A Fully-Integrated Highly-Efficient RF Class E SiGe Power Amplifier With an Envelope-Tracking Technique for EDGE Applications

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***Abstract*— This paper reports on the results of a highly efficient monolithically fully-integrated SiGe Class E power amplifier using envelope tracking techniques for EDGE applications. The Envelope-tracking (ET) system includes a discrete linear op-amp and a switching power converter. The RF Class E amplifier was fabricated in a 0.18μm BiCMOS SiGe technology. The RF Class E power amplifier achieved a collector efficiency (CE) of 62.7% and the overall power added efficiency (PAE) of the ET system is 44.4% at an output power of 20.4dBm for an 881MHz EDGE modulated signal. A discrete envelope switching amplifier achieved 82.8% efficiency while driving the Class E PA voltage supply. The linearized SiGe PA passed the stringent EDGE transmit spectrum mask**

***Index Terms*— power amplifier, switching amplifiers, heterojunction bipolar transistors**

I. Introduction

The SiGe heterojunction bipolar transistor (HBT) technology has been instrumental in increasing performance and reducing cost for wireless consumer products and handsets. A key benefit is the co-availability of high ft and high breakdown device options in most commercial SiGe process technologies. This makes the SiGe BiCMOS technology very attractive for integrating the power amplifier (PA) with other transmit and receive microcircuitry, especially for cellular handsets and WLAN products. Achieving this integration allows decreased bill of materials, reduced packaging requirements and form factors, and potentially decreased unit cost.

The GSM 900 wireless handset specification includes the constant amplitude envelope GMSK waveform, and the newer non-constant envelope EDGE (Enhanced Data Rate for GSM Evolution) 8-PSK waveform. Both modulation formats are modulated at 270k symbols/s and occupy 200kHz transmit channels from 880MHz to 910MHz. The EDGE signal provides 3 bits of information for every symbol (i.e. better spectral efficiency) for a maximum bit throughput of 810kB/s. The disadvantage of the EDGE signal is that it has a moderate peak-to-average power ratio (PAR) of 3.3dB. The spectral mask requirements are -54dBc at 400kHz and -60dBc at 600kHz, and worst case rms EVM requirement is 10%. The EDGE linearity requirement is achieved using traditional current mode PA typologies (Class A/AB) by operating the amplifier several dB below the P_{1dB} compression point. This causes significant degradation in RF PA power efficiency.

Switched mode PA typologies, particularly the Class E PA, can afford dramatically increased power added efficiency (PAE) over current mode PA typologies. The distinct feature of switched mode power amplifiers, including the Class E PA, is that the active power devices are used as switches as opposed to transconductors. The appeal of the Class E PA is that it can be monolithically integrated in silicon technologies and have good PAE [1]. Four requirements characterize ideal Class E PA operation: (a) the switch voltage is zero when the switch is 'ON'; (b) the voltage slope is zero when the switch if first turned 'ON';(c) all the current during the 'OFF' state is integrated onto the shunt capacitor; and (d) the output tank delivers in phase current and voltage at the fundamental frequency to the load. This guarantees that the voltage and current across the switch are never simultaneously non-zero, and charge is not shunted by the switch during each RF cycle.

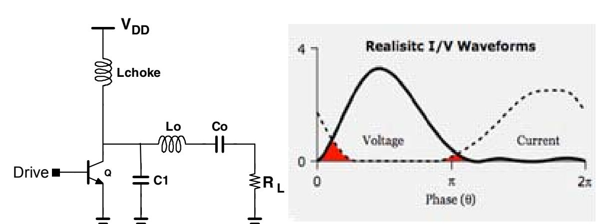

Fig. 1 Class E Amplifier with Collector I/V Waveforms

Therefore, power is dissipated across the switch is minimized and the power at the fundamental is transferred to the load. These requirements can be optimized with proper sizing of the switch device, shunt capacitance, choke inductor, and the high Q-factor output resonant tank [1,2,3].

Circuit non-idealities that limit the practical RF Class E PA power efficiency to <70-80% includes the finite switching speed, switch loss, passive component loss, device breakdown, and voltage rail limitations. The optimum Class E PA switch device has attributes of a fast digital device and high breakdown power device. The higher device breakdown becomes important because the Class E PA switch voltages can peak as much as 3.57 times the voltage supply rail even for ideal matching at the output load [2,3].

The saturated nature of the switched mode PA's causes signal distortion and loss of power efficiency for non-constant envelope driving signals. The classic Class E PA has a linear response of output amplitude peak to the supply voltage [3]. This feature makes the usage of Envelope Elimination Restoration (EER) and/or Envelope tracking (ET) techniques with Class E PA's very applicable. The EER system provides constant amplitude phase-only signals to the Class E PA input, and the amplitude envelope modulation to the Class E PA voltage supply. The ET system adds the amplitude envelope modulation to the Class E PA input as well. These techniques allow the PA to operate in a high efficiency saturated (or nearly saturated) mode, and the amplitude envelope of modulation signals, such as EDGE, can be implemented.

II. RF Class E PA Design and Results

This work focuses on the development of RF Class E PA's because of their ability to be monolithically integrated in silicon based technologies, while still achieving good performance. The Class E design equations in open literature have been found to provide sub-optimal results at RF frequencies [1,4]. Extensive large signal simulations were run in Cadence Spectre/SpectreRF to optimize components values across temperature, process, and voltage supply.

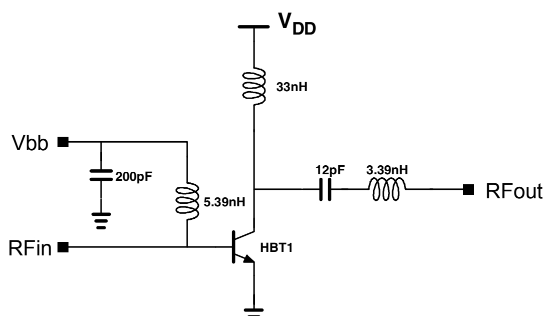

Fig. 2 SiGe Class E Amplifier Design Schematic

The quality factor of the choke inductor plays a crucial role in overall power efficiency, due to the fact that all the average current (RF and DC) must flow through the choke inductor. The low achievable quality factors at 900MHz available in the SiGe technology (Q~10-12) required the choke inductor to be implemented off chip. All the rest of the components are fully-integrated on-chip. Fig. 2 shows the schematics of this monolithic PA. The fabricated SiGe amplifier die shown in Fig. 3 is 1.1mm x 1.7mm.

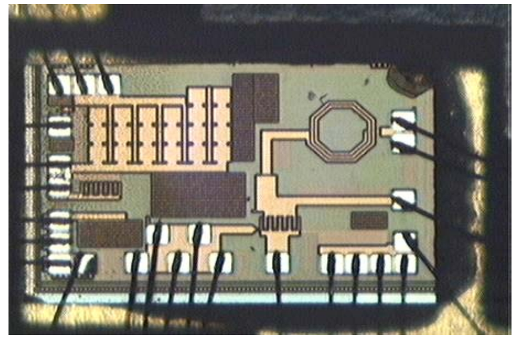

Fig. 3 Fabricated SiGe Class E Amplifier Micrograph

The SiGe PA dies were bonded onto RF PC boards for testing. Single tone testing was completed on the RF Class E PA. Fig. 3 shows a micrograph of the fabricated SiGe Class E PA.

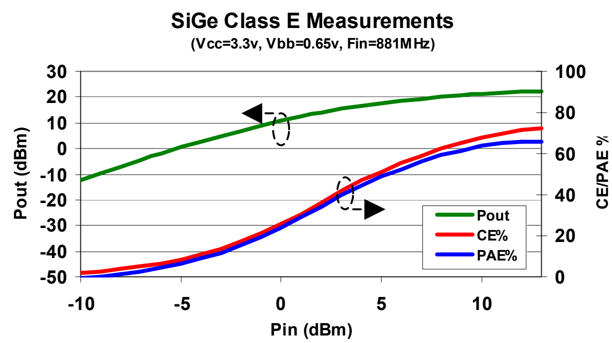

Fig. 4 Measured Class E Output Power/PAE vs. input power

Fig. 4 shows that the best Class E PA measured performance was 72.5% CE, 65.6% PAE, at 22.5dBm output power with single-tone input. Increases in the input power show the saturating nature of the Class E above Pin~5dBm.

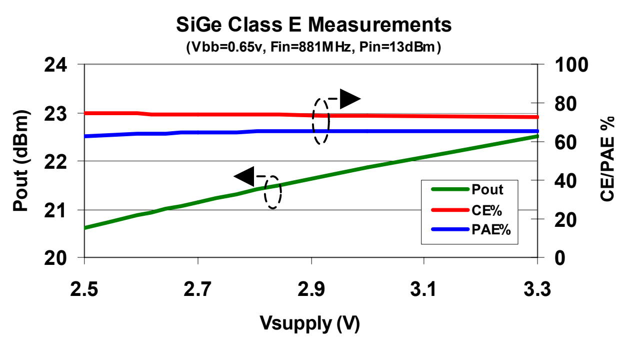

Fig. 5 Measured Class E Output Power/PAE vs. Vsupply

Figure 5 shows a linear in dB change in output power of 2.6dB per 1 volt supply change.

III. Envelope Tracking and GSM EDGE

The wide band envelope tracking (WBET) system block diagram used in this work is shown in Fig. 6.

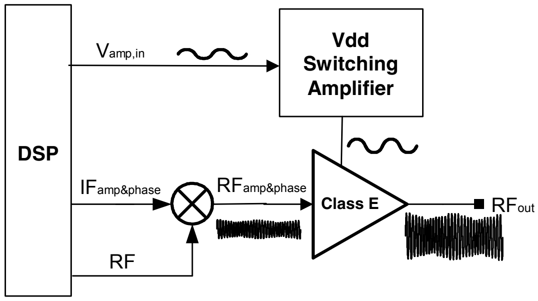

Fig. 6 Simplified ET System Block Diagram

The time delay mismatch between the RF input signal and voltage supply amplitude modulation in dynamic power supply schemes is a significant concern for EVM distortion. As concluded in [5], the ET technique applied to hard limiting PA's provides less sensitivity to delay mismatch than the EER technique. Envelope-Tracking also relaxes the bandwidth requirement for the envelope amplifier and the RF path vs. EER. In addition, ET system provides higher gain at low output power than EER since the device is nearly saturated at low output power (while saturated at high output power). No amplitude or phase predistortion was applied to the ET Class E operated with EDGE. This is due to the smaller 3.3dB PAR of EDGE and the very linear V_{supply} amplitude response of the Class E when moderately saturated.

The simplified circuit schematics of the parallel voltage-controlled wideband envelope amplifier (i.e., the V_{dd} amplifier) is shown in Fig. 7, which provides amplitude modulation envelope to the Class E PA voltage supply. Optimum Class E system PAE is achieved by balancing the distribution of power supply current between the linear amplifier and the MOS switcher [6].

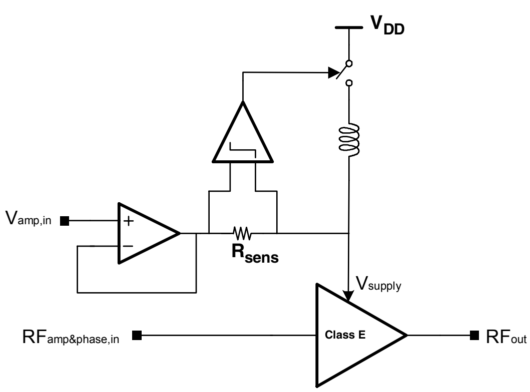

Fig. 7 The simplified circuit schematic of the parallel voltage-controlled envelope amplifier

It is critical to design a highly efficient envelope amplifier, since the overall ET system efficiency is

$$\eta_{\text{WBET}} = \eta_{\text{Envelope\_Amp}} * \eta_{\text{RF\_PA}} \quad (2)$$

The envelope amplifier bandwidth was optimized by adjusting the switcher inductor in Fig. 7. An optimum inductance was found to be 56uH providing a ~5MHz 3dB bandwidth. Also the best envelope amplifier efficiency was achieved by slightly overdriving the envelope amplifier introducing some signal clipping. A direct tradeoff of EVM and AM-AM distortion was observed. An envelope amplifier efficiency of 82.6% was achieved at 6% EVM while satisfying the EDGE spectral mask by introducing 10% clipping. Further clipping degraded EVM and the EDGE spectral mask requirements were not met.

IV. ET RESULT OF THE LINEARIZED CLASS E PA IN EDGE

The measured RF Class E PA AM-AM performance for the RF output amplitude versus input $V_{desired}$ signal amplitude for EDGE-modulated ET system is shown in Fig. 8. The $V_{desired}$ signal is generated in the DSP before it is split into the V_{supply} and the phase envelope signals.

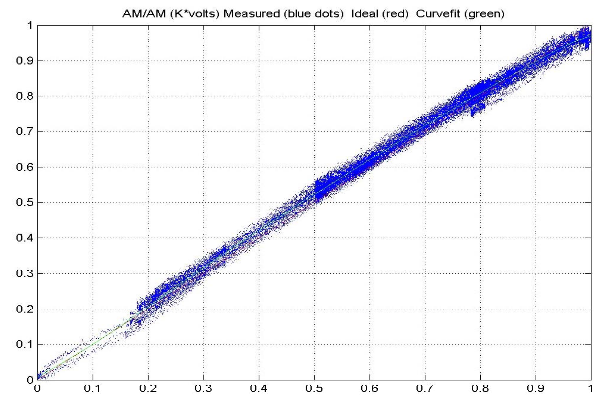

Fig. 8 Measured Class E AM-AM characteristics (i.e., RF Output Amplitude vs. $V_{desired}$ Amplitude) in the ET system (P_{in}=12dBm)

The measured AM-PM response for the RF output phase versus $V_{desired}$ signal amplitude is shown in Fig. 9. The measured standard deviation is 1.12 degrees. An explanation for the low AM-PM response at this large input power of 12dBm is that the RF input amplitude envelope and V_{supply} amplitude envelope are moving in unison, which keeps V_{cb} relatively constant and minimizes C_{bc} nonlinear distortion. Low AM-PM distortion for linear power amplifiers using ET techniques have also been reported in GaAs recently [7].

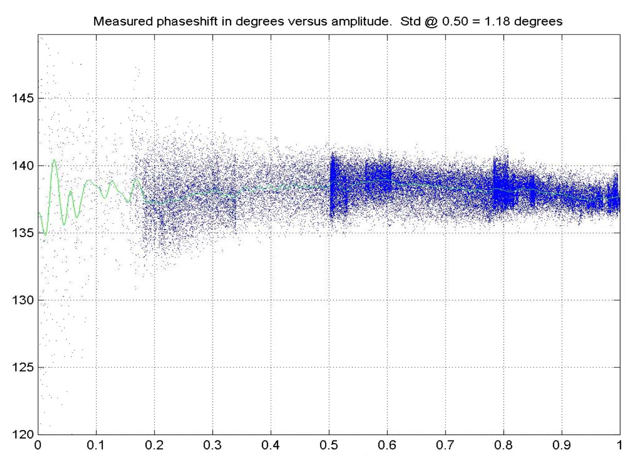

Fig. 9 Measured Class E AM-PM characteristics (i.e., RF Output Phase vs. $V_{desired}$ Amplitude) in the ET system (P_{in}=12dBm)

Measurements of the Class E PA output spectrum and the ET Class E PA output spectrum are shown in Fig. 10 and Fig. 11, respectively, for GSM EDGE with the transmit spectra mask specifcation (Vcc=3.0V, Vbb=0.60V, Fin=881MHz). It is clear that the nonlinearity of the Class E PA causes significant distortion when ET is not present as shown in Fig. 10.

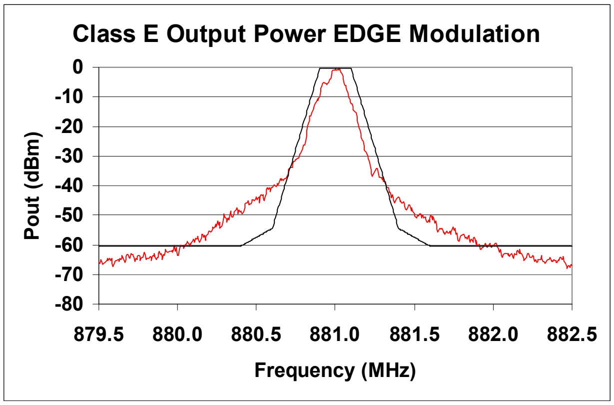

Fig. 10 Class E EDGE Output Spectrum

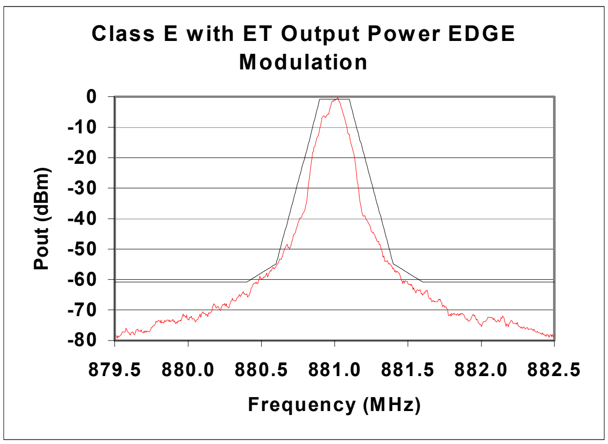

Fig. 11 ET Class E EDGE Output Spectrum

Measured results in Table 1 show a >*14dB* improvement at the 400kHz and 600kHz offsets in spectral mask margin using ET on the Class E PA with EDGE modulation signal.

V. CONCLUSION

We have reported a highly efficient fully-integrated SiGe Class E PA linearized with the ET technique for EDGE applications. The RF Class E PA achieved a collector efficiency (CE) of 62.7% with EDGE signal and the overall PAE of 44.4% for the ET system at an output power of 20.4dBm for an 881MHz EDGE modulated signal. A bandwidth optimized envelope amplifier was demonstrated with 82.8% efficiency. Overdriving the envelope amplifier showed a tradeoff in efficiency versus EVM and spectral mask degradation. The linearized SiGe PA passed the stringent EDGE transmit spectrum mask and EVM specification. To be used for a final stage PA in EDGE applications, this Class E amplifier can be scaled up to meet the 24dBm minimum output power requirement. The PAE of the ET system is expected to increase further if off-chip matching elements were added to improve the matching of the monolithic PA. Finally, this work has demonstrated the feasibility of applying the ET technique on fully-monolithic switched mode PA's using Si-based technologies for advanced transmitter designs where spectrally efficient non-constant-envelope modulation schemes can be employed.

TABLE I
COMPARISON OF EDGE MODULATED CLASS E

	EDGE Modulation	ET EDGE Modulation
Vcc	3.0 V	2.5 V-rms
Vbb	0.6 V	0.6 V
Pin	12dBm	12dBm
Pout	20.6.dBm	20.4dBm
Gain	8.6dB	8.4dB
Class E Efficiency	62.8%	62.7%
Switcher Amp Eff.	-	82.8%
Total PAE	54.2%	44.4%
400KHz Offset Worst	-40dBc	-55dBc
600KHz Offset Worst	-48dBc	-64dBc
Meets EDGE Spectral Mask	NO	**YES**
Rms EVM	-	6.0%

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