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Envelope Tracking Linearizability of Power Amplifier

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***Abstract* — Envelope tracking (ET) linearizability of a power amplifier (PA) is studied in this paper. ET linearization can be explained as the cancellation between two intermodulation distortion (IMD) components [1,2]. The phase difference θ₀ between the two IMD components is identified as the criterion of ET linearizability. The IMD improvement by incorporating ET module with PA can be analytically calculated in terms of θ₀. Excellent agreement between the prediction and measurement is achieved. Determination of θ₀ using three-tone measurement is proposed and demonstrated. ET linearizability is an inherent feature of a standalone PA itself, and can be quantitatively predicted before incorporating an ET module.**

Index Terms — amplifier, envelope tracking, intermodulation distortion, microwave power amplifier, nonlinearities.

I. INTRODUCTION

While envelope tracking (ET) has long been known as an effective technique for power amplifier (PA) efficiency enhancement[3], ET linearization, the linearity improvement by incorporating an ET module, has also been reported recently[4]-[6]. ET linearization can be explained as the cancellation between the two intermodulation distortion (IMD) components inside an ET PA [1]-[2].

An ET PA consists of a standalone PA and an ET module. It will be of great help if ET linearizability can be predicted before incorporating ET module. In this paper, we are trying to answer the following questions. 1) How can it be determined whether a PA is ET linearizable or not? 2) How much improvement can be expected if a PA is ET linearizable?

An inherent parameter of a standalone PA, the phase difference θ_0 between the two IMD components, is identified to quantitatively describe the ET linearizability. Analytical expression depicting ET linearizability in terms of θ_0 is derived in II. In III, extraction of θ_0 based on a three-tone measurement is proposed and demonstrated, and the comparison between prediction and measurement is also provided. The paper is then summarized in IV.

II. ET LINEARIZABILITY

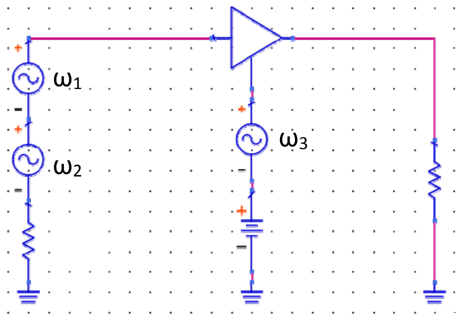


Fig. 1. Set up of three-tone power measurement.

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

$$v_g = v_i[\cos(\omega_1 t) + \cos(\omega_2 t)] \ . \tag{1}$$

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

$$v_d = v_e \cos(\omega_3 t + \alpha) \ . \tag{2}$$

input is injected into the drain where $\omega_3=\omega_2-\omega_1$, v_e and α are the magnitude, and the phase delay, respectively. The three-tone configuration represents a de-composed ET PA, and the drain injected signal can be regarded as an ET signal [2].

Two IMD components are generated in an ET PA, IMD_{PA} the mixing of gate injected two-tone signal, and IMD_{ET} the mixing of gate and drain injected signals. The former is the original IMD inside a standalone PA, and the latter is ET signal related. IMD_{ET} depends on both v_e and α. If the two IMD voltages are represented with V_{PA} and V_{ET}, respectively, the resultant IMD voltage of the ET PA can be expressed as

$$\left|V_{ET\_PA}\right| = \sqrt{\left|V_{PA}\right|^2 + \left|V_{ET}\right|^2 + 2\left|V_{PA}\right|\left|V_{ET}\right|\cos\theta_0} \ . \tag{3}$$

where θ_0 is the phase difference between V_{PA} and V_{ET} when $\alpha=0$, as shown in Fig.2.

ET linearization can now be described as achieving minimal V_{ET_PA} via optimizing V_{ET}. $\partial\left|V_{ET\_PA}\right|/\partial\left|V_{ET}\right|$ is at first calculated using (3), and the optimal V_{ET} can then be obtained from $\partial\left|V_{ET\_PA}\right|/\partial\left|V_{ET}\right| = 0$ as

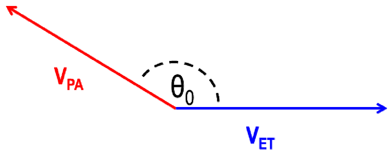


Fig. 2. Phase difference θ_0 between two IMD components.

$$|V_{ET}| = -|V_{PA}|\cos\theta_0 \,. \tag{4}$$

Since we always have $|V_{ET}|>0$, the extremum of V_{ET_PA} only exists when $\theta_0>90°$. Inserting (4) into (3), the minimal IMD voltage can be obtained as

$$|V_{ET\_PA}| = |V_{PA}|\sin\theta_0 \,. \tag{5}$$

Therefore, the IMD improvement with incorporating ET module can be expressed as

$$\frac{IMD_{ET\_PA}}{IMD_{PA}} = 20\log\frac{|V_{ET\_PA}|}{|V_{PA}|} = 20\log(\sin\theta_0)\,. \tag{6}$$

(6) gives a quantitative description of ET linearizability.

A PA with $\theta_0>90°$ is ET linearizable, and the improvement in IMD can be predicted with (6). On the other hand, a PA with $\theta_0<90°$ is not ET linearizable, and the degradation in IMD is expected by incorporating ET module. By incorporating ET module, both the improvement and degradation in PA linearity have been reported so far.

III. VALIDATION

A. Extraction of θ_0

The low and high side IMD_{ET}, (IMD_{PA}) are denoted as IMD_{ET_low} and IMD_{ET_high} (IMD_{PA_low} and IMD_{PA_high}), respectively. As mentioned in II, IMD_{ET} is the mixing between gate and drain injected signals. When there is a phase delay in the drain injected signal, namely $\alpha\neq0$ in (2), the α dependence of the instantaneous phase for IMD_{ET_low} and IMD_{ET_high} are $(\omega_1-\omega_3)t-\alpha$ and $(\omega_2+\omega_3)t+\alpha$, respectively. In phasor diagram, IMD_{ET_low} (IMD_{ET_high}) rotates anti-clockwise (clockwise) with increasing α.

If the phase difference between IMD_{PA_low} and IMD_{ET_low} (IMD_{PA_high} and IMD_{ET_high}) is defined as θ_{low} (θ_{high}), we have

$$\theta_{low} = \theta_0 - \alpha \;, \tag{7}$$

and

$$\theta_{high} = \theta_0 + \alpha \;. \tag{8}$$

It is worth to note that α is the phase delay appeared just at the drain terminal, what can be controlled and measured directly, however, is the external phase delay β, the phase delay of the signal generator. We have $\alpha=\beta-\beta_0$, where β_0 is the offset between α and β. (7) and (8) can be written as

$$\theta_{low} = \theta_0 - \beta + \beta_0 \;, \tag{9}$$

and

$$\theta_{high} = \theta_0 + \beta - \beta_0 \;. \tag{10}$$

Three-tone measurement was performed on a GaN HEMT. The total gate width of the HEMT is 400um, which was biased at V_{gs}=0.3V and V_{ds}=4V, respectively. The frequencies of the two gate injected signals are 1400 and 1420 MHz, respectively. A 20 MHz signal is injected via the drain.

The IMDs were measured by sweeping β. As shown in Fig. 2, IMD_{low} and IMD_{high} reach their minimums at β_1 and β_2, respectively. Since the cancellation between IMD_{PA_low} and IMD_{ET_low} is achieved at β_1, we have $\theta_{low}(\beta_1)=180°$, and (9) can be written as

$$180° = \theta_0 - \beta_1 + \beta_0 \;. \tag{11}$$

In the similar way, (10) can be written as

$$180° = \theta_0 + \beta_2 - \beta_0 \;. \tag{12}$$

Therefore, both θ_0 and β_0 can now be obtained by combining (11) and (12) as

$$\theta_0 = (360° - \Delta\beta)/2 \;, \tag{13}$$

where $\Delta\beta=|\beta_1-\beta_2|$, and

$$\beta_0 = (\beta_1 + \beta_2)/2 \;. \tag{14}$$

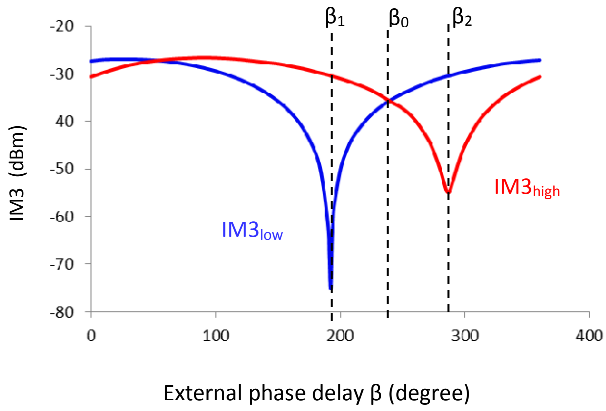


Fig. 3. Measured low and high side IM3 versus external phase delay.

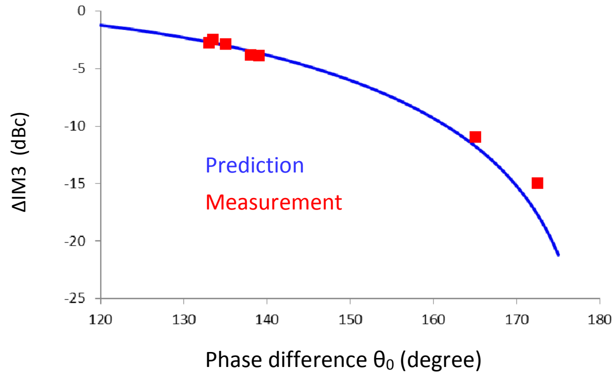
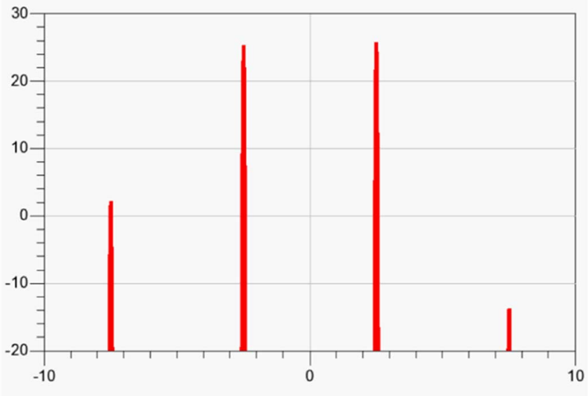
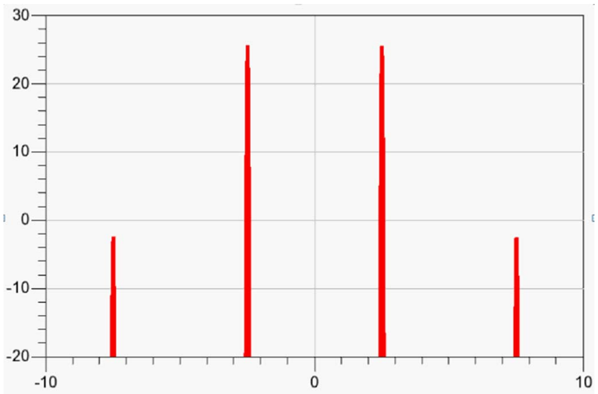


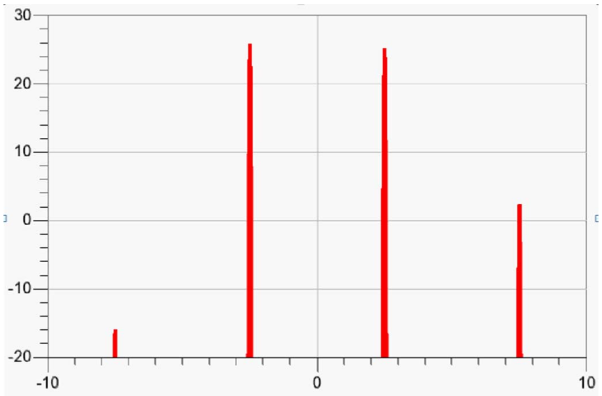
Fig. 4. Comparison between predicted and measured IMD improvement versus phase difference θ_0.



(a) $\beta = \beta_1$



(b) $\beta = \beta_0$



(c) $\beta = \beta_2$

Fig. 5. Simulated spectrum of ET PA with different phase delay. (a) $\beta=\beta_1$, (b) $\beta=\beta_0$, and (c) $\beta=\beta_2$.

B. Prediction versus Measurement

θ_0 of GaN HEMT was extracted using (11) at different gate voltage V_g. It was found that θ_0 depends sensitively on V_g. The IMD improvements of the GaN HEMT were predicted with the extracted θ_0 by using (6).

The IMD improvements are then measured directly with three-tone measurement at different V_g. The IMD_{PA} is first measured with two-tone signal. The IMD_{ET_PA} is then obtained by optimizing the magnitude of ET signal v_e at the fixed external phase delay $\beta=\beta_0$. The IMD improvements by incorporating ET module were obtained as IMD_{ET_PA}/ IMD_{PA}.

The θ_0 dependences of IMD improvements are shown in Fig. 4, and very good agreement between prediction and measurement is achieved. Predicting ET linearizability before incorporating an ET module is of great help for ET linearization scheme design.

An interesting phenomenon by sweeping β (α) is that the low and high side IMD3s can be controlled separately, as shown in Fig. 5. A perfect cancellation of low (high) IMD3 can be achieved at $\alpha=180-\theta_0$ ($\alpha=180+\theta_0$), which will be useful for the applications where only single side IMD3 is of concern.

IV. CONCLUSION

The phase difference θ_0 between the two IMD components is identified as a criterion of ET linearizability. Determination of θ_0 based on three-tone measurement is proposed and demonstrated. Analytical expression predicting the IMD improvement in terms of θ_0 is derived. Very good agreement between prediction and measurement is achieved. ET linearizability can be quantitatively predicted before incorporating an ET module, which is of great help for ET linearization scheme design.

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