High Efficiency and Wideband Envelope Tracking Power Amplifier with Sweet Spot Tracking

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***Abstract* — This paper describes the implementation of a high efficiency and wideband envelope tracking power amplifier with sweet spot tracking. By modulating supply voltage of power amplifier (PA), efficiency can be increased significantly. And linearity is improved by envelope shaping and sweet spot tracking. The supply modulator has a combined structure of a switching amplifier and a linear amplifier to achieve high efficiency as well as wide bandwidth. The measurement results show efficiencies of 36.4/34.1 % for 10/20 MHz long term evolution (LTE) signals with peak to average power ratio (PAPR) of 7.5/7.42 dB.**

***Index Terms* — Boost converter, envelope tracking, linear amplifier, long term evolution (LTE), power amplifier (PA), sweet spot, switching amplifier.**

I. Introduction

As wireless communication systems provide high data rate services, the channel bandwidth and PAPR of the signals are increased and the efficiency for the power amplifier is decreased. In the case of conventional PA with fixed supply voltage (Fig. 1a), the PA should be operated in the back off power region to linearly amplify the modulated signal with high PAPR and its efficiency is much lower than its peak value as shown in Fig. 2. On the other hand, the envelope tracking PA (Fig. 1b) operates under modulated supply voltage according to its output power level and its efficiency is degraded slightly.

Because overall efficiency of the envelope tracking PA is proportional to efficiency of the supply modulator and its linearity is affected by linearity of the supply modulator, a realization of the supply modulator with a high efficiency and good linearity is very important. In [1], they have designed a low dropout (LDO) regulator as a supply modulator, but its efficiency is very low for high PAPR signals. In [2], a switching amplifier is used as a supply modulator. Although it achieves high efficiency, it requires high order passive filter and its bandwidth is too narrow to use for wide bandwidth signals such as LTE and WiMAX. To achieve high efficiency and wide bandwidth, we use hybrid switching supply modulator combining the advantages of two supply modulators [3]-[7]. To improve the performance of power amplifier, a boost converter is added to the supply modulator as shown in Fig. 3. By boosting the supply voltage of the linear amplifier from 3.4V to 5V, the output voltage of the supply modulator is increased up to 4.5V and the power amplifier shows higher gain, efficiency, output power and wider bandwidth.

In [8], they analyze nonlinear distortion of envelope tracking PA. Because of knee voltage and nonlinear capacitance, AM-AM and AM-PM distortion are generated. By adopting envelope shaping and sweet spot tracking, linearity can be improved.

In this paper, we implement a high efficiency and wideband envelope tracking PA for LTE applications using a hybrid switching supply modulator, HBT PA, envelope shaping, and sweet spot tracking.

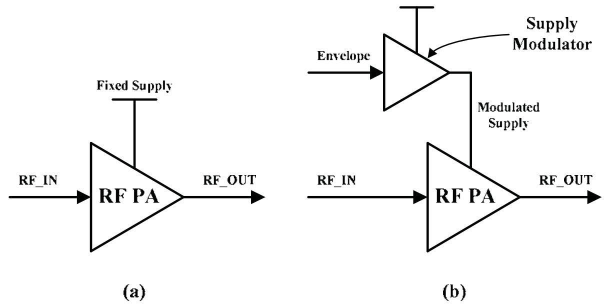

Fig. 1. (a) Conventional PA with fixed supply voltage. (b) Envelope tracking PA with modulated supply voltage.

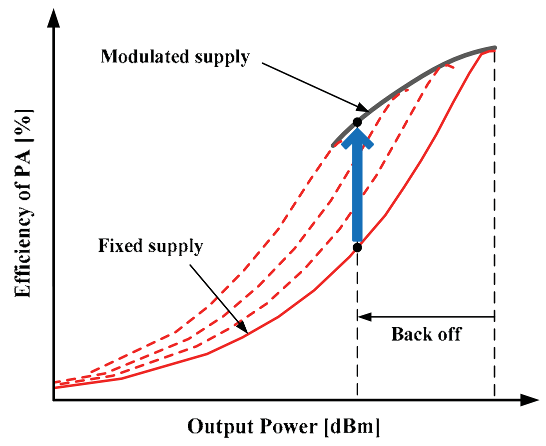

Fig. 2. PA's efficiency curves with fixed supply voltage and modulated supply voltage.

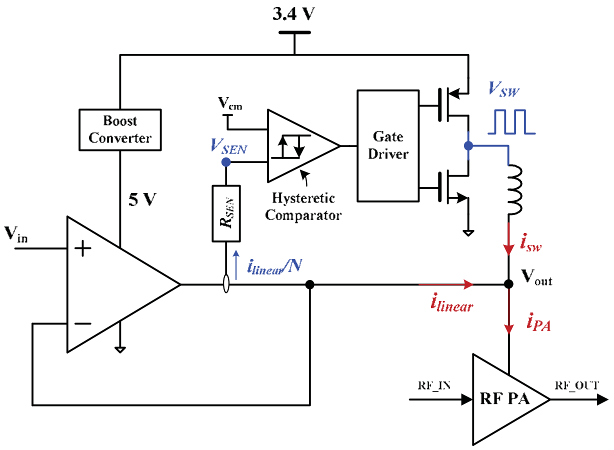

Fig. 3. Block diagram of the hybrid switching supply modulator with boost converter.

II. Design of High Efficiency and Wideband Supply Modulator

The proposed supply modulator consists of a wideband linear amplifier, a high efficiency low speed switching amplifier, and a boost converter. Usually the switching amplifier supplies low frequency component of the envelope signal with high efficiency and the linear amplifier supplies other high frequency component with high speed. Because most of the power of the envelope signal is located at a low frequency, this structure is suitable for an operation with high efficiency and wideband.

In Fig. 3, the wideband linear amplifier operates as a voltage-controlled voltage source (VCVS). It means the output voltage of the linear amplifier is the same with its input voltage up to tens of MHz due to its high gain, wide bandwidth, and negative feedback. As shown in Fig. 4, we use folded-cascode OTA as a gain stage to achieve a large bandwidth and high DC gain. For large current driving capability and rail-to-rail operation, the output buffer has a common source configuration and it is biased as class-AB for linearity and efficiency.

The high efficiency, low speed switching amplifier operates as a dependent current source. It senses the direction of the linear amplifier's current and controls the switching amplifier using a hysteretic comparator. Generally, the average switching frequency is dependent on the hysteresis width, inductor value, and some other parameters for a narrow-band signal. For a wideband signal, the average switching frequency is mainly determined by its bandwidth. The sizes of the power switches are determined by considering the conduction loss and switching loss at the specific load resistance, switching frequency, and duty ratio. For the protection, high efficiency, and low switching noise of the switches, anti-shoot-through circuit and divided switches with current control technique are employed (Fig. 5) [9]. Gate driver for the divided switches, which is shown in Fig. 6, turns on / off the 4 switches with a little delay. It can be designed easily using 4 MUXs and inverter chains.

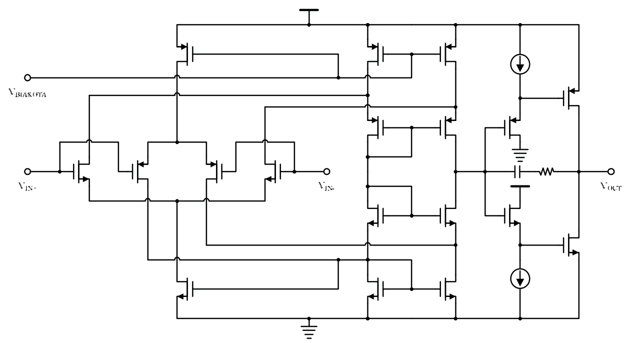

Fig. 4 Wideband linear amplifier.

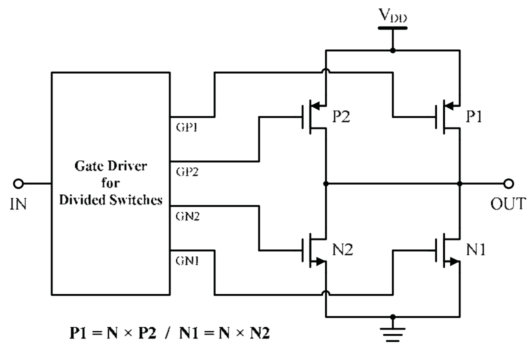

Fig. 5 High efficiency switching amplifier.

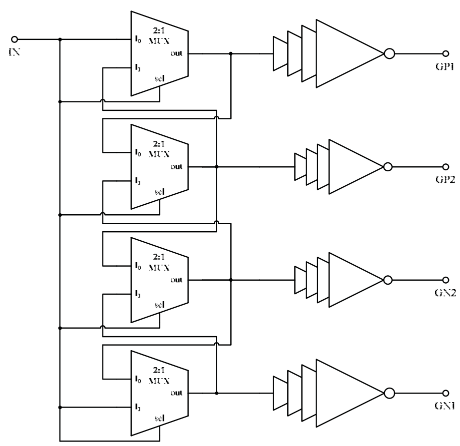

Fig. 6. Gate driver for divide switches with current control technique.

III. Envelope Shaping and Sweet Spot Tracking

The modulated PA operates differently according to the supply voltage level. Especially at a low supply voltage, a power amplifier shows severe nonlinear characteristics such as AM-AM and AM-PM distortions because of knee voltage effect and nonlinear capacitance. To compensate these effects, an envelope shaping method should be used [7].

In addition to this basic method, a sweet spot tracking is proposed in this work. Fig. 7 is third-order and fifth-order intermodulation distortions (IMD) of PA in two-tone analysis. In this figure, there are sweet spots which are local minimums of IMD and are occurred by cancellation of the harmonics. As supply voltage decreases, the sweet spot also moves to lower power. By adjusting the supply voltage to minimize the distortions at each power level, the linearity of the envelope tracking PA can be improved significantly.

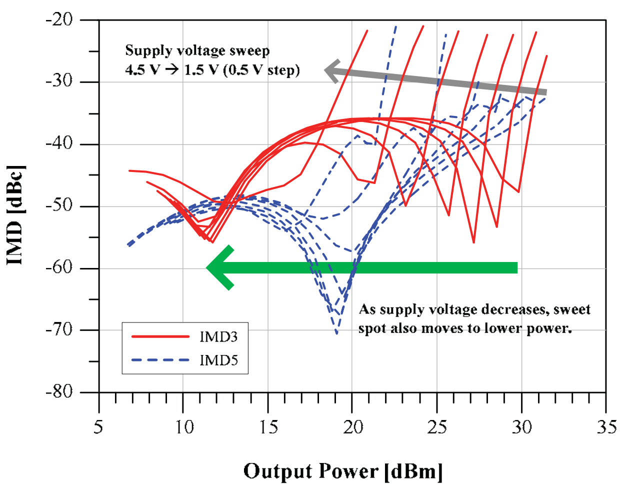

Fig. 7. Simulated third-order and fifth-order intermodulation distortions of PA in two-tone analysis.

IV. Measurement Results

The designed supply modulator is fabricated using 65nm CMOS process and it uses thick oxide I/O devices for a high voltage operation. Chip photograph is shown in Fig. 8 and its size is 2.6 mm × 1.7 mm. The supply voltage for the supply modulator is 3.4 V (the battery voltage) and the boost converter generates 5 V for supply of the linear amplifier. In this configuration, output voltage range of the supply modulator is 0.5 to 4.5 V regardless of the battery voltage fluctuation, replacing the DC-DC converter [10]. The linear amplifier shows over 100 MHz bandwidth and over 55 dB DC gain. The average switching frequency of the switching amplifier is varied from 3 MHz to 6 MHz according to the bandwidth of an input signal.

To implement the envelope tracking PA, 2.535GHz class-AB PA, which is fabricated using InGaP/GaAs 2um HBT process, is used. It has about 30 dBm peak output power at 3 V supply voltage. By boosting the supply voltage of the linear amplifier, PA's supply voltage increases up to 4.5 V and peak output power of the PA also increases to 33.4 dBm. Performance of the envelope tracking PA is measured using 10/20 MHz LTE signals with 7.5/7.42 dB of PAPR.

Fig. 9 shows the measured efficiency and gain of the envelope tracking PA. For the 10 MHz LTE signal, the envelope tracking PA has efficiency of 36.4 % at output power of 27.2 dBm. For the 20 MHz LTE signal, its efficiency is 34.1 % at output power of 26.1 dBm. Estimated efficiencies of the supply modulator are about 75/71 % for 10/20 MHz LTE signals. These values can be calculated from PA's efficiency curve at each supply voltage. Fig. 10 is measured output spectra of the envelope tracking PA at the peak output powers without any linearization technique.

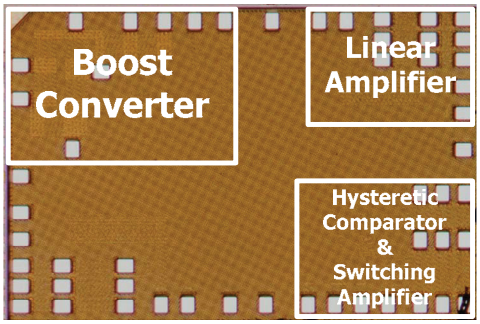

Fig. 8. Fabricated chip photograph of the supply modulator.

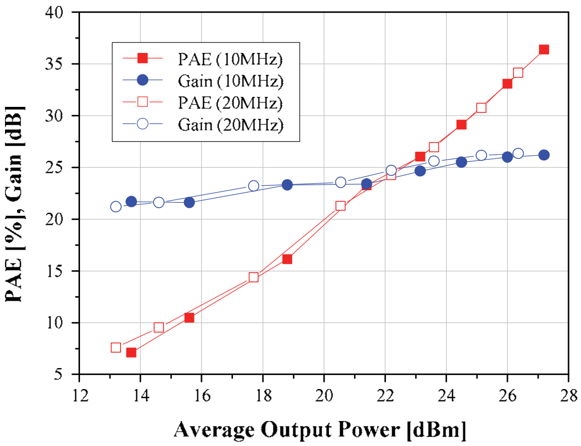

Fig. 9. Measured efficiency and gain of the envelope tracking PA.

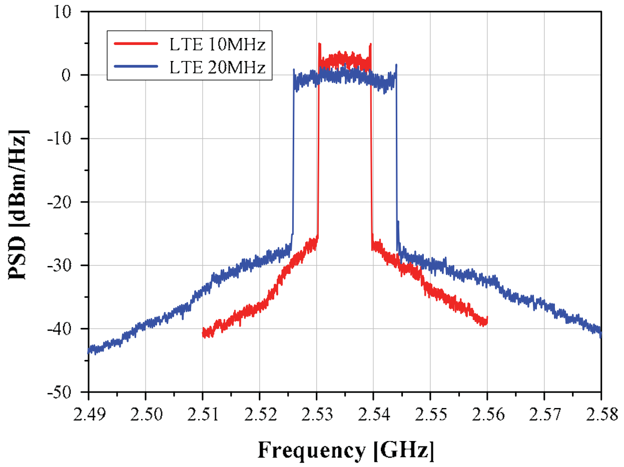

Fig. 10. Measured output spectra of the envelope tracking PA at peak output power.

TABLE I
PERFORMANCE SUMMARY OF ENVELOPE TRACKING POWER AMPLIFIER FOR LTE APPLICATIONS

Signal bandwidth	10 MHz	20 MHz
PAPR	7.5 dB	7.42 dB
Supply voltage	3.4 V	
Peak output power	27.2 dBm	26.1 dBm
Peak efficiency	36.4 %	34.1 %
Estimated efficiency of supply modulator @ peak output power	75 %	71 %

V. CONCLUSIONS

A high efficiency and wideband envelope tracking PA with sweet spot tracking technique is proposed and implemented for LTE applications. For the supply modulation, a hybrid switching supply modulator with boost converter is fabricated using 65nm CMOS process. An envelope shaping with sweet spot tracking is adopted to compensate AM-AM and AM-PM distortions. Efficiencies of the implemented envelope tracking PA are 36.4/34.1 % at output power of 27.2/26.1 dBm for 10/20 MHz LTE signals, respectively. Measured results show the proposed supply modulator with sweet spot tracking is a suitable structure to achieve a high efficiency and wideband envelope tracking PA.

ACKNOWLEDGEMENT

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