Novel Shaping Function for Envelope Tracking Linearization

Yu Zhu  
Skyworks Solutions, Inc.  
Woburn, USA  
yu.zhu@skyworksinc.com

Oleksiy P Klimashov  
Skyworks Solutions, Inc.  
Woburn, USA  
alexy.klimashov@skyworksinc.com

Boshi Jin  
Skyworks Solutions, Inc.  
Woburn, USA  
boshi.jin@skyworksinc.com

Florinel Balteanu  
Skyworks Solutions, Inc.  
Irvine, USA  
florinel.balteanu@skyworksinc.com

Serge Drogi  
Skyworks Solutions, Inc.  
Irvine, USA  
serge.drogi@skyworksinc.com

Dylan C Bartle  
Skyworks Solutions, Inc.  
Woburn, USA  
dylan.bartle@skyworksinc.com

Paul T DiCarlo  
Skyworks Solutions, Inc.  
Woburn, USA  
paul.dicarlo@skyworksinc.com

Abstract—Envelope tracking (ET) linearization can be explained as the cancellation between two kinds of intermodulation distortions (IMD) [1]. A novel shaping function for ET linearization can thus be constructed by balancing the two IMDs. A dynamic approach of shaping function extraction, called slope tuning, is proposed and demonstrated in this study. Significant linearity improvements in a heterojunction bipolar transistor (HBT) power amplifier are experimentally achieved with extracted shaping function for both two-tone and long-term evolution (LTE) signals.

Keywords—circuit analysis, circuit simulation, intermodulation distortion, linearization techniques, power amplifier

I. INTRODUCTION

While envelope tracking (ET) has long been known as an effective technique for power amplifier (PA) efficiency enhancement [2], it has also been reported as a powerful approach for PA linearization [3]-[5]. Stimulus to a PA can be regarded as either a bias or a signal. The former is provided to keep a PA operating, and the latter is the object to be processed by the PA. RF input is usually regarded as a signal, and DC supply a bias. However, is envelope injection a bias or a signal? Depending on how envelope signal is viewed, ET linearization analyses published so far falls into two categories: the time domain and frequency domain approaches.

In the time domain approach, the ET signal is considered as a time varying bias. ET linearization is achieved by the waveform alignment between the RF input envelope and the drain bias of PA transistor. The mapping between the RF input envelope and the drain bias applied is called envelope shaping function. The shaping function for linearity improvement is formulated either to maintain a constant gain or to track the intermodulation distortion (IMD) sweet spots. Significant linearity improvements have been reported [6]-[8].

However, the time domain approach is somewhat empirical. A shaping function has to be represented by a shaping table, since we do not know the exact form of the shaping function. Implementation of shaping table increases circuitry cost and complexity, and provides no further understanding about the physical mechanism behind the ET linearization.

In the frequency domain approach, any amplifier operated with a time varying supply voltage is viewed as a three-port circuit, as pointed out in [9], having two inputs and one output. Namely, the envelope injection is viewed as a signal. Interaction between the RF input and its envelope were studied in [3], [4], analytical expressions, depicting ET linearization as distortion cancellation in frequency domain, have been derived. Related analyses have also been reported in the names of baseband injection [9], [10], and difference frequency injection [12]-[14]. Further analysis was performed in [1]. Two kinds of IMD components were highlighted, and it’s between them that the cancellation happens. An analytical expression was given to predict the optimal condition for the cancellation based on device characteristics. ET linearization was experimentally achieved in GaN and SOI amplifiers [1].

In this study, a three tone analysis, performed in [1], is reexamined and a generalized explanation is provided. A dynamic approach for shaping table extraction is proposed and demonstrated. In addition to GaN and SOI amplifiers, ET linearization has also been achieved with heterojunction bipolar transistor (HBT) amplifier.

II. ANALYSIS

As shown in Fig. 1, RF input represented by a two-tone signal of with magnitude of $v_i$

$$v_g = v_i \cos(\omega_1 t) + \cos(\omega_2 t)$$

is injected into the gate, and the difference frequency of RF input is injected into the drain

$$v_d = v_i \cos(\omega_3 t)$$

where $v_i$ is the magnitude, and $\omega_3=\omega_2-\omega_1$. Two kinds of IMDs, $\text{IMD}_{\text{amp}}$ and $\text{IMD}_{\text{env}}$, are generated, the former is the $3^{rd}$ order mixing of gate injected two-tone and the latter the $2^{nd}$ order mixing.
order mixing of gate and drain injected signals. The optimal drain injection signal for linearization can be obtained by balancing the two IMDS as [1]

$$v_{e_{-}opt} = -\frac{g_m i_0}{4 g_d g_m} v_i^2,$$

(3)

where $g_m$ ($g_d$) is the derivative of $i_d$ respect to $v_e$ ($v_d$), $g_m3$ the 3rd derivative of $i_d$ respect to $v_g$, $i_0$ the quiescent current. The conclusion so far is that the linearization can be achieved by injecting a two-tone signal and its difference frequency into the gate and the drain, respectively.

The IMD cancellation was then reproduced with simulation. Three tone harmonic balance (HB) simulation was performed on a Silicon on insulator (SOI) PA with Advance Design System (ADS). Since the phase information is lost in power spectrum, the simulated voltage spectrum is shown in Fig. 2. Taking the fundamental output voltage as reference, the IMD voltage is negative (positive) when the IMD$_{env}$ (IMD$_{env}$) is dominating at low (high) $v_e$.

The three tone analysis, performed in [14], is reexamined here to demonstrate the relation between a difference frequency signal and an envelope signal. If the two-tone signal is viewed as a modulated signal, (1) can be rewritten as

$$v_g = 2v_i \cos\left(\frac{\omega_2 - \omega_1}{2} t\right) \cos\left(\frac{\omega_2 + \omega_1}{2} t\right)$$

(4)

and its envelope is

$$v_{g_{-}env} \approx v_i \cos\left(\frac{\omega_2 - \omega_1}{2} t\right).$$

(5)

On the other hand, inserting (3) into (2), the drain injection signal can be expressed as

$$v_d \approx v_i^2 \cos(\omega_2 - \omega_1) t]$$

$$= 2v_i^2 \cos^2 \left(\frac{\omega_2 - \omega_1}{2} t\right) - v_i^2.$$ 

(6)

Comparing (5) and (6), we have

By neglecting the DC offset, the drain injection signal for linearization is exactly the square of the envelope signal. Therefore, the conclusion can now be expressed in a more general way; the linearization can be achieved by injecting a modulated signal and the square of its envelope into the gate and the drain, respectively.

Equation (3) is actually the analytical expression of shaping function for ET linearization. If the argument of the shaping function is defined as the RF input envelope, not the RF input power, a quadratic shaping function is required for achieving IMD cancellation as shown in (3).

Two shaping functions were formulated experimentally in [15], a linear shaping function was obtained from the maximum PAE tracking for high efficiency, and a quadratic
shaping function was obtained from the iso-gain tracking for high linearity. Our analysis matches perfectly with the experimental results in [15]. It is worthwhile to note the inclusion of quiescent current $i_0$ in (3). The dependence of ET PA linearity on $i_0$ has also been experimentally observed [16].

III. MEASUREMENTS

As shown in (3), the drain ET injection for linearization is a quadratic function of input envelope voltage, and thus a linear function of input power. For simplicity, shaping function is defined between $v_d$ and input power thereafter. Eq. (7) yields a linear shaping function as

$$v_d = v_{d0} + \alpha P_i$$

(8)

where $v_{d0}$ is the quiescent DC voltage, $P_i$ the RF input power, and $\alpha$ the linear function slope. The magnitude of the drain injection voltage can now be tuned via the slope $\alpha$ as shown in (8). In other words, the cancellation between the two IMDs, namely, the ET linearization, can be achieved by tuning the slope of the linear shaping function. The process of finding the best shaping function by tuning the slope is called slope tuning thereafter.

A HBT PA was tested in an ET evaluation platform. The slope tuning approach was first performed using a two-tone signal with carrier frequency of 1.88GHz. The IMDs of the ET PA were measured by changing the shaping function slope. The measured dependence of IMD on the shaping function slope is shown in Fig. 3. The optimal slope corresponding to the minimum IMD can thus be extracted. Fig. 4 pictures the process of slope tuning. Fig. 5 (a) and (b) show the measured spectrums under fixed bias and optimized ET bias, respectively. A 30 dB improvement in IMD was achieved.

The slope tuning approach was then performed with a 4-MHz LTE signal. The shaping function extracted for LTE signal is slightly different from that for two-tone signal. Fig. 6 (a) and (b) show the measured spectrums under fixed bias and optimized ET bias, respectively. A 19dB improvement in ACPR was achieved.

An iso-gain shaping table was also extracted for comparison. A one tone power measurement was performed on the standalone PA by tuning both $P_i$ and the DC $V_d$. Fig. 7 shows the measured dependence of the power gain on $P_i$ with DC $V_d$ as a tuning parameter. The iso-gain shaping table can then be extracted by correlating $V_d$ and $P_i$ while tracking the iso-gain trajectory as shown in Fig. 7. Highly comparable improvements in IMD (ACPR) for two-tone (LTE) signal were achieved by using the iso-gain and the slope tuning shaping tables, respectively.

![Fig. 3. Measured slope dependence of IMD of HBT PA.](image)

![Fig. 4. Shaping functions evaluated with two tone signal for HBT PA, the red line represents the optimized shaping function.](image)

![Fig. 5. HBT PA test results with two-tone signal: (a) Fixed bias; (b) ET bias.](image)
Since both the iso-gain and the sweet spot tracking shaping functions are extracted with static drain bias, the stimulus to the PA transistor during the shaping function extraction is different from that during ET operation. In the slope tuning approach, however, the shaping function is extracted with dynamic drain bias; the stimulus during the shaping function extraction is exactly the same as that during ET operation.

IV. CONCLUSIONS

ET linearization is due to the IMD cancellation and can be achieved by injecting a modulated signal and the square of its envelope into the gate and the drain, respectively. A dynamic approach called slope tuning is proposed for shaping function extraction. Significant linearity improvement is experimentally observed for both two-tone and LTE input RF signals.

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