DC bias modulation (as opposed to RF load modulation for the Doherty) effectively moving the efficiency boost operation into the baseband electronics which simplifies the RF amplifier design to a class AB style topology, enabling high efficiency to be achieved across a broader band (eliminating the band limiting affect related to RF load modulation for the Doherty). The overall system for Envelope Tracking is more complex compared to that required for a Doherty PA. The ET PA requires a high current collector modulator, a separate DPD path for the modulator, and time alignment of the collector and RF signal. However, the advantages offered by HVHBT/ET including very high overall average-power PAE for a wide range of signal backoff, increased available peak power, very low correction gain, and improved thermal management together make HVHBT/ET solution a compelling alternative for high efficiency power amplifiers. Modulating the collector voltage to track the envelope of the waveform greatly reduces power dissipated in the RF device as illustrated in Figure 6. To explore the suitability of HVHBT technology with envelope tracking, researchers at UCSD performed the following study.

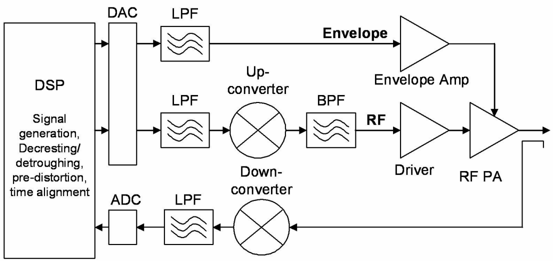

Fig. 5. Block diagram of envelope tracking basestation amplifier.

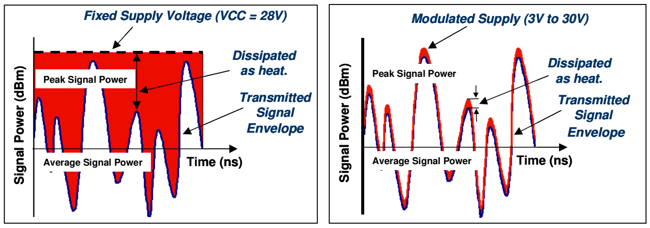

Fig. 6. Illustration of regions of dissipated power for fixed collector (left) and modulated collector (right).

A. HVHBT/ET Evaluation at UCSD

An HVHBT/ET amplifier was developed to boost efficiency for high PAR signals [7]. Testing was performed using an envelope tracking test bed developed at the University of California San Diego. Figure 7 shows a HVHBT amplifier co-located with the UCSD envelope amplifier. The 100W HVHBT-GEN1.5 device is mounted on a single ended class AB test fixture that has been optimized for power and efficiency at a constant 28V collector bias. RF matching was not modified for ET operation, an area for future investigation and potential improvement. Baseband envelope decoupling capacitors have been removed for compatibility with the envelope amplifier.

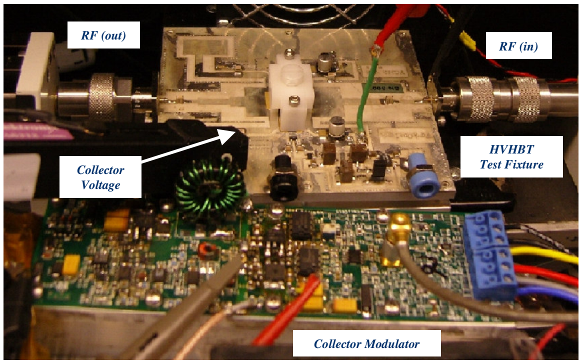

Fig. 7. HVHBT Test Fixture in UCSD ET test bed.

The UCSD test bed utilized for this effort was optimized for 5MHz signals, with future development focused on expanding capability of the test bed to handle 20MHz signals. Researchers at UCSD performed all ET testing including linearization using digital predistortion. Measurement of the high voltage envelope amplifier used in this work shows efficiency of approximately 71% for a 1xWCDMA signal. At full output power, the peak output voltage of the modulator was set to 29V and the RMS voltage was 12.8V.

B. HVHBT/ET Measurement Results

The HVHBT/ET PA was evaluated using a variety of waveforms including the UCSD benchmark single carrier WCDMA signal with 3.84 MHz bandwidth and peak-to-average power ratio of 7.7dB.

Figure 8 shows the measured AM-AM and AM-PM performance before pre-distortion, expressed in terms of the output signal envelope, plotted versus the corresponding instantaneous input signal envelope value recorded for a WCDMA waveform. Virtually all of the nonlinearity is

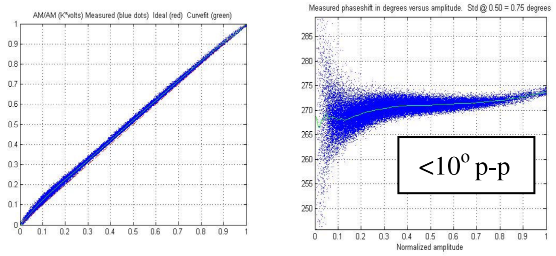

Fig. 8. Left, measured AM-AM distortion, Right, AM-PM distortion bottom, before predistorion, x-axis: normalized input amplitude on a linear scale. 1xWCDMA PAR=7.7dB

associated with AM/PM. The AM/AM characteristic is near ideal, a result of proper envelope tracking, suggesting DPD correction gain will be near 0dB. The scatter for the different values of input power indicates a modest memory effect and phase distortion. These characteristics are a first indication that digital pre-distortion (DPD) should function well.

Output WCDMA signal quality improves dramatically using DPD with memory mitigation. We observed greater than 57% PAE (including dissipation in both the RF amplifier and the envelope amplifier) at 45.2dBm (33.2W) average output power while achieving -70dBc linearized ACPR at a 5MHz offset using a single carrier WCDMA input signal with 7.7dB PAR measured at .01% on the CCDF. At this average power level, EVM measured to be 0.3% and correction gain was near 0dB as expected. Average linearized power increased by 1.2dB compared to constant collector operation.

Figure 9 shows the measured instantaneous collector efficiency versus collector voltage after linearization. Notice collector efficiency is very flat and near 85% efficiency from 7V to 29V. The output power tracks the square of the collector voltage and results in 85% collector efficiency over a 12.5dB range, well in excess of the 6dB range for symmetric Doherty amplifiers and 9dB for an asymmetric Doherty amplifier. This performance becomes especially important for maintaining high efficiency in average power back-off.

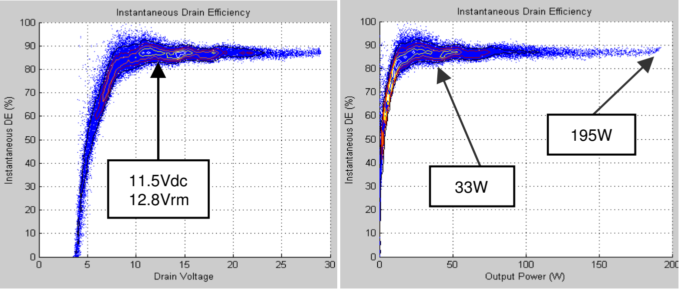

Fig. 9. Measured Power vs Instantaneous Collector Efficiency, 1xWCDMA 7.7dB PAR at 2140MHz

IV. HVHBT/ET VERSUS HVHBT/ DOHERTY

Figure 10 illustrates a comparison of Envelope Tracking and Doherty PA solutions implemented using HVHBT, GaN, and LDMOS for a PA final stage. The point of comparison is achievable PAE versus signal PAR.

First, let's look only at HVHBT (highlighted in blue). The 2-way symmetric Doherty is shown here with 53% PAE for a 6.5dB PAR waveform. The 2-way asymmetric Doherty is shown here at 49% PAE for 9.6dB PAR. Recall that these are two very different HVHBT Doherty designs, where the load modulation of each design is optimized to boost efficiency at a specific level of backoff. Therefore when a basestation transmitter is designed using a Doherty final, there will be little flexibility in using higher PAR modulation schemes beyond the target backoff, without significantly degrading efficiency, necessitating a hardware modification.

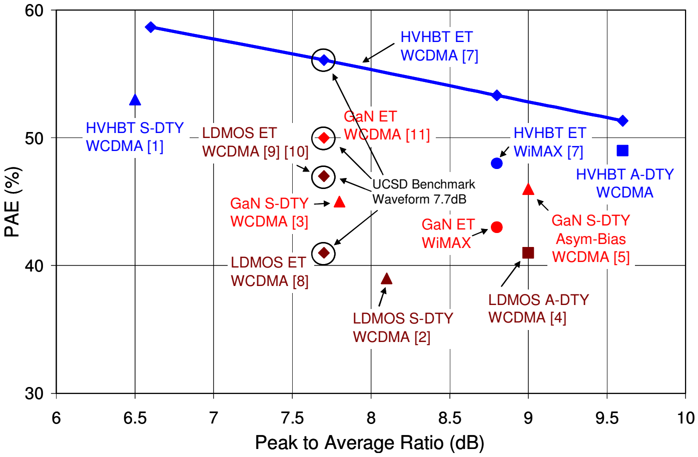

Fig. 10. PA final-stage efficiency versus signal PAR for HVHBT, LDMOS, and GaN in 2-Way Doherty and Envelope Tracking configurations.

Also shown in blue is HVHBT/ET. In this case, only one HVHBT/ET amplifier was built. The blue line represents WCDMA results measured on the same HVHBT/ET amplifier using 4 different PAR signals. In addition, the same HVHBT/ET amplifier was evaluated with a 10MHz WiMAX signal at 2140MHz and reported as a solid blue circle. The small decrease in PAE is due to increased dissipation in the collector modulator. Notice that the same HVHBT/ET amplifier is capable of achieving better than 50% efficiency for signals PAR spanning 6.5dB through 9.6dB. This gives unprecedented flexibility to basestation hardware, enabling use of different modulation signals with different PAR for the same hardware with little impact on average power PAE.

V. TECHNOLOGY COMPARISON

Shown in Figure 10, is Envelope Tracking and Doherty performance reported for HVHBT, GaN and LDMOS solutions. Comparing envelope tracking performance for different device technologies is relatively easy since researchers at USCD have published evaluation results of several technologies measured under similar conditions, using the same bias modulator, same test set, and using the same benchmark 1xWCDMA waveform with 7.7dB PAR.

Reported WCDMA performance of various 2-Way Doherty finals implemented with GaN and LDMOS are also shown in Figure 10. Please note that some small adjustments were applied in the case of [5] to convert from 50% drain efficiency to 46% PAE (we assumed 11dB gain). In the case of [3] we estimated the final stage efficiency by subtracting the reported driver dissipation and drive power from the overall lineup performance. For the various Doherty technologies in Figure 10, the reported test signals, test conditions, linearization methods, and achieved linearity vary in each case. Therefore, an accurate benchmark for technology comparison of Doherty amplifiers, similar to that offered by UCSD for envelope tracking amplifiers, is not presently available. As an example, for both of our reported Doherty amplifiers, a 5 point improvement in efficiency could be realized by reporting linearized efficiency at -50dBc instead of the reported -55dBc linearization level. Notice [2] and [3] report linearized efficiency at -50dBc. In addition there are other variables such as reporting efficiency versus signal crest factor as in the case of [6] or versus signal PAR which is more generally accepted as .01% probability on the CCDF. Also, in some cases, linearization is not applied, such as in [4] at -32dBc and [5] at -38dBc, which is reasonable since predistortion technology is generally not a core competency of device providers.

An alternate method of comparing Doherty efficiency would be to compare efficiency at a specific backoff level. However, the literature differs in reporting backoff from P1dB or backoff from Psat, and the measurement methods vary from CW (as in our case) to various forms of pulsed RF. Also, in Doherty, it is well known that AM/AM and AM/PM, a key ingredient to linearization, can be traded for efficiency, yet another variable. Therefore, accurate comparison of backoff efficiency is rather challenging. In our case, we report CW backoff performance after the PA has been adjusted for best linearization and verified using industry standard DPD.

The TriQuint authors applaud UCSD for providing a relatively unambiguous method for comparing linearized device performance in an envelope tracking configuration.

From the results reported in Figure 10, it is evident that HVHBT technology has demonstrated highest efficiency across a broad range of signal PAR when combined with Doherty and Envelope Tracking efficiency enhancement solutions for use in WCDMA, WiMAX, and LTE basestation applications.

VI. SUMMARY AND CONCLUSIONS

In this paper, we presented results for Doherty and envelope tracking power amplifiers using GaAs HVHBT technology. The symmetric Doherty is a relatively simple solution utilizing RF load modulation to achieve very high efficiency. Due to the characteristics of load modulation, the efficiency boost is band-limited and sensitive to variation in the phase offsets, requiring each design to be optimized for a relatively narrow range of WCDMA signals. However, Doherty is widely used due to inherent simplicity. On the other hand envelope tracking utilizes collector voltage modulation to achieve high efficiency b operating the RF amplifier in saturation across a wide dynamic signal range. Envelope tracking is much more complex to implement compared to Doherty, requiring a collector voltage modulator, a separate DPD path for the modulator, and modulator timing alignment. However, as an advantage, this technique does not limit the bandwidth of the RF amplifier, and a single design can achieve high PAE for a wide range of WCDMA and WiMAX signals.

HVHBT has been shown to be compatible with both efficiency enhancement techniques, achieving impressive performance in each technique with envelope tracking achieving best overall performance.

These results illustrate the potential of GaAs HVHBTs, in combination with advanced amplifier architectures, to achieve dramatic improvements in basestation power amplifiers.

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