A Highly Integrated Multiband LTE SiGe Power Amplifier for Envelope Tracking

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***Abstract*— This paper presents a highly integrated SiGe power amplifier (PA) for multiband long-term evolution (LTE). Two different harmonic loadings are investigated for the PA to achieve the optimized efficiencies for the envelope tracking (ET) and average power tracking (APT), respectively. By adopting the proper PA structure, our ET PA delivers >39% overall power-added efficiency (PAE) at the maximum output power (P_{out}) of 26.5 dBm with $ACLR_{EUTRA}$ below -42 dB and EVM below 1% for the LTE QPSK 10 MHz at 699-716 MHz, 824-915 MHz and 1710-1980 MHz. At the back-off more than 5 dB below the maximum P_{out}, the ET PA is reconfigured to APT for remaining high overall PAE and linearity across a broad P_{out} range.**

***Index Terms*—average power tracking (APT), envelope tracking (ET), long-term evolution (LTE), multimode multiband (MMMB), power amplifier (PA), SiGe, supply modulator**

I. Introduction

As the demands of wireless services grow, advanced standards such as long-term evolution (LTE) were developed to enable high data transfer rates. As these standards use spectrally efficient complex modulation schemes, the peak to average power ratio (PAPR) of the modulated signal correspondingly increases. To maintain the system level linearity, the power amplifier (PA) must have sufficient headroom of collector or drain voltage to avoid clipping the peaks of the modulated signal, causing an increase of power loss and low battery life of mobile devices. Further exacerbating the PA efficiency problem is the adoption of multiband PAs, due to several market factors that reduce the real-estate available for implementing the front end. These factors include the increasing number of bands being incorporated into mobile devices, the level of integration of other sub-systems (e.g., Wi-Fi), and the trend toward larger displays. The multiband PA comes at the cost of reduced PA efficiency, due to the additional losses imposed by the broadband tuners and a band switch which allows multiple bands to be covered by one amplifier chain.

To improve the efficiency of the PA for modern handset applications, the envelope tracking (ET) and average power tracking (APT) are two promising solutions widely used. In the ET system, an envelope signal from the supply modulator dynamically modulates the PA collector/drain voltage in responding to the *instantaneous* output power (P_{out}). To achieve a good balance between the wide tracking bandwidth and high efficiency, the hybrid switching supply modulator consisting of a linear regulator and a switching converter is widely used in the ET system [1]-[3]. For APT, on the other hand, the supply modulator only responds to the peak of the envelope at each average P_{out} level, thus the APT PA suffers the power lost in the valleys of the envelope. Nevertheless, the APT system allows for less stringent tracking bandwidth and no requirement for timing alignment. Additionally, since the supply modulator for APT only consists of a single switching converter, its efficiency is generally higher over a broad P_{out} range than that of ET.

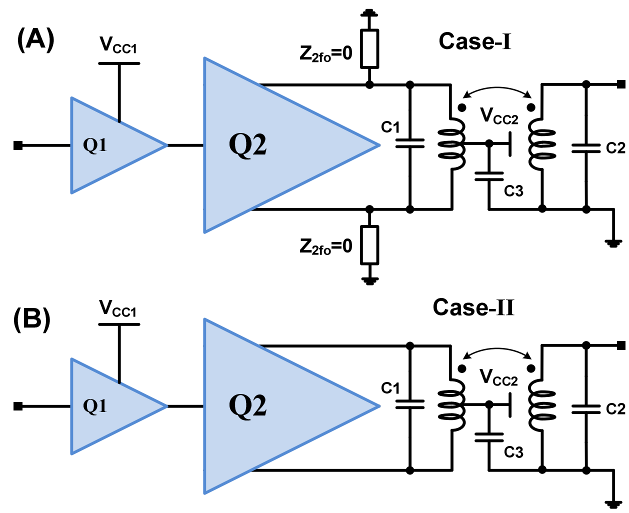

Fig. 1. Simplified schematics of our SiGe PAs: (A) with $2f_O$ traps (case-I), (B) without $2f_O$ traps (case-II)

Although the literature has extensively demonstrated that the efficiency of a stand-alone PA (i.e., PA directly connected to the battery) can be greatly improved by the ET technique [1]-[3], there has not been much research presenting the efficiency difference between ET and APT using different PAs optimized for ET and APT, respectively. To achieve the optimized efficiencies for ET and APT, respectively, different design trade-offs need to be considered. In APT systems, the PA operates in a linear mode, as the linearity specs are the dominant factor for the system. Recent research has shown that by shaping the output current or voltage waveform of the PA, a high efficiency can be achieved without driving the PA into deep compression [4], [5]. In contrast, the PA in ET systems is run into compression for high efficiency, since the linearity specs can be met by digital predistortion (DPD) [3] or envelope shaping techniques [6]. The level of the compression needs to be carefully chosen for the ET PA, as it determines the PA conversion gain from the collector/drain supply to the RF output, a dominant factor for the receive-band noise performance.

Furthermore, recent literature only focuses on the efficiency improvement of ET PAs at the maximum P_{out}, but it is also critical for the PA to achieve high efficiency at the back-off below the maximum P_{out}, due to the power control strategy of the 4G mobile applications. In the low power region, the hybrid switching supply modulator used in ET systems suffers rapid efficiency degradation from the linear regulator. Additionally, the ET system linearity starts to be degraded by the supply modulator in the low power region, which cannot be corrected by DPD. One of the solutions is to switch the ET system to an APT mode, while the switching point is critical to be determined.

In this paper, we will first discuss two PA harmonic loadings that lead to different behaviours of efficiency for ET and APT, respectively. Next, a proper PA structure for ET will be chosen for our multimode multiband (MMMB) PA module. The LTE QPSK 10 MHz signal will be used to showcase the multiband performances of our MMMB PA in the ET platform. The supply modulator in our system supports both ET and APT modes, and its DC consumption is included in all the measurement data.

II. SiGe Power Amplifier Designs

To determine the proper PA structures for the optimized APT and ET performances, we designed two PAs with different harmonic loadings as shown in Fig. 1. The two PAs operate with the same fundamental load (Z_{fo}) and biasing current. The PA shown in Fig. 1 (A) (case-I) has a short 2nd harmonic load (Z_{2fo}) provided by the 2nd harmonic ($2f_O$) traps at the output collectors. On the other hand, the PA shown in Fig. 1 (B) (case-II) has a relatively large Z_{2fo} (close to open) by carefully tuning the capacitor C_3 and the output transformer. Both PAs were fabricated in a 0.35 μm SiGe BiCMOS technology, and the output matching was realized on the laminate module. The loss of the laminate module is included in the measurement data.

Due to different harmonic loadings, different enhanced efficiency can be obtained at the back-off region or the compression region. Fig. 2 shows the measured power-added efficiency (PAE) and gain of the two PAs for the continuous-wave (CW) signal at 1.71 GHz. The gain compression of the case-I PA is more gradual than that of the case-II PA. In addition, the case-I PA has higher PAE at back-off, but its PAE becomes flat at compression. In contrast, the PAE of the case-II PA peaks at compression. The characteristics of PAE and gain shown in Fig. 2 are similar to those reported in [4], [5].

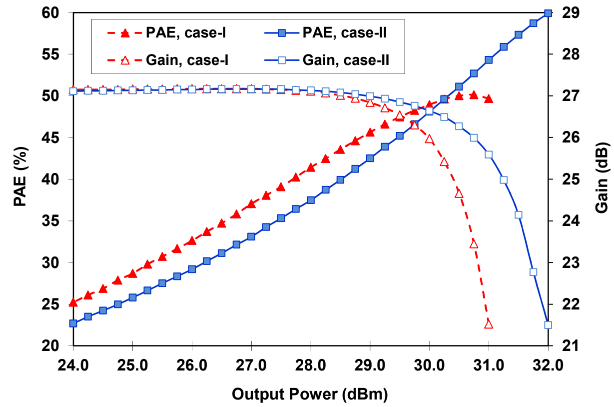

Fig. 2. Measured PAE and gain of the two PAs for the CW signal at 1.71 GHz

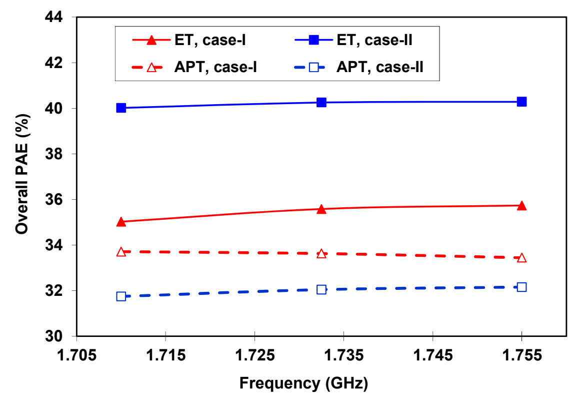

Fig. 3. Measured overall PAE of the two PAs in the ET and APT modes for LTE QPSK 10 MHz (P_{out} = 26.5 dBm)

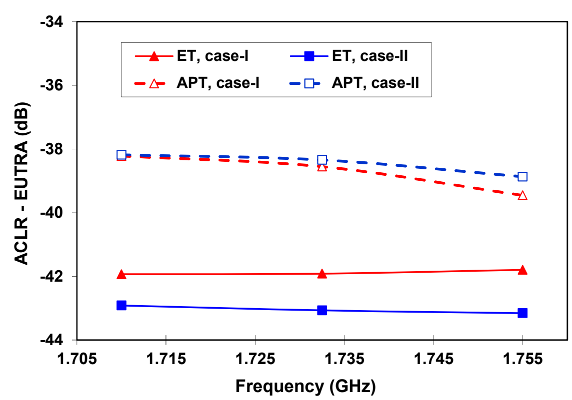

Fig. 4. Measured $ACLR_{EUTRA}$ of the two PAs in the ET and APT modes for LTE QPSK 10MHz (P_{out} = 26.5 dBm, DPD applied to ET and APT)

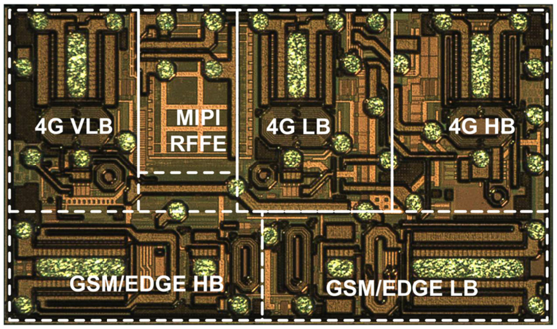

Fig. 5. Die picture of the MMMB SiGe PA

In our ET system, the PA is required to constantly operate at compression, thus the case-II PA is preferred for higher overall efficiency, while the case-I PA is more suitable for an APT system. To further investigate the efficiency behaviour resulted from different harmonic loadings, the two PAs were connected with a supply modulator that supports both ET and APT modes. Fig. 3 shows the overall PAE of the two PAs at the maximum P_{out} of 26.5 dBm in ET and APT, respectively. The DC consumption of the supply modulator is included in the overall PAE. The case-I PA has higher overall PAE than the case-II PA in the same APT system, but the PAE difference becomes opposite once the system is switched to ET. Based on Fig. 3, the optimized ET system using the case-II PA has 6-7% higher overall PAE than the optimized APT system using the case-I PA. Fig. 4 shows the measured $ACLR_{EUTRA}$ at 26.5 dBm with the DPD applied to both ET and APT modes. The ET has better linearity than APT at the maximum P_{out} for both PAs.

III. SiGe ET Power Amplifier for Multiband LTE

With the primary goal targeting to the ET platform, the case-II PA structure shown in Fig. 1 (B) is adopted into our MMMB PA module. Fig. 5 shows its die picture including the MIPI RF front end (RFFE), fabricated in a 0.35 µm SiGe BiCMOS process. The total die size is 2.3×1.3 mm^2. The CMOS supply modulator used in the system (V_{DD} = 3.7 V) supports both ET and APT modes, but its detailed information cannot be revealed yet. The LTE QPSK 10 MHz 50 resource-block (RB) signal is used to showcase our MMMB PA. The overall PAE reported includes the DC consumption of the supply modulator.

A. Multiband Performances for LTE

Our MMMB PA supports multiband LTE at 699-716 MHz (band 12, 17 (VLB)), 824-915 MHz (band 5, 8 (LB)), and 1710-1980 MHz (band 1, 2, 3, 4 (HB)), plus quad-band GSM/EDGE. This section only focuses on its LTE multiband performances at the maximum P_{out} in ET. Fig. 6 shows the overall PAE in the ET mode at the maximum P_{out} of 26.5 dBm using two tracking methods, tracking V_{CC2} only and tracking V_{CC2}/V_{CC1}. To achieve the same

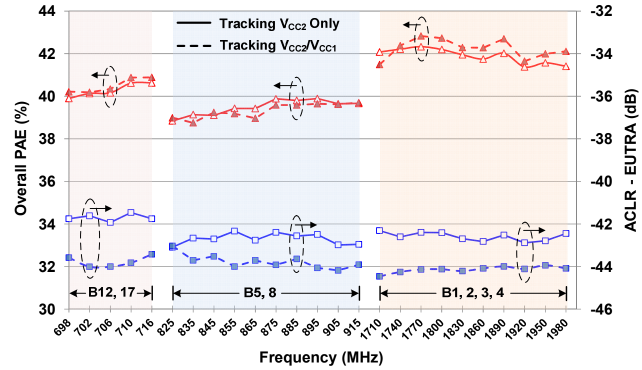

Fig. 6. Measured overall PAE and $ACLR_{EUTRA}$ of the multiband ET PA at the maximum P_{out} of 26.5 dBm

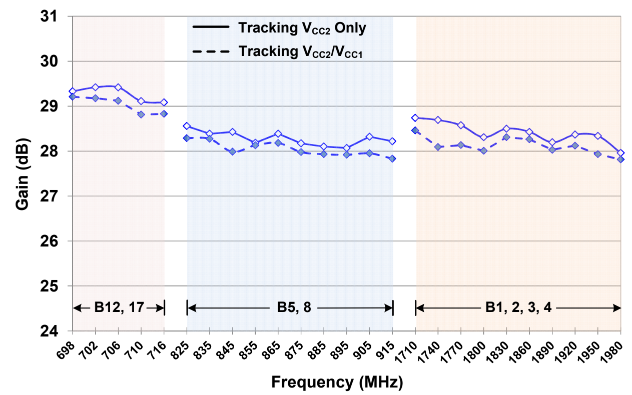

Fig. 7. Measured gain of the multiband ET PA at the maximum P_{out} of 26.5 dBm

conversion gain from the V_{CC} supply to RF output for the targeted receive-band noise, the PA is operated at P_{2dB} for both tracking methods. As shown in Fig. 6, sufficient linearity margins are obtained by both tracking methods to handle the temperature variation and impedance mismatch from duplexers. In addition, tracking V_{CC2}/V_{CC1} achieves the similar overall PAE, but better ACLR compared to tracking V_{CC2} only. Fig. 7 shows the measured gain of our multiband ET PA at 26.5 dBm. The maximum gain variation is only 0.9 dB across all LTE bands of interest.

B. Mode Control for ET and APT

To remain high efficiency and linearity at the low power region, the hybrid switching supply modulator is reconfigured to a single switching converter for the APT operation. Fig. 8 shows the measured $ACLR_{EUTRA}$ and overall PAE over a broad P_{out} range in the ET and APT modes for LTE band 4. In the measurement, the DPD was applied to both ET and APT modes. In the APT mode, the supply modulator steps down V_{CC} at each discrete P_{out} level according to a look-up table (LUT). The LUT of V_{CC} is determined to achieve the highest PAE while keeping the $ACLR_{EUTRA}$ below -38.5 dB. At the P_{out} less than 21.5 dBm (i.e, 5 dB back-off from the maximum P_{out} of 26.5

TABLE I

SUMMARY OF OUR MULTIBAND SIGE ET PA (V_{CC2}/V_{CC1} TRACKING) AND THE COMPARISON WITH THE STATE-OF-THE-ART ET RESULTS

	Freq. (GHz)	V_{DD} (V)	P_{out} (dBm)	Gain (dB)	PAE (%) @back-off			ACLR (dB)	EVM (%)	DPD	Modulation	Technology
					0 dB	5 dB#	10 dB#					
[1]	1.74	3.4	27	23.4	38.1	27	23.5	-32.9	4.74	No	LTE 16QAM 10 MHz	InGaP/GaAs HBT
[2]	1.85	5	26	10	34.1	23	12.5	-34.2	2.8	No	LTE 16QAM 10 MHz	0.18-μm CMOS
[3]†	2.535	---	29	28.5	43	30	16.5	-49*	1.9	Yes	LTE 16QAM 20 MHz	GaAs HBT
[7]§	1.9	4.2	24	15	41	26	12.5	---	4.9	No	LTE 16QAM 5MHz	0.35-μm SiGe BiCMOS
[8]	2.35	3.5	24.7	41.1	25.5	12	---	-33	4.5	No	LTE 16QAM 20MHz	0.18-μm SiGe BiCMOS
This work	0.7	3.7	26.5	29	40	---	---	-44	0.8	Yes	LTE QPSK 10 MHz	0.35-μm SiGe BiCMOS
	0.9	3.7	26.5	28	40	---	---	-44	0.8			
	1.9	3.7	26.5	28	42	26.1	15.5‡	-44	0.86			
								-36.6	3.5	No		

The PAEs at back-off of the other works are graphically estimated. † [3] used a commercially available GaAs HBT PA.
* It is unclear if the reported ACLR in [3] is for EUTRA or UTRA. ‡ This work achieved the PAE at 10 dB back-off in the APT mode.
§ [7] de-embedded the loss of the output transformer. With a typical loss of 0.4 dB on laminate, its overall PAE drops to 37.5%.

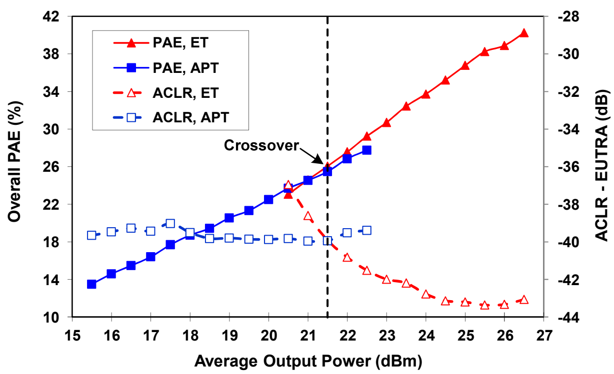

Fig. 8. Measured overall PAE and $ACLR_{EUTRA}$ vs. P_{out}

dBm), the APT mode has higher overall PAE and better $ACLR_{EUTRA}$ than the ET mode. This indicates the point where the ET PA needs to be switched to APT mode.

IV. CONCLUSION

A highly integrated SiGe PA for MMMB ET handset applications is presented. By choosing a proper 2nd harmonic loading, the PA efficiency can continuously increase at the compression region, which is a desired behaviour for ET operation as verified by our experiment. In the showcase for the LTE QPSK 10 MHz signal, the ET PA delivers >39% overall PAE at the maximum P_{out} of 26.5 dBm with $ACLR_{EUTRA}$ below -42 dB and EVM below 1% at 699-716 MHz, 824-915 MHz and 1710-1980 MHz. To remain high overall PAE and linearity across a broad P_{out} range, the ET PA is reconfigured to APT at the back-off more than 5 dB. Table I summarizes the multiband LTE performances of our SiGe ET PA and the state-of-the-art ET results. The literature survey shows that our SiGe ET PA has achieved the similar efficiency as the GaAs ET PAs. Note that even without DPD our ET-PA still achieves reasonably good linearity.

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