SiGe Power Amplifier ICs for 4G (WIMAX and LTE) Mobile and Nomadic Applications

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***Abstract* — SiGe 4G PA development is a key element in enabling integrated 4G front end SiGe ICs. In this paper, we report on a wideband SiGe 4G PA IC which meets WIMAX (802.16e) and LTE specifications. For 802.16e, the SiGe PA produces 25 dBm linear power at Vcc=3.3V for 2.3-2.7 GHz operation with <4% EVM and 18% efficiency while meeting spectral mask and exhibiting -43 dBm/MHz second harmonic levels. For TD-LTE, Band 40 (2.3-2.4 GHz) and FDD-LTE, Band 7 (2.500-2.570 GHz), this SiGe PA produces 28.5 dBm linear power while meeting 3GPP spectral mask and EVM specification for QAM 16.**

***Index Terms* — Power amplifier, PA,, LTE, SiGe, WIMAX, 4G.**

I. INTRODUCTION

SiGe BiCMOS IC technology provides the potential of integrating all the active RF components for next generation 4G (WIMAX, TD-LTE) RF Front Ends (PA, T/R Switch, LNA) into one IC. SiGe BiCMOS technology enables high performance PAs and LNAs with HBT (Heterojunction Bipolar Transistor) devices while the T/R switch can be developed with a variety of CMOS devices (i.e. triple well NMOS, 5V NMOS). Linear 4G / WLAN SiGe PA performance has been documented extensively in the literature and in products for the past few years [1]-[2]. One key advantage of a SiGe 4G Front End IC is the ability to integrate intelligent controls and digital communications (e.g. SPI Bus) to provide programmability and dynamic optimization for the 4G RF Front End IC.

One key competitive technology to SiGe for 4G RF Front End IC is CMOS. The current drawback with a CMOS solution is the relatively poor 4G PA performance. For WIMAX (802.16e) applications, CMOS PAs have shown efficiencies of 12% at 23 dBm output power for operation in 2.3 GHz to 2.4 GHz band [3]. This is significantly lower than the near 20% efficiencies reported by commercial 4G PAs. The use of Digital Pre-Distortion (DPD) has shown improved CMOS PA linear output power and efficiencies but adds more system complexity and requires close collaboration between the baseband IC and the PA IC [4].

The key component of a 4G RF Front End which has the most impact on the overall performance of a 4G mobile or nomadic device is the power amplifier. The relatively high peak to average power ratio (PAPR) for the WIMAX/LTE uplink, the high output power levels (23 dBm at the antenna), along with the WIMAX/LTE spectral mask requirements impose stringent requirements on the power amplifier. In this paper, a 2.3-2.7 GHz SiGe 802.16e, 2.3-2.4 GHz TD-LTE and 2.500-2.570 GHz FDD-LTE PA is demonstrated. The performance of this SiGe 4G PA is comparable to commercial GaAs PAs and is a key step towards achieving a fully integrated 4G RF Front End IC. For FDD applications, a SiGe 4G PA can enable integration of multi-band/multi-mode PAs (3G and 4G) with intelligent controls and digital communications into one IC.

II. DESIGN CONSIDERATIONS

The 4G SiGe PA is a three stage fully differential design with three power modes (high, medium, low),an integrated input match, an external output match and an external balun. The PA input is a 100 ohm differential input and a single ended 50 Ohm impedance is provided at the balun output. The differential PA input alleviates the need for a balun between the differential transceiver output and the PA. Figure 1 depicts the 4G SiGe PA topology. For future applications, the output match and balun can be combined into a transformer balun in either a Si IPD (Integrated Passive Device), a LTCC (Ceramic) substrate, or fully integrated onto the SiGe IC. The differential topology was chosen to avoid the negative effects of emitter degeneration due to ground wire bonds in single ended designs. The SiGe 4G PA was designed to output 25 dBm for the 802.16e 2.3-2.7 GHz band for a Vcc=3.3V. The RF Front End losses after the PA are estimated to be between 1 to 1.5 dB (low pass filter and T/R switch) for a typical single band Front End Module resulting in 23.5 to 24 dBm delivered to the antenna. The 2.3-2.7 GHz band combines the 2.3-2.4 GHz 802.16e/TD-LTE and 2.5-2.7 GHz FDD-LTE/802.16e bands allowing for global 4G coverage. For a PAPR of approximately 6 dB for the 802.16e uplink signal, the P1dB for this PA was targeted to be approximately 31 dBm.

The PA unit cell is a cascode structure with the common-base and common-emitter device consisting of 3.5V BVCEO SiGe HBTs. To further improve the

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breakdown characteristics, the impedance presented to the base of HBT devices by the bias circuit is very low (< 300 Ohms) and as a result, the PA voltage swing is dominated by BVCER. For this case, we estimate BVCER to be ~5.5V. For a cascode structure, the stacking of two HBTs further eases the SiGe HBT breakdown requirements since the maximum voltage swing is approximately 6.3V for a Vcc of 3.3V at 31 dBm CW output power. This effect of BVCER on breakdown has been validated in prior work on SiGe HBT PAs [5].

The sizing of the common emitter devices for the three differential stages are as follows: 440um for Stage 1, 880 um for Stage 2, and 3500um for Stage 3. This translates to a 2:1 emitter area ratio between Stage 1 and Stage 2 and a 4:1 emitter area ratio between Stage 2 and Stage 3. Simulation results showed that the sizing of each stage was sufficient to overcome the inter-stage losses and provide enough margin to compensate for the gain variation of each stage.

Linearization for this SiGe PA IC was performed using VT Silicon's patented Linearity Enhancement Technology (LET) [6]. LET consists of optimizing the biasing of the individual branches within each stage along with tailoring the impedances of the bias circuits to obtain reduction in inter-modulation products (i.e. IM3, IM5). Improvements up to 1.5dB in linear power have been experimentally observed in previous linear SiGe PAs with this technique.

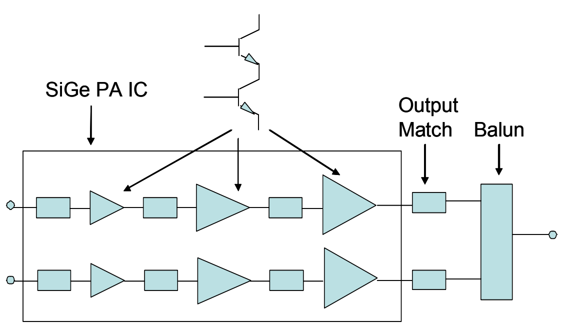

Fig. 1. Simplified view of the 3-stage fully differential SiGe 4G power amplifier topology

III. Measurement Results

The SiGe PA IC, measuring approximately 1.7mm x 1.7mm, was epoxy attached and wire bonded onto a four layer BT laminate . The module size is 5mm x 5mm and contains a discrete output match. Figure 2 depicts the SiGe PA module. The PA module is mounted onto a FR-4 evaluation PCB which contains an Anaren balun (part # BD2425N50100A00) with an insertion loss of approximately 0.6 dB. In addition to providing a balun function, the Anaren balun also serves as a low pass filter and provides reasonable harmonic rejection.

The SiGe PA module was tested using a 16 QAM 10 MHz 802.16e and a TD-LTE uplink signal generated by a Rohde & Schwarz SMJ100A Vector Signal Generator. The EVM and spectral mask measurements were performed with a Rohde & Schwarz FSQ26. The duty cycle for the uplink was set to 100% for the measurements. The reference plane for the power and linearity measurements is immediately after the output match. The measurements were performed with the case temperature held at 25C.

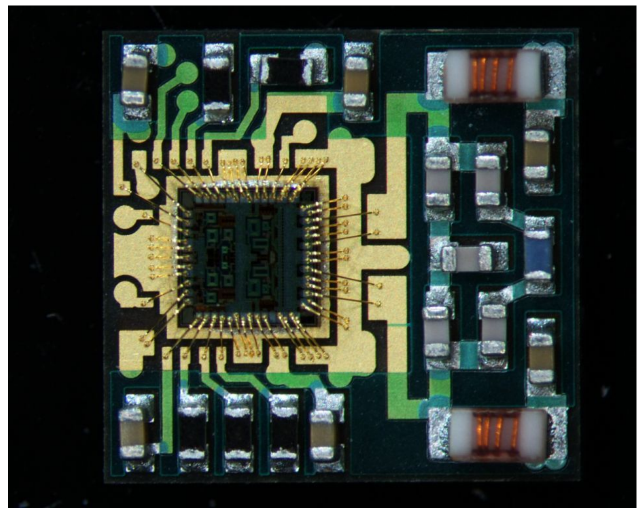

Fig. 2. Photograph of the SiGe 4G PA laminate module

One of the key metrics for 4G PAs is gain. A sufficient gain is needed from the PA to deliver approximately 25 dBm output power considering that the 4G 802.16e CMOS transceiver can deliver typically -3 dBm to -5 dBm linear power especially at elevated temperatures (i.e. 85C). Fig 3 shows a plot of measured CW gain versus power for the 2.3-2.7 GHz band at 25C.

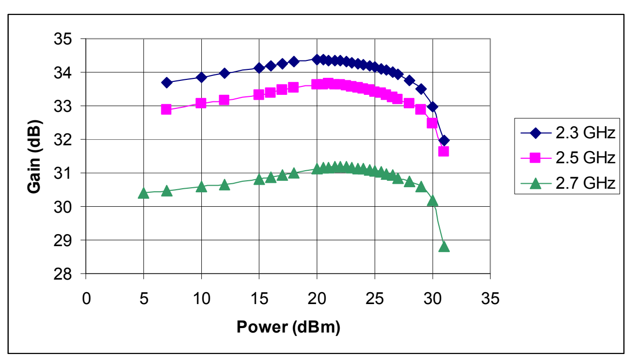

Fig. 3. 4G SiGe PA CW gain for the 2.3-2.7 GHz band

We observe that the gain varies from approximately 31 dB to 34 dB at power for the 2.3-2.7 GHz band. This variation is primarily due to detuning of the input and inter-stage matches resulting in a gain roll off at 2.7 GHz. Initial measurements have shown that the PA gain degrades by approximately 2-3dB at 85C indicating that achieving a 25 dBm PA output power with the gain levels of figure 3 is feasible. Also from figure 3, we can infer that the P1dB is approximately 30 dBm for 2.3-2.7 GHz.

The key linearity metrics for 802.16e and TD-LTE are EVM and spectral emission mask (SE. For 802.16e, the specification for a QAM16 WIMAX uplink signal is 6.3% (-24 dB) for EVM. Typically, EVM requirements for the PA itself are set to approximately 4%. One characteristic that is observed in many 4G PAs is the EVM "hump" at low to medium output powers. If the EVM "hump" is above 4%, network performance may suffer. For the SiGe 4G PA, the linearization technique, LET, was used to maintain the IM3 levels below -30 dBc over a wide range of power levels resulting in an EVM below 4%. Figure 4 depicts EVM versus output power for 2.3 GHz to 2.7 GHz.

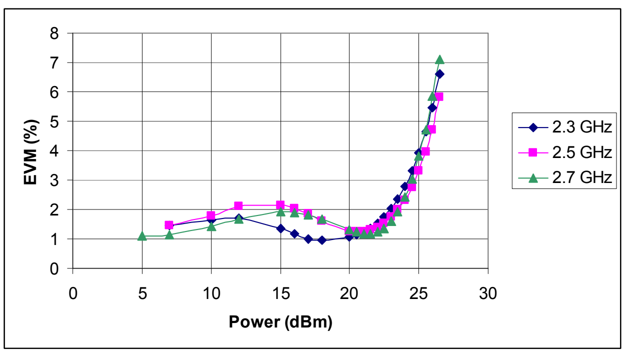

Fig. 4. EVM (%) versus power for SiGe 4G PA using a 802.16e 10 MHz QAM16 signal

From figure 4, we observe that the EVM is under 4% across 2.3 GHz to 2.7 GHz for PA output powers up to 25 dBm. From the PA gain measurements of figure 3, we estimate that the back off required from P1dB to achieve 4% EVM is 5 dB for 802.16e. The use of the linearization technique has provided at least 1dB improvement in back off since the PAPR for an 802.16e uplink signal is at least 6 dB.

The spectral mask for 802.16e for the 2.5-2.7 GHz band is the most stringent of any wireless standard. For a 10 MHz channel bandwidth, the 6.5 MHz offset from the channel edge is typically the most challenging for mask compliance. At this offset, the spectral mask limit at the antenna is -25 dBm/MHz. For TD-LTE in Band 40 (2.3-2.4 GHz), the spectral mask is significantly more relaxed. Figure 5 shows a comparison of the spectral masks for the 802.16e, 2.5-2.7 GHz and the TD-LTE 2.3-2.4 GHz band. In figure 5, we observe that the TD-LTE spectral mask is relaxed by 12 dB at the 6.5 MHz offset compared to the 802.16e spectral mask. This should result in a higher compliant output power for the SiGe 4G PA for TD-LTE compared to 802.16e.

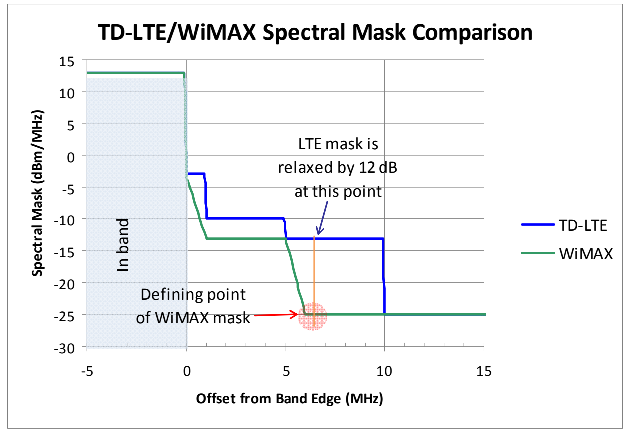

Fig. 5. Comparison of the TD-LTE and 802.16e spectral mask

The 802.16e spectral mask with a 10 MHz QAM16 uplink signal was measured for the SiGe 4G PA. The PA complied with the 802.16e spectral mask from 2.3-2.7 GHz. Figure 6 shows the spectral mask at an output power of 25 dBm.

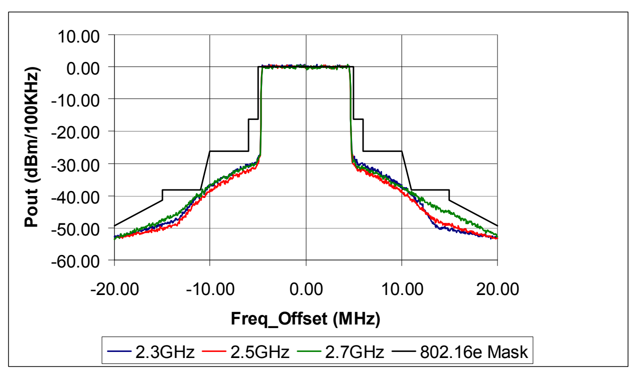

Fig. 6. 802.16e spectral mask for 2.3 GHz to 2.7 GHz at a Vcc =3.3V and a PA output power of 25dBm

In figure 6, we observe that the adjacent channel power (ACP) at the 11.5 MHz offset from the channel center with a 1MHz integration bandwidth at 2.5 GHz is -42 dBc compared to the 802.16e specification of -38 dBc at the antenna. This indicates that there is reasonable margin with spectral mask and therefore further optimization of the PA match and biasing can be performed to improve the PA efficiency at the expense of ACP. EVM and spectral mask were also measured for the TD-LTE standard and the FDD-LTE Band 7. For an EVM limit of 12.5% and 3GPP mask compliance, the SiGe 4G PA was able to produce 28.5 dBm output power for LTE. This is significantly higher than the 25 dBm PA output power needed to deliver 23.5 to 24 dBm at the antenna for TD-LTE assuming 1 to 1.5 dB of post PA losses (balun and T/R switch) for a single band implementation. For FDD-LTE applications, the desired PA output power is approximately 27.5 dBm assuming ~4dB of post PA losses including the duplexer and multi-pole switch.

The current consumption of 4G PAs is critical for mobile and nomadic applications. Figure 7 depicts the DC supply current for a 802.16e 10 MHz QAM 16 uplink waveform. The PA was operated in the high power mode for this measurement. We observe that the current consumption is relatively constant varying from 522mA to 540mA at a Vcc of 3.3V. The power added efficiency (PAE) is approximately 18% across the entire 2.3-2.7 GHz band. For lower power levels, the PA can be placed into a medium or low power mode. Initial measurements at the low power mode reveal approximately 100 mA of current consumption at 0 dBm.

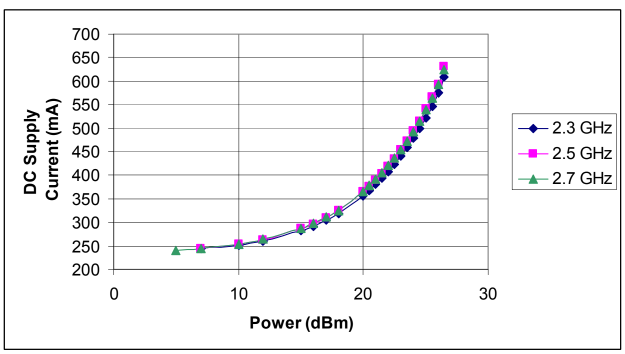

Fig. 7. SiGe 4G PA current versus output power for a QAM16 10 MHz 802.16e uplink signal.

Another important specification is harmonics. For the testing of the harmonics, the measurements were recorded at the output of the balun. The balun provides between 15 dB to 20 dB of common mode rejection at the second harmonics of the 2.3-2.7 GHz band. For a 2.5 GHz 802.16e QAM16 uplink signal with a PA output power of 25 dBm (24.4 dBm following the balun), the second harmonic measured -43 dBm/MHz and the third harmonic measured -23 dBm/MHz. The 802.16e specification for harmonics is -30 dBm/MHz. The second harmonic performance meets the 802.16e specifications but more third harmonic suppression is required. One potential solution is to implement a third harmonic "trap" or a higher order low pass filter characteristic in the output match. For future implementations, the output match and balun can be integrated as a transformer balun with harmonic traps either onto the SiGe PA IC, or onto a separate Si IPD or onto a multi-layer LTCC substrate.

Finally, VSWR ruggedness testing was performed. The PA module with the external balun was subjected to a 10:1 VSWR mismatch for 360 degrees of phase and no instabilities or degradation in performance was observed.

IV. Summary

We have successfully demonstrated a key element in the realization of a fully integrated 4G RF Front End IC; the 4G SiGe PA IC. The 4G SiGe PA produces an output power of 25 dBm for the 2.3-2.7 GHz 802.16e band with a PAE of 18% and second harmonic levels of -34 dBm/MHz after the balun. For TD-LTE Band 40 and FDD-LTE Band 7, this PA produces 28.5 dBm of output power while meeting the 3GPP EVM and spectral mask requirements.

Acknowledgement

The authors wish to acknowledge Yalin Jin for transformer balun discussions.

References

[1] Hsin-Hsing Liao, Hao Jiang, Shanjani, P., King, J., Behzad, A., "A Fully Integrated 2x2 Power Amplifier for Dual Band MIMO 802.11n WLAN Application Using SiGe HBT Technology," *IEEE Journal of Solid State Circuits.*, vol. 44, no.5, pp. 1361-1371, May 2009.

[2] Yan Li, Lopez, J., Lie D.Y.C., Chen K., Wu, S., Tzu-Yi Yang,," SiGe Class-E Power Amplifier With Envelope Tracking For Mobile WIMAX/WiBro Applications,"*IEEE International Symposium on Circuits and Systems,* pp. 2017-2020, May 2009.

[3] Chowdhury, D., Hull, C. D., Degani, O.B., Wang Y., Niknejad, A. M., "A Fully Integrated Dual Mode Highly Linear 2.4 GHz CMOS Power Amplifier For 4G WIMAX Applications," *IEEE Journal of Solid State Circuits,* vol. 44, no. 12, pp. 3393-3402, December 2009

[4] Degani, O., Cossoy, F., Shahaf, S., Chowdhury, D., Hull, C.D., Emanuel, C., Shmuel, R., "A 90nm CMOS Power Amplifier for 802.16e (WIMAX) Applications," *IEEE RFIC Symposium,* pp. 373-376, June 2009

[5] Arvind Keerti, Anh-Vu H. Pham, "RF Characterization of SiGe HBT Power Amplifiers Under Load Mismatch," *IEEE Trans. Microw. Theory and Tech.,* vol. 55, no.2, pp. 207-214, February 2007

[6] V.B. Krishnamurthy, T.K. Khanijoun, K.M. Hershberger, J.T. Reed, P.E, Pace, US Patent #7,573,329, August, 11th, 2009