# A Fully Monolithic BiCMOS Envelope-Tracking Power Amplifier With On-Chip Transformer for Broadband Wireless Applications

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***Abstract*—This letter presents a power-combined BiCMOS power amplifier (PA) system using envelope-tracking (ET) to serve as a fully monolithic solution for high peak-to-average ratio (PAR) broadband signals. The system consists of two cascode unit PAs combined by an on-chip transformer and modulated by a single envelope modulator. Without needing predistortion, the maximum linear output power of 24.6 dBm/23.8 dBm/23.2 dBm can be achieved with overall power-added-efficiency (PAE) of 26%/24%/22.5% for the LTE 16QAM 5 MHz/LTE 16QAM 10 MHz/WiMAX 64QAM 5 MHz signals at 1.9 GHz. The proposed power-combined ET-PA is fabricated in the TSMC 0.35 $\mu$m SiGe BiCMOS technology.**

***Index Terms*—Envelope-tracking (ET), envelope modulator, on-chip transformer, power-combined power amplifier (PA).**

## I. Introduction

The Silicon (Si)-based power amplifiers (PAs) using on-chip power combining have shown good potential for future handset applications, as their saturated power ($\mathrm{P_{sat}}$) levels have reached 27–34 dBm to compete with III-V compound semiconductor based PAs [1]–[5]. Unfortunately, for non-constant-envelope modulated signals with inherent high peak-to-average ratios (PARs) and wide bandwidths (e.g., LTE and WiMAX), these reported Si-based PAs need a back-off of $\sim$7–14 dB from $\mathrm{P_{sat}}$ to pass the stringent linearity specs. Such large power back-off results in serious power-added-efficiency (PAE) degradation, often from a PAE of 50% at $\mathrm{P_{sat}}$ to a PAE below 15% at the linear output power ($\mathrm{P_{out}}$) [1]–[4]. In order to boost the linear $\mathrm{P_{out}}$ and PAE, the predistortion technique was used in [5]. On the other hand, the envelope-tracking (ET) technique has demonstrated promising linearity and efficiency performances [6]–[8]. In [7], the ET technique was applied to a Doherty GaAs PA, achieving an efficiency enhancement over the extended output dynamic range. In this letter, we will propose a fully monolithic power-combined ET-PA and demonstrate its efficiency and linearity enhancements for the LTE/WiMAX signals.

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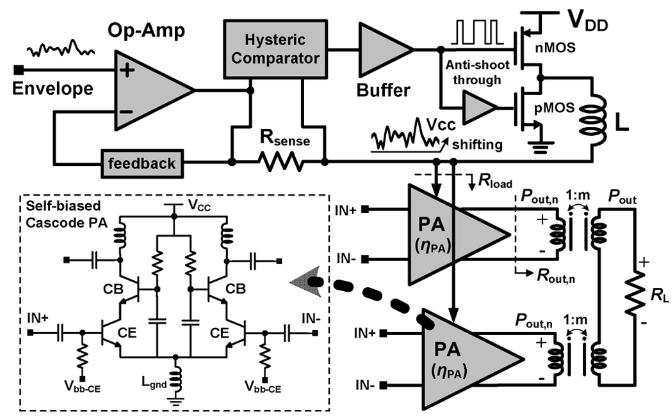


Fig. 1. Simplified block diagram and circuit schematic of the power-combined ET-PA system presented in the work.

## II. Design and Implementation

The overall system diagram of our power-combined ET-PA is shown in Fig. 1. As proposed in [10], the envelope signal is first shifted to a predetermined minimal level, while its ac magnitude is reduced to avoid clipping. The shifted envelope is then used to modulate the two self-biased cascode unit PAs for linearity enhancement in the ET-PA system.

Our power-combined PA was designed in the TSMC 0.35 $\mu$m SiGe BiCMOS technology. This process provides a 3-metal stack with only one thick AlCu metal (3 $\mu$m). The on-chip transformer performs both power combining and impedance transformation, which reduces the number of off-chip components. For a $N$-way series-combining transformer (SCT) with turn ratio of $m$ ($N$ is the number of unit PAs combined), the output power of each unit PA ($\mathrm{P_{out,n}}$) can be expressed as [2]

$$P_{\mathrm{out,n}} \propto V_{\mathrm{CC}}^2/R_{\mathrm{out,n}} = N \cdot m^2 V_{\mathrm{CC}}^2/R_{\mathrm{L}} \tag{1}$$

where $\mathrm{R_{out,n}}$ is the transformed load impedance seen by each unit PA and $\mathrm{V_{CC}}$ is the average modulated supply voltage.

The power-combined PA presents a load ($\mathrm{R_{load}}$) to the envelope modulator, directly related to $\mathrm{P_{out,n}}$ and the collector efficiency of each unit PA ($\eta_{\mathrm{PA}} = \mathrm{P_{out,n}/P_{DC,n}}$) [6]. Substituting $\mathrm{P_{out,n}}$ by (1), $\mathrm{R_{load}}$ can be expressed as

$$R_{\mathrm{load}} = \frac{V_{\mathrm{CC}}^2}{N \cdot P_{\mathrm{DC,n}}} = \frac{\eta_{\mathrm{PA}} V_{\mathrm{CC}}^2}{N \cdot P_{\mathrm{out,n}}} \propto \frac{\eta_{\mathrm{PA}} R_{\mathrm{L}}}{m^2 N^2}. \tag{2}$$

Based on (1), higher $\mathrm{P_{out}}$ can be achieved by designing a transformer with high-$N$ and high-$m$, but this approach will inevitably result in a very low $\mathrm{R_{load}}$ as indicated by (2). This

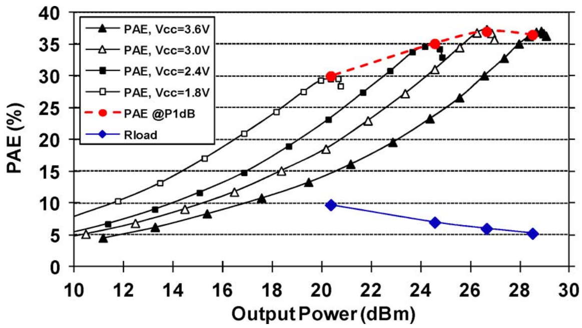


Fig. 2. Measured PAE and $\mathrm{R_{load}}$ versus $\mathrm{P_{out}}$ of the stand-alone power-combined PA tested at CW mode at 1.9 GHz by sweeping $\mathrm{V_{CC}}$.

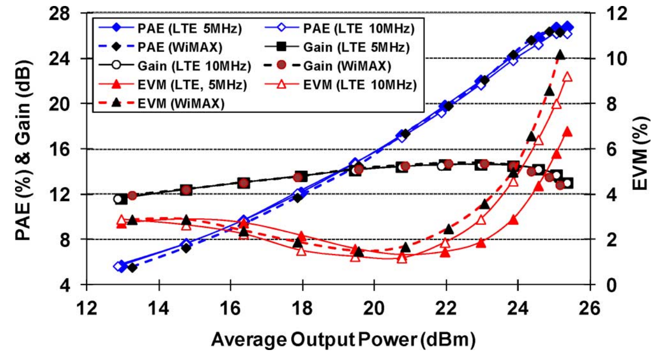


Fig. 3. Overall PAE, gain and EVM of the power-combined ET-PA for LTE 16QAM 5 MHz/10 MHz and WiMAX 64QAM 5 MHz signals at 1.9 GHz.

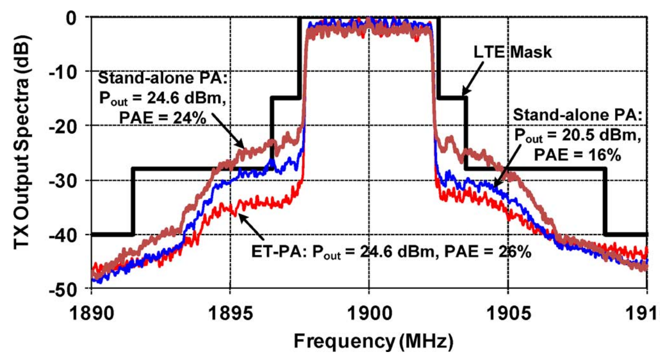


Fig. 4. Measured output spectra of the power-combined ET-PA and the stand-alone power-combined PA for the LTE 16QAM 5 MHz signal.

makes the design of the integrated envelope modulator more difficult as it has to supply larger output current with sufficient bandwidth. In our design, the SCT consists of two primary windings ($N = 2$) and one secondary winding with 1:1 turn ratio ($m = 1$). The insertion loss (IL) of the SCT obtained from the Momentum simulation is 1.4 dB ($\eta_x = 72\%$). In the measurement, the external input/output baluns will be used and the balun losses are excluded from the measurement data.

The linear-assisted switching envelope modulator utilizes the similar configuration as [10], but here necessary adjustments have been made for driving a lower $\mathrm{R_{load}}$. For example, the biasing of the Op-Amp output stage is optimized for this power-combined ET-PA to achieve a good compromise between linearity and efficiency. The inductor of the buck converter is chosen as 10 $\mu$H to have a higher average switching frequency than [10], so that the buck converter can supply more current to help relax the output current requirement of the linear stage. The linear stage can effectively suppress the switching ripples as long as the switching frequency is within its bandwidth [7]. Moreover, the switching frequency is time-varying according to the instantaneous envelope, and thereby the switching noise is spread over a wide frequency range, reducing the peak magnitude of the spurs. The measured efficiency of the envelope modulator is 81% when driving $\mathrm{R_{load}}$ of 7.5 Ω with the envelope of the LTE 16QAM 5 MHz signal.

## III. Experimental Results

The stand-alone power-combined PA (i.e., the envelope modulator disabled) was first evaluated at the continuous- waveform (CW) mode without the concern of linearity. Fig. 2 shows the measured PAE versus $\mathrm{P_{out}}$ at 1.9 GHz by sweeping $\mathrm{V_{CC}}$. At $\mathrm{V_{CC}}$ of 3.6 V, its $\mathrm{P_{sat}}$ is 29.1 dBm with a peak PAE of 37%. The PAE at $\mathrm{P_{1\ dB}}$ maintains above 30% at $\mathrm{V_{CC}}$ of 1.8–3.6 V as shown by the dashed line. The $\mathrm{R_{load}}$ seen by the envelope modulator is also plotted in Fig. 2, obtained at each $\mathrm{P_{1\ dB}}$ point.

The LTE 16QAM (PAR $\sim$ 7.5 dB) and WiMAX 64QAM (PAR $\sim$ 10 dB) are then used to evaluate the linearity and efficiency of the power-combined ET-PA at $\mathrm{V_{DD}}$ of 3.6 V. As shown in Fig. 3, the maximum linear $\mathrm{P_{out}}$ is 24.6 dBm/23.8 dBm with overall PAE of 26%/24% and EVM of 4.4%/4.6% for the LTE 16QAM 5 MHz/10 MHz signals, respectively. Due to higher PAR, the maximum linear $\mathrm{P_{out}}$ for WiMAX is 23.2 dBm with overall PAE of 22.5% and EVM of 3.6%. To prove the effectiveness of our ET technique, Fig. 4 shows the output spectra of the power-combined ET-PA and the stand-alone power-combined PA ($\mathrm{V_{CC}} = 3.6$ V) for 5 MHz LTE. The maximum linear $\mathrm{P_{out}}$ of the stand-alone PA can only be at best 20.5 dBm for passing the spectral mask, leading to a PAE of only 16% (i.e., 10% lower than the ET-PA). The linearity of the PA is improved by using ET, because the envelope shaping method reduces the intermodulation distortions (IMDs) [8].

The far-out spectrum of the power-combined ET-PA at 24.6 dBm is shown in Fig. 5. By using the Tektronix 6120A real-time signal analyzer (RSA), insightful information can be observed regarding the switching noise of the output signal. The gradual change of color (or shade in print) on the trace represents the distribution of the output power. Over 80% power resides in the red area (or dark area in print), while less than 20% power resides in the green-blue area (or light area in print). By taking the root-mean-square of the real-time output spectrum, the spurious emission of our ET-PA is $-51$ dBm/MHz at 100 MHz offset, satisfying the LTE spurious emission spec of $-50$ dBm/MHz. Compared with the far-out spectrum of the stand-alone PA (not shown), the spectral regrowth of the ET-PA at 20–30 MHz offset from the center frequency (see Fig. 5) is increased by $\sim$3 dB due to the switching noise. The noise power density only accounts for $\sim$3.8% within this specified frequency range. Such reasonably small noise power is non-observable using the traditional spectrum analyzer (e.g., Agilent E4448A). The emission noise can be suppressed further by adding extra filtering or duplexer isolation.

Table I summarizes the performances of our design and state-of-the-art PAs for high-PAR broadband signals. Without using predistortion (i.e., "PD" in Table I), the ET technique enabled our power-combined PA to have a PAE above 20% at the maximum linear $\mathrm{P_{out}}$, outperforming the fixed-supply

TABLE I
SUMMARY OF OUR MONOLITHIC POWER-COMBINED ET-PA WITH STATE-OF-THE-ART PAS [1]–[5], [9] AND ET-PA [10]

| | Freq. (GHz) | $V_{DD}$ (V) | Linear $P_{out}$ (dBm) | {2}PAE | EVM | Modulation | BW (MHz) | PD | Technology |
|---|---|---|---|---|---|---|---|---|---|
| [1] | 2.3 | 3.3 | 22.7 | 12.4% | 5.4% | WiMAX 64QAM | 10 | No | 90 nm CMOS |
| [2] | 2.4 | 1.2 | 14.5 | 9% | 4.48% | WLAN 64QAM | 20 | No | 0.13 μm CMOS |
| [3] | 3.3-3.8 | 3.3 | 15 | 8% | --- | WiMAX 64QAM | 10 | No | SiGe:C bipolar |
| [4] | 2.5 | 3.3 | 21 | 7% | 5.6% | WLAN 64QAM | 20 | No | 0.18 μm CMOS |
| | | | 17 | 4% | 2.8% | WiMAX 64QAM | 10 | No | |
| [5] | 2.3-2.7 | 3.3 | 25 | 24% | 4% | WiMAX 64QAM | 10 | *Yes* | 90 nm CMOS |
| [9] | 0.77-0.8 | 3.4 | 27.5 | 36% | --- | LTE | --- | No | InGaP HBT |
| {1}[10] | 1.9 | 3.6 | 23 | 40% | 4.3% | LTE 16QAM | 5 | No | 0.35 μm SiGe BiCMOS |
| This work | 1.9 | 3.6 | 24.6 | 26% | 4.4% | LTE 16QAM | 5 | No | 0.35 μm SiGe BiCMOS |
| | | | 23.8 | 24% | 4.6% | LTE 16QAM | 10 | No | |
| | 1.9 | 3.6 | 23.2 | 22.5% | 3.6% | WiMAX 64QAM | 5 | No | |

Note: {1}. For the comparison with this work, the ET-PA without using power combining in [10] was tested at $V_{DD}$ of 3.6 V at 1.9 GHz.
{2}. In this work and [10], the overall PAE includes the power consumption of the envelope modulator.

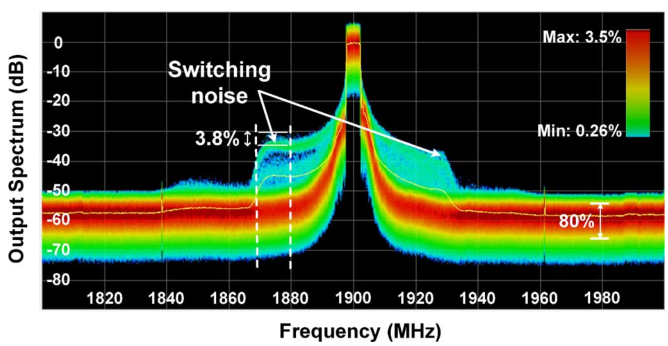


Fig. 5. Measured far-out spectrum of ET-PA for LTE 16QAM 5 MHz signal.

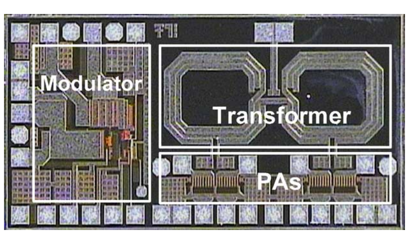


Fig. 6. Die picture of the fully monolithic power-combined ET-PA system.

power-combined PAs in [1]–[4]. Note that an off-chip output balun was used in this work as [10], but our transformer can also be used to transform the single-ended load impedance to differential load impedances as [1]–[5]. Even though the overall PAE of this work did not reach as high as [9], [10], further efficiency improvement is expected if a low-loss transformer can be implemented by using multiple thick metal layers [4] or an integrated passive devices (IPD) technology on the high-resistivity silicon substrate [11]. In future implementation, the driver stage will be added to achieve the gain above 30 dB. Moreover, the linearity of the ET-PA is expected to be improved by predistortion, allowing deeper compression with higher efficiency. The die picture of our power-combined ET-PA is shown in Fig. 6.

## IV. CONCLUSION

We have presented a fully monolithic power-combined ET-PA. The maximum linear $P_{out}$ is 24.6 dBm/23.8 dBm/23.2 dBm with overall PAE of 26%/24%/22.5% for the LTE 16QAM 5 MHz/LTE 16QAM 10 MHz/WiMAX 64QAM 5 MHz signals, respectively. Compared with the conventional fixed-supply PA, the ET technique improved the PA linearity, allowing higher $P_{out}$ and PAE without violating the linearity specs. These results demonstrated the effectiveness of the ET technique for power-combined Si-based PAs in high-PAR wideband applications.

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