Efficiency and Linearity of Power Amplifiers with External Harmonic Injection

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***Abstract* — This paper discusses a method for improving the efficiency of linear power amplifiers by externally injecting power into the output at the second harmonic frequency. An experimental proof-of-concept PA based on class-A/AB mode with a 10-W GaN pHEMT at 2.45GHz is presented, and its efficiency improved from 58% to 75% with –6.5 dBc injected 2nd harmonic power. Two-tone measurements confirm improved linearity with simultaneous increase in efficiency, accompanied by gain compression at higher input power.**

***Index Terms*—power amplifier, high-efficiency, nonlinear analysis, GaN pHEMT**

I. Introduction

A large portion of current research in high-power amplification of signals with carriers in the microwave range focuses on improving efficiency and linearity [1]. Topologies such as the Class F and F^{-1} achieve high efficiency by driving the active device into a non-linear region and shaping voltage and current waveforms across the device via proper selection of the output loading network at harmonic frequencies [2]. The concept of harmonic injection, however, refers to architectures in which power at a harmonic of the operating frequency is supplied to either the input, output, or both input and output of the active device [3-10]. This paper presents experimental results of a harmonically-injected power amplifier (HI PA) at f_0=2.45GHz showing significant improvement in the efficiency and linearity over a class AB PA based on a Cree pHEMT device with an output power of 40dBm. Fig.1 shows a general block diagram of the HI PA concept with harmonic injection at the output.

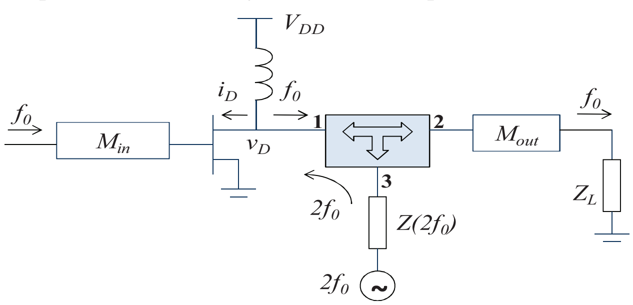

Fig. 1. Block diagram of a harmonic-injection power amplifier (HI PA) with $2f_0$ injection at the output. A three-port network at the output allows isolation between waves at f_0 and $2f_0$ between ports 2 and 3, while allowing low loss at f_0 between ports 1 and 2. The phase of the injected harmonic is critical to obtaining high efficiency.

II. Harmonically-Injected PA Concept

To achieve high efficiency, the voltage and current waveforms should have minimal overlap in time domain. In harmonically-terminated PAs [11], this is accomplished by heavily driving the device so that the nonlinear input capacitance generates harmonics at the output, resulting in a highly nonlinear PA. In contrast, the PA in Fig.1 is not driven to generate harmonics; instead harmonic power is injected externally at the output. A three-port output network satisfying the following conditions is required when injecting only the second harmonic at the output of the PA:

$$S(f_0,2f_0)=\begin{bmatrix} 0,0 & \exp[j\phi_{21}(f_0)],0 & 0,\exp[j\phi_{31}(2f_0)] \\ \exp[j\phi_{21}(f_0)],0 & 0,\exp[j\phi_{22}(2f_0)] & 0,0 \\ 0,\exp[j\phi_{31}(2f_0)] & 0,0 & \exp[j\phi_{33}(f_0)],0 \end{bmatrix}$$

Such a network is implemented in microstrip on a Rogers 4350B 30-mil thick substrate with dielectric constant of 3.66 and loss tangent of 0.0031, similar to the work reported in [9] at 900MHz and in [10] from 0.6-2.4GHz. Fig. 2 shows the relevant measured S-parameters extending beyond the second harmonic of the 2.45GHz fundamental.

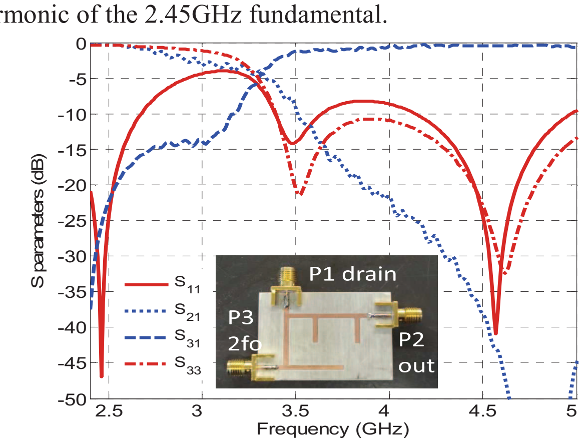

Fig. 2: Measured S parameters for the 3 port harmonic injection circuit at the output of the fundamental amplifier. A photograph of the 3 port network is shown in the inset.

The analysis of the HI PA concept is performed using normalized class-A waveforms resulting in an output power of 1W with 50% efficiency. Addition of only cosine terms at the second harmonic will result in a current waveform consistent

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with the finite harmonic class-B amplifier, with a voltage waveform of the same shape and 180° out of phase:

$$\bar{v}_D(\theta)=\bar{V}_{DD}+\sqrt{2}\sin\theta+a_2\cos(2\theta) \quad (1)$$

$$\bar{i}_D(\theta)=\bar{I}_{DD}-\sqrt{2}\sin\theta+a_2\cos(2\theta) \quad (2)$$

where, a_2 is the amplitude of injected $2f_0$ power, and the bars indicate normalized quantities. These waveforms result in a negative impedance at the virtual drain of the transistor at the second harmonic, which means that power is delivered to the transistor output at $2f_0$. The normalized total DC power consumed by the PA is also dependent on the efficiency of the injection circuit η_{inj}, defined as the ratio of available injected power $P_{inj}(2f_0)$ to the DC power consumed by the injection circuit $P_{inj,DC}$. The required DC power is given by:

$$\bar{P}_{DC}=\bar{V}_{DD}\bar{I}_{DD}+\frac{a_2^2}{2\eta_{inj}}=\bar{V}_{DD}^2+\frac{a_2^2}{2\eta_{inj}} \quad (3)$$

The output power normalized to class A can be found to be

$$P_{out}(f_0)=\frac{8}{\left(\frac{1+8a_2^2-4\sqrt{2}a_2}{4a_2}\right)^2},\eta_{inj}\geq\frac{1}{6}$$

$$P_{out}(f_0)=\frac{8}{\left(2\sqrt{2}\right)^2}=1,\eta_{inj}<\frac{1}{6} \quad (4)$$

The total efficiency can be analytically derived to be

$$\eta_{total}=\eta_{inj}\left(\sqrt{\frac{8}{\eta_{inj}}+16}-4\right),\eta_{inj}\geq\frac{1}{6}$$

$$\eta_{total}=\frac{2\eta_{inj}+1}{2},\eta_{inj}<\frac{1}{6} \quad (5)$$

and reaches a maximum of 90% for a 100% efficient injection circuit. The total efficiency degrades reasonably slowly with decreasing injection efficiency, e.g., for η_{inj}=1/6, we obtain η_{total}=66%. With a 100% injection efficiency, the output power is reduced by 0.13dB and the normalized supply voltage is approximately 0.7107. This analysis gives bounds on expected efficiency and relates output power, DC power, injected power and efficiency, providing design guidelines.

III. EFFICIENCY AND LINEARITY RESULTS

The HI PA setup for f_0 = 2.45GHz, $2f_0$ = 4.9GHz utilizes two Cree GaN pHEMTs (CGH40006P) in broadband (DC-6GHz) class-A test-boards provided by the manufacturer. A sweeper and low-efficiency commercial frequency doubler (Mini-Circuits ZX90-2-36-S) are used to generate the f_0 and $2f_0$ CW signals, respectively. A manual phase shifter and attenuator are used to adjust the phase and power level of the injected second harmonic signal. The input power to the fundamental PA is swept from 22 to 34dBm (linear to saturation) with the drain bias at 22 and 28V. The gate bias was set to -1.6, -1.8 and -2V, for class A/AB mode. The fundamental PA starts compressing at an input power level of 27dBm when no harmonic injection is present.

Fig. 3 compares the measured efficiency, output power and gain for the PA with and without harmonic injection. It is seen that the HI PA saturates at a higher input power (32dBm) as compared to the class-A PA (27dBm), resulting in higher linearity. The gain of the HI PA is lower by about 1dB as compared to the fundamental PA in the linear region, but remains higher in saturation. Harmonic balance simulations using a nonlinear model provided by the manufacturer show the same trends for gain as the measured data.The drain efficiency is calculated at the output terminal of the test board which is designed for a 50Ω system. This efficiency calculation takes into account the $2f_0$ injected power and the DC power dissipated by the $2f_0$ generating amplifier. The drain efficiency is calculated using the following formula [12]:

$$\eta_d(f_0)=\frac{P_{out}(f_0)}{P_{dc}+\frac{P_{inj}(2f_0)}{\eta_d(2f_0)}} \quad (6)$$

where, $P_{inj}(2f_0)$ is the second harmonic power injected into the PA, $\eta_d(2f_0)$ is the drain efficiency of $2f_0$ PA, $P_{out}(f_0)$ is the fundamental output power and P_{dc} is the DC power dissipated from the fundamental amplifier.

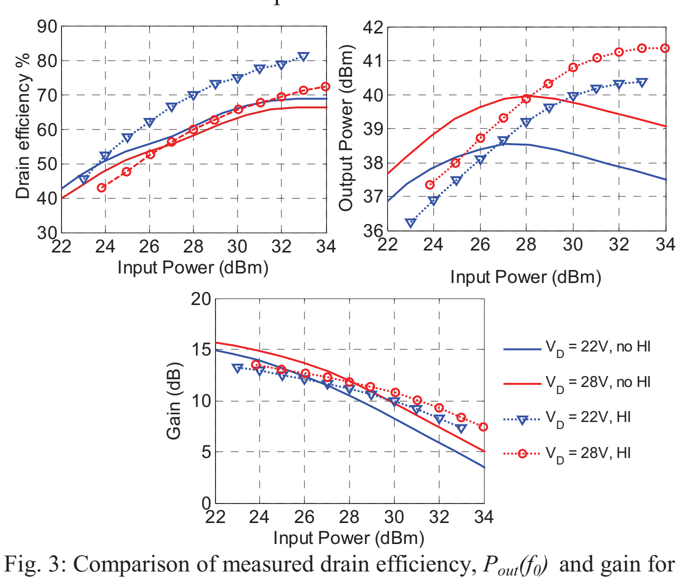

Fig. 3: Comparison of measured drain efficiency, $P_{out}(f_0)$ and gain for the HI PA compared to the PA with no harmonic injection at V_D = 22V, 28V and V_G = -1.6V (Class A/AB).

Measured results show that higher efficiency can be achieved for a constant output power with HI PA by changing the operating bias point. For instance, the drain efficiency of the PA with no injection improves from 58% to 75% for an output power of 40dBm by changing the drain bias from 28V to 22V for the HI PA case. Table I shows that efficiency also depends on gate bias, which is shifted more towards a class-AB mode for the HI PA. Fig. 4 shows the ratio of the measured injected $2f_0$ power to the f_0 output power for the HI PA. As expected, the HI PA is sensitive to the phase of the injected harmonic. Measurements show that the phase needs to be adjusted by about a 100° for input power 22 to 34dBm in order to achieve optimal efficiency.

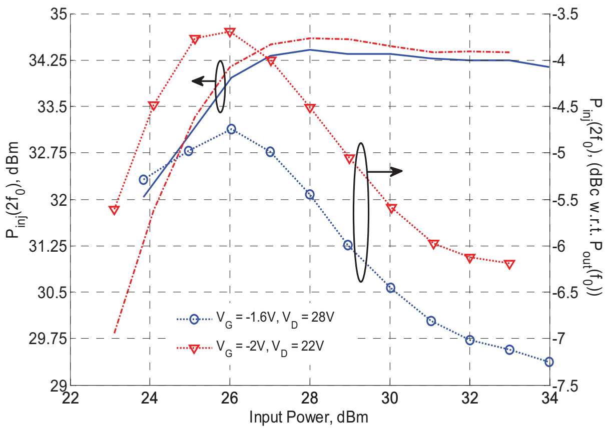

Fig. 4: Measured ratio of injected 2nd harmonic power, $P_{inj}(2f_o)$, to output power at the fundamental, $P_{out}(f_o)$, for various bias points as a function of input power at the fundamental.

Table I: Comparison of efficiency of HI PA for different bias points at output power of 7W. The efficiency of PA with no HI at V_G = -1.6V is 55%.

V_G / V_D	22V	25V	28V
-1.6V	67.3%	58.25%	52.5%
-1.8V	69.2%	60.2%	52%
-2V	70%	61%	50.5%

A two-tone linearity test is performed at V_D = 28V and V_G = -1.8V. The two tones are kept 5MHz apart with f_1=2.45GHz and 3rd order IMD products generated at $2f_1$-f_2 = 2.445GHz and $2f_2$-f_1 = 2.46GHz. Simultaneously, $2f_1$ (Fig. 5), $2f_2$, or f_1+f_2 is injected at the output, each requiring a different phase adjustment. The measured results in Fig. 5 show that the HI PA (red line) saturates at a higher input power than the PA with no HI (blue line). At lower input powers, the IMD3 level is over 30dB lower for the HI PA and remains 10dB lower after the PA saturates. In Fig. 5, only the $2f_1$ frequency is injected, resulting in a decrease in the $2f_1$-f_2 IMD while the $2f_2$-f_1 is unchanged. Symmetrically, when $2f_2$ is injected, the $2f_2$-f_1 will be decreased. Both IMD products will be equally reduced for a signal injected at (f_1+f_2).

IV. Discussion

It should be noted that it is important to use the appropriate efficiency definition when characterizing HI PAs. For example, in the excellent work reported in [8] and [10], two different definitions are used which can either over-estimate or under-estimate the efficiency. The authors feel that the definition from [12] (Eq. (6)) gives a realistic efficiency value.

In summary, this paper demonstrates efficiency and linearity improvements for a class A/AB PA with second harmonic injection at the output. A theoretical model for HI PAs based on Fourier analysis is developed, and only briefly presented due to space limitations. Harmonic balance simulations agree with measurements and will be presented in the talk. Because the harmonic content at the output is not generated by the device non-linearities, the HI PA has improved linearity compared to harmonically-terminated efficient PAs and class-A/AB PAs. Two tone tests for the HI PA show over 30dB improvement in IMD3 level over a class-A/AB PA for a 5MHz tone spacing with efficiency increased from 58% to 75%.

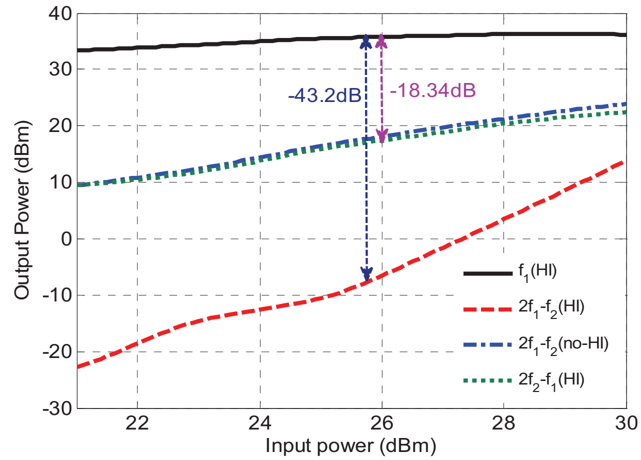

Fig. 5: Comparison of power levels for single tone and 3rd order IMD products for the HI PA and class-AB PA without harmonic injection.

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