

Linearization of Highly-Efficient Monolithic Class E SiGe Power Amplifiers with Envelope-Tracking (ET) and Envelope-Elimination-and-Restoration (EER) at 900MHz

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Abstract—The linearization of highly efficient monolithic SiGe Class E power amplifiers (PAs) using both Envelope-Tracking (ET) and Envelope-Elimination-and-Restoration (EER) techniques has been studied at 900MHz. Without applying any linearization, the fully-integrated SiGe PAs achieve power-added efficiency (PAE) of 66% with no off-chip matching. The overall PAE of an ET-linearized PA system is 45% at an output power of 20dBm for an 881MHz EDGE (Enhanced Data Rate for GSM Evolution) modulated signal. The ET-linearized PAs pass the stringent EDGE transmit spectrum mask, but the EER-linearized PAs do not. The PAE of the ET system is expected to reach ~50% with further efficiency improvement on the envelope amplifier.

I. INTRODUCTION

The power-added-efficiency (PAE) of a RF power amplifier (PA) is critical for the overall system performance, size, and reliability for portable transceiver products where power consumption is desired to be kept as low as possible. Switching-mode amplifiers (i.e., class D/E/S) can provide the highest possible PAE by operating the devices as switches to minimize the overlapping of current and voltage waveforms. A class E PA is easier for integration compared with a class F PA, and it is arguably the most efficient class of PAs because of the optimal switching conditions that minimize power dissipation [1-3]. In reality, non-idealities such as finite switching speed, switch resistive loss, passive component loss, device breakdown and voltage rail limitations, etc. have kept the PAE of the best Si-based RF class E PAs below 70% at 2 GHz and above [4-6]. The Class E PA operation requires both high peak voltage and current for the switching device, which seriously limits the safe operation region for deep-submicron CMOS Class E PAs [4].

With modern wireless communication systems utilizing more spectrally efficient and higher data rate modulation schemes, highly linear PAs are required to avoid the out-of-channel interference and distortion. For example, the EDGE (Enhanced Data Rate for GSM Evolution) waveform occupies 200kHz transmit channels within 880-910MHz with a moderate peak-to-average power ratio (PAR) of 3.3dB but it has stringent transmit (TX) spectral mask specs as GSM at -54dBc (400kHz), -60dBc (600kHz), and worst case rms EVM of 10%. Typically, the EDGE linearity requirement is achieved by using traditional current-mode PA typologies (Class A/AB) and operating the amplifier several dB below its P_{1dB} compression point, which has

inevitably degraded its PAE significantly. Therefore, current commercial III-V EDGE PA modules can only achieve ~30% peak PAE at its maximum power because the PA is forced to operate in a back-off mode to keep it linear. Switched-mode PAs are intrinsically nonlinear in nature so they need to be linearized using techniques such as EER/ET for EDGE applications. The EER technique achieves this by providing constant amplitude phase-only signals to the Class E PA input, and separately drives the amplitude envelope modulation on the voltage supply of the PA. The ET technique also adds a percentage of the amplitude envelope modulation to the PA input. Classical ET-technique has been applied mainly to current-mode PAs. Our current research indicates that ET can be extended to switch-mode PAs and provide better linearization than the EER techniques. Fig. 1 shows a simplified block diagram of the ET PA linearization system used for this work. This paper details the implementation of highly-efficient monolithic SiGe class E RF PAs linearized using an ET technique to meet the linearity requirement for low-band EDGE modulated signals.

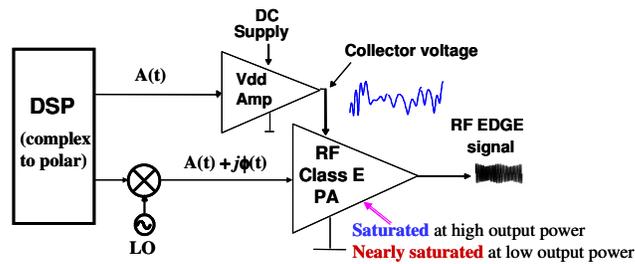


Fig. 1 A general ET PA linearization system diagram

II. RF CLASS E PA DESIGN AND RESULTS

A simplified schematic for our monolithic 1-stage Class-E PA for 900MHz operation is shown in Fig. 2.

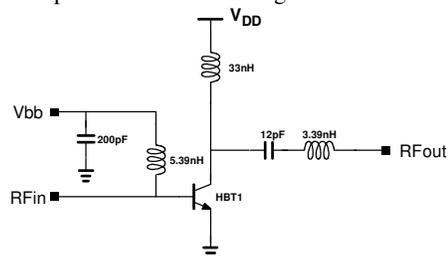


Fig. 2 Schematics of a single-stage SiGe class E PA at 900MHz.

We purposely left the RF Choke (RFC) inductors off-chip because of the available low Q and large size for on-chip inductors at 900MHz. All the rest of the components are fully-integrated on-chip. The results shown in this paper are all obtained with fix- V_{be} voltage biasing. The SiGe PA dies were bonded onto RF PC boards by bondwires for testing. A fabricated SiGe PA die is shown Fig. 3. The IBM 7HP technology high- f_T HBT device has a typical $f_T/f_{max} \sim 100/120$ GHz, $BV_{CEO}=1.8$ V, and $BV_{CBO}=6.4$ V while the high-breakdown HBT device has a typical $f_T/f_{max} \sim 27/57$ GHz, $BV_{CEO}=4.2$ V, and $BV_{CBO}=12.5$ V. Both HBT device options were investigated for in fabricated PAs. We designed these PAs with a voltage supply of 2.5-3.6V in mind, deliberately pushing above the BV_{CEO} limit of these HBTs. Both PAs designed using high- f_T and high-breakdown devices are tested. As expected, PAs designed with high-breakdown devices can withstand significant higher supply voltages and deliver higher output power P_{out} . No off-chip I/O matching for PAs is used here (measurement using off-chip tuning increased PAE further).

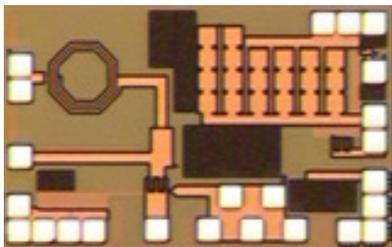


Fig. 3 A fabricated SiGe Class E PA micrograph (1.1mm x 1.7mm)

Single tone testing was first completed on the RF Class E PA. Fig. 4 shows the measured PA performance at 3.3V (72.5% CE, 65.6% PAE, and 22.5dBm P_{out}). Increases in the input power show the saturating nature of the Class E above $P_{in} \sim 5$ dBm.

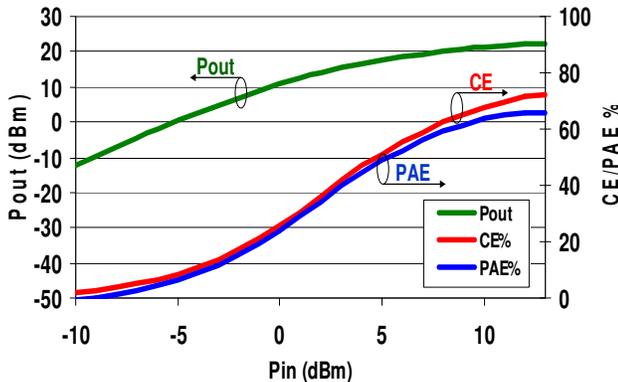


Fig. 4 Measured Class E Output Power/PAE vs. input power

Figure 5 shows a surprisingly *linear* relationship between P_{out} (in mW) vs. supply voltage V_{cc} and vs. base bias V_b . This is very different from the classical class E PA equations where a quadratic relationship between P_{out} vs. V_{cc} is expected. The reason is likely due to that the loaded Q of our PAs are only ~ 0.38 at 900MHz, significantly lower than the low-end validity limit of classic class E model of $Q \sim 1.78$ [7]. The PA is more sensitive to changes in V_b than in V_{cc} , which is expected considering the exponential I-V behavior of the base-emitter diode. These linear relationships suggest that ET may be effective in linearizing this switch-mode PA, since to 1st-order the output power level can be *linearly* controlled by the base and collector bias voltages *independently* across wide ranges [8]. The device saturation voltage is ~ 0.8 V as suggested from Fig. 5.

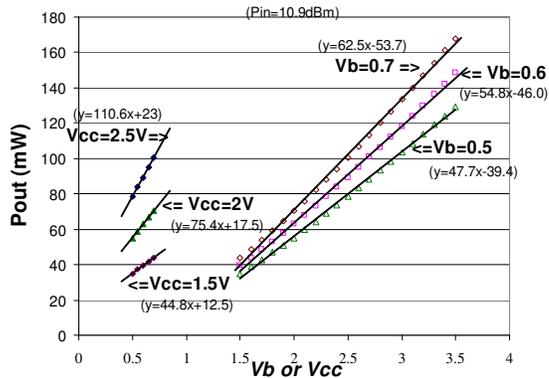


Fig. 5 Linear change in P_{out} (in mW) vs. supply V_{cc} and bias V_b ($P_{in}=10.9$ dBm)

III. ENVELOPE TRACKING AND EER FOR EDGE

Both EER and ET utilize dynamic power supply control schemes. Either the bias current and/or voltage is varied to control the instantaneous power. EER uses a combination of a switching-mode PA and an envelope modulation circuit. Classical ET utilizes a switch-mode PA and a supply modulation circuit where the supply voltage V_{supply} tracks the input AM envelope. In modern EER/ET systems, the amplitude and phase signals are generated directly in the baseband domain and up-converted to RF. For the complex modulated signal, the complex baseband signal $s_{BB}(t)$ can be expressed with $I(t)$, $Q(t)$ or amplitude signal $A(t)$ and phase signal $\phi(t)$ as:

$$s_{BB}(t) = I(t) + j \cdot Q(t) = A(t) \cdot e^{j\phi(t)} \quad (1)$$

where $A(t) = \sqrt{I(t)^2 + Q(t)^2}$, $\phi(t) = e^{j \arctan(Q(t)/I(t))}$. Due to these nonlinear operations, bandwidth of $A(t)$ and $\phi(t)$ are much wider than that of baseband signal $s_{BB}(t)$ [9]. A block diagram of UCSD's open-loop ET system is shown in Fig. 6. Compared to EER, ET can reduce the bandwidths of both envelope amplifier (i.e., V_{dd} amplifier) and the EER-limiter for phase input [10].

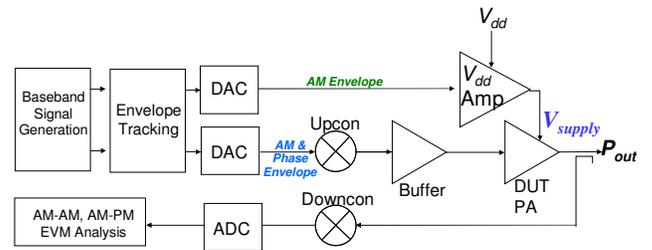


Fig. 6 Simplified Block diagram of UCSD's open-loop ET system (delay not shown; output feedback for analysis only)

The time delay mismatch between the RF input signal and voltage supply amplitude modulation in EER/ET is a significant concern for EVM distortion. As concluded in [11], the ET technique applied to hard limiting PA's provides less sensitivity to delay mismatch than EER. An ET system also relaxes the bandwidth requirement for the V_{dd} amplifier and for the RF path vs. EER. ET system also provides higher gain at low output power than EER since the device is nearly saturated at low output power (and saturated at high output power). An additional advantage of the PA operated with EDGE is that the moderate 3.3dB PAR and the linear P_{out} vs. V_{cc} and V_b responses (shown in Fig. 5) make it possible that digital pre-distortion is *not* needed to meet spectral mask and EVM requirements.

The simplified circuit schematics of the V_{dd} amplifier has been reported before [10,12,13], which uses a discrete linear op-amp and a switching power converter to provide amplitude

modulation envelope to the Class E PA voltage supply. Optimum PA system PAE is achieved by balancing the distribution of power supply current between the linear amplifier and the MOS switcher. It is critical to design a highly efficient V_{dd} amplifier, since the overall ET/EER system efficiency is a product of the PAE of the PA with that of the V_{dd} amplifier. In our current ET/EER system setup, the bandwidth of the envelope amplifier was purposely designed to be very wideband ($\sim 20\text{MHz}$) to also accommodate WLAN applications, and subsequently the amplifier only has an efficiency of 60-70% while generating the EDGE envelope. Work has been done to reduce the bandwidth of V_{dd} amplifier and therefore improves its PAE to $\sim 80\%$ range so that the overall PAE of the ET system is expected to improve to $\sim 50\%$ for the narrow-band EDGE signal.

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

The measured RF Class E PA AM-AM performance for the RF output amplitude versus V_{supply} for EDGE amplitude modulated ET signal is shown in Fig. 7, without applying any ET/EER linearization. One can see the AM-AM relationship is very nonlinear and with considerable memory effects. Fig. 8 shows the AM-PM behavior for the class E PA, where the output phase behavior has large data variation, and it becomes very large at low input amplitude envelope levels. It has been reported that for EDGE signal, the phase is not only dependent on the instantaneous amplitude but also a function of the history of the amplitude, causing some memory effects [14]. Figs. 9-10 show the measured AM-AM, AM-PM performances for the Class E PA linearized with the EER system, respectively (no pre-distortion). Great improvement on AM-AM linearity is accomplished; however, significant nonlinearity can still be observed at low input amplitude envelope level (<0.15 in Fig. 9), which is related to the low-end collector saturation voltage for the device and difficult to eliminate this nonlinearity in practice. The data variation in AM-PM curve for the EER-linearized PA is also very noticeably improved in Fig. 10. However, the AM-AM non-linearity apparently caused significant distortion as the best EER-linearized PA still failed the EDGE TX spectrum mask by several dB ($-53\text{dBc}@400\text{kHz}$ and $-62\text{dBc}@600\text{kHz}$). Figs. 11-12 show the measured AM-AM, AM-PM behaviors for the ET-linearized class E PA system, respectively. Excellent AM-AM linearity is observed in Fig. 11, while the AM-PM behavior is reasonably good and similar to the case in Fig. 10 for EER-linearized PA. Note unlike CMOS PA, the linearity of our SiGe switch-mode PAs appears fairly insensitive to AM-PM variation for an EDGE modulated signal [15].

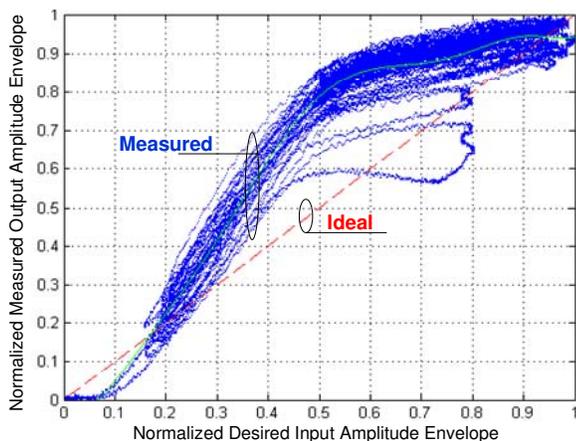


Fig. 7 Measured Class E SiGe PA AM-AM characteristics (i.e., output amplitude vs. V_{supply}) without using any linearization.

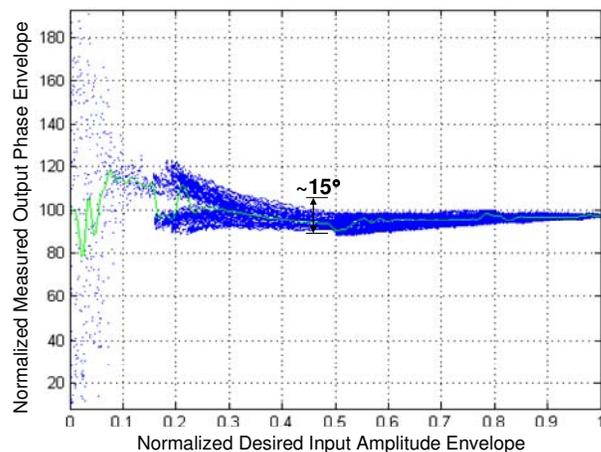


Fig. 8 Measured Class E SiGe PA AM-PM characteristics (i.e., output phase vs. V_{supply}) without using any linearization.

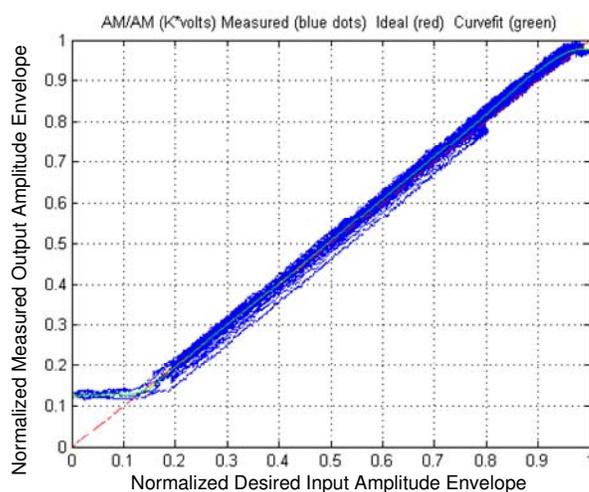


Fig. 9 Measured Class E SiGe PA AM-AM characteristics. PA linearized using the EER technique without pre-distortion.

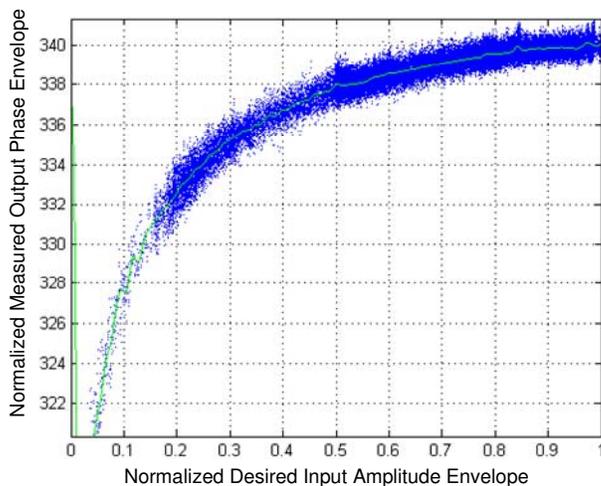


Fig. 10 Measured Class E SiGe PA AM-PM characteristics. PA linearized using the EER technique without pre-distortion.

Measurements of the Class E PA output spectrum and the ET Class E PA output spectrum are shown in Fig. 13 for EDGE signal ($V_{cc}=3.0\text{V}$, $V_{bb}=0.65\text{V}$, $F_{in}=881\text{MHz}$). It is clear that the nonlinearity of the Class E PA causes significant distortion when ET is not present. Measured results show a $>14\text{dB}$ improvement

at the 400kHz and 600kHz offsets using ET on the Class E PA with EDGE modulation signal.

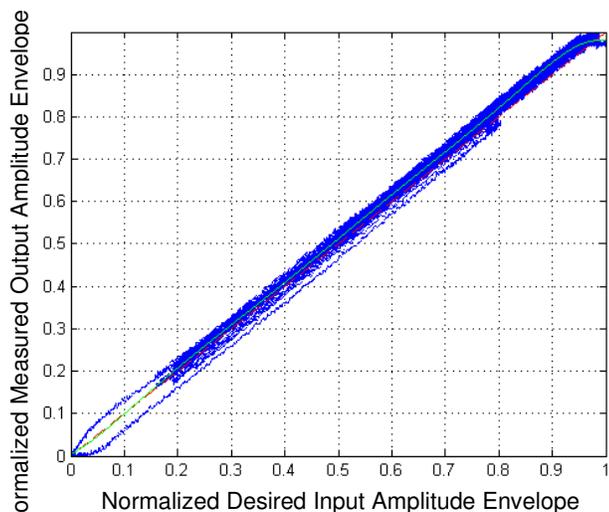


Fig. 11 Measured Class E SiGe PA AM-AM characteristics. PA linearized using the ET technique without pre-distortion.

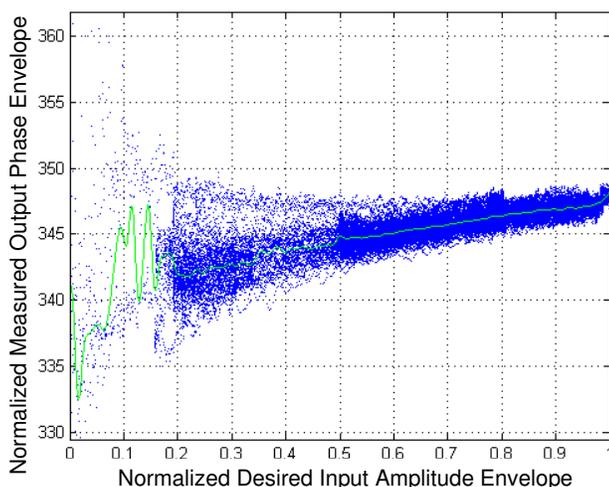


Fig. 12 Measured Class E SiGe PA AM-PM characteristics. PA linearized using the ET technique without pre-distortion.

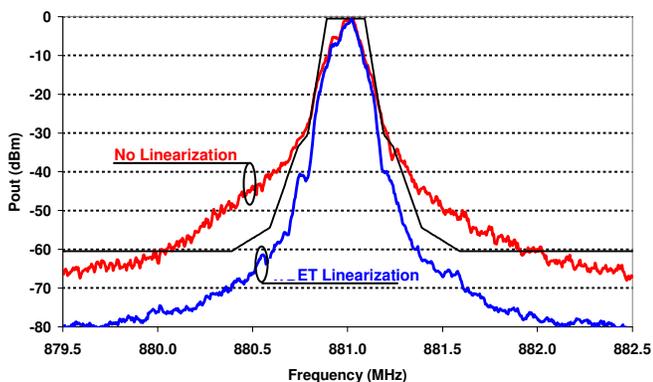


Fig. 13 Class E SiGe PA EDGE TX output spectrum before and after ET linearization.

V. CONCLUSION

The linearization of highly efficient monolithic SiGe Class E PAs using both EER and ET techniques has been studied using an EDGE modulated signal. The ET-linearized PAs passed the

stringent EDGE transmit spectrum mask without pre-distortion, while the EER-linearized PAs did not. Nonlinearity in the AM-AM characteristics present in the EER-linearized PAs (from saturation of the output power at low input power levels) suggests why ET is better than EER for this case. The overall PAE of the ET-linearized PA system is $\sim 45\%$ at 20dBm output for an 881MHz EDGE modulated signal. The PAE of the ET system is expected to reach $\sim 50\%$ with further efficiency improvement on the V_{dd} amplifier and with off-chip matching.

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