Linearization of Efficient Harmonically-Injected PAs

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***Abstract*— This paper presents a technique for improving the linearity of a power amplifier using external second harmonic injection at the output. The amplifier is biased in class-A mode with no harmonic terminations in the output network and 50% drain efficiency at 1 dB compression point. External second harmonic injection at the output is used to shape the drain voltage and current waveforms to minimize the odd order harmonic content produced by the amplifier, simultaneously reducing the total DC power dissipation. Both CW and two-tone measurements with 1 MHz tone spacing are performed on a 2.45 GHz 6-W GaN PA with harmonic injection at one of the two harmonic tones. The lower or upper sidebands for the IMD3 and IMD5 are reduced by >15dB and 10 dB respectively along with a 6% increase in the total drain efficiency.**

***Index Terms*— Microwave power amplifiers, harmonics, amplifier drain efficiency, waveform shaping, linearity, third order intercept, fifth order intercept**

I. Introduction

There is an increasing demand in the wireless communications industry today for highly efficient and linear transmitters due to complex signals which are aimed at increasing channel capacity. Nonlinearity in the transmitter results mostly from the final stage PA. There are many PA classes which achieve high efficiency by driving the amplifier into the nonlinear region and shaping the output voltage and current waveforms utilizing the harmonic content internally produced by the transistor (e.g. Classes B, C, F, F^{-1}) [1], [2]. Other techniques enhance the linearity of an amplifier by harmonic injection at input and/or output of the PA as presented in [3]. In 1992, a patent was issued for a harmonic injection amplifier in which a second harmonic signal was injected at the output [4]. Demonstration of reduction in IMD3 by over 24 dB for the upper sideband using a two tone signal with 5 MHz spacing is shown in [5] with harmonic injection at the input of a TWT amplifier. In [6], second harmonic injection at the output of a class-AB PA with a CW signal improves the overall drain efficiency by over 15% at the 1 dB compression point. It is also shown in [6] that the P_{1dB} point shifts to a higher input power value resulting in higher linearity.

In this paper, both CW and two-tone measurements are presented for second harmonic injection at the output of a 6-W TriQuint GaN PA with the fundamental signal (f_0) at 2.45 GHz. Measurements for the 2^{nd} and 3^{rd} harmonic output power are analyzed as a function of the phase and amplitude of the injected second harmonic in order to understand the linear behavior of the amplifier. These measurements are then validated using a two-tone signal by measuring the inter modulation distortion products of third (IMD3) and fifth order (IMD5) for the harmonic injection PA (HI-PA) which show a similar reduction in power level as the CW harmonics resulting in higher linearity.

II. Power Amplifier Design and Test

A class-A power amplifier is designed using a TriQuint TGF2023-01 discrete GaN on SiC transistor which is capable of producing 6 W of output power at 1-dB compression at 2.45 GHz. The amplifier exhibits 22 dB of small signal gain. When driven 1-dB into compression, the output power is 5 W with 50% power-added efficiency. The die is mounted on a copper-molly pedestal and into a hybrid circuit implemented with a Rogers' 4350B 30-mil thick substrate. The block diagram of the test setup in Fig.1 shows the Class-A PA and an external passive 3-port second-harmonic injection network at the output, integrated with the PA in a 65-Ω inter-stage environment. The design is similar to that described in [6].

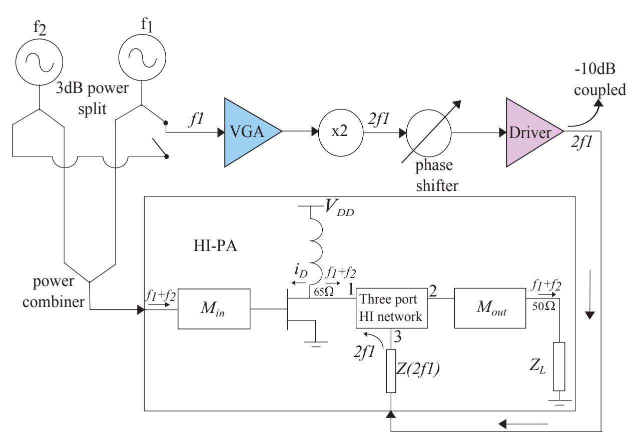

Fig. 1. Block diagram of measurement setup for two tone test on the harmonic injection power amplifier.

A power series approximation of the transistor nonlinearity shows the importance of the third-order nonlinearity as seen from the expression for the output voltage corresponding to a two-tone input signal $v_{in} = A(\cos\theta_1 +$

$\cos\theta_2$):

$$
\begin{aligned}
v_{out}(t) &= k_1 v_{in} + k_2 {v_{in}}^2 + k_3 {v_{in}}^3 + ... \\
v_{out}(t) &= k_2 A^2 + \left(k_1 A + \frac{9}{4} k_3 A^3\right)(\cos\theta_1 + \cos\theta_2) \\
& \quad + k_2 A^2 \cos(\theta_1 \pm \theta_2) + \frac{1}{2} k_2 A^2 (\cos 2\theta_1 + \\
& \quad \cos 2\theta_2) + \frac{1}{4} k_3 A^3 (\cos 3\theta_1 + \cos 3\theta_2) + \\
& \quad \frac{3}{4} k_3 A^3 (\cos(2\theta_1 \pm \theta_2) + \cos(2\theta_2 \pm \theta_1)) + ...
\end{aligned} \tag{1}
$$

where $\theta_1 = 2\pi f_1 t$ and $\theta_2 = 2\pi f_2 t$. Note that the odd-order nonlinearities ($k_3, k_5 ...$) cause the inter-modulation distortion (IMD) terms in the output voltage. In reality, as discussed in [7], other mixing products caused by even-order nonlinearities also contribute to the IMD products. This additional distortion can be controlled by synthesizing the proper impedance at the output through, e.g. impedance matching. Here, the impedances are synthesized through injection of power at 2^{nd} harmonic ($P_{inj}(2f_0)$) with precise amplitude and phase. The measurement setup in Fig.1 was used to determine the optimal amplitude and phase of the injected harmonic signal which minimizes 2^{nd} and 3^{rd} order nonlinearities. The analysis was performed by measuring the output power at $2f_0$ and $3f_0$ for a CW input signal, following the discussion in [8]. Following CW measurements, two-tone measurements are performed to validate the conclusions and understand the behavior of the distortion products (IMD3 & IMD5) due to external second harmonic injection.

III. Measurements and Results

CW measurements are performed at f_0 = 2.45 GHz and the two-tone measurements are performed at f_1 = 2.45 GHz and f_2 = 2.451 GHz. Harmonic injection is performed at $2f_1$ for the two-tone tests. The drain efficiency is calculated as [6]:

$$\eta_D = \frac{P_{out}(f_0)}{P_{DC,f_0} + P_{inj}(2f_0)} \tag{2}$$

A. CW Measurements

Injection at the second harmonic results in the fundamental voltage and current waveform shaping causing minimum DC power dissipation when the amplifier operates in the linear region. However, once the amplifier starts becoming nonlinear, the injected second harmonic also impacts the odd and even order harmonic content produced by the amplifier. The injected second harmonic needs to be at a particular phase and amplitude in order to shape them and eliminate the even or odd order harmonic content produced by the amplifier. Hence, as the input drive level increases, the amount of second harmonic injected power required to enhance both efficiency and linearity also increases.

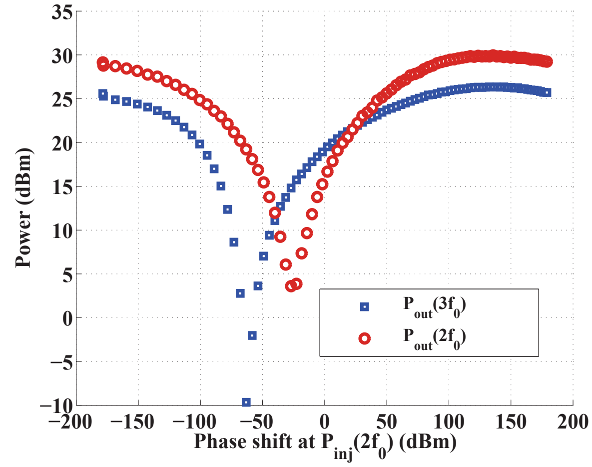

Fig. 2. Harmonic power de-embedded to virtual drain of the HI-PA for $P_{in}(f_0)$ = 16.2 dBm. The minimum for $P_{out}(2f_0)$ is obtained with $P_{inj}(2f_0)$ = -17.8 dBc w.r.t. $P_{out}(f_0)$, whereas minimum for $P_{out}(3f_0)$ is obtained for $P_{inj}(2f_0)$ = -8.9 dBc.

Fig.2 shows the minimum power levels obtained for $P_{out}(2f_0)$ and $P_{out}(3f_0)$ for different optimum values of amplitude and phase of the injected second harmonic for CW measurement with $P_{in}(f_0)$ = 16 dBm. The drain efficiency of the amplifier at P_{1dB} is calculated to be 79% for lowest third harmonic content and 70% for lowest second harmonic content. Since both 2^{nd} and 3^{rd} harmonics impact the IMD3, a trade-off needs to be performed to minimize both harmonics.

B. Two-tone measurements

Two-tone measurements with optimization for the amplitude and phase of the injected second harmonic for lowest power levels for IMD3 are performed. Here, the injection of $2f_1$ affects the performance of IMD3$_L$ at $2f_1$-f_2 and IMD5$_L$ at $3f_1$-$2f_2$ due to active impedance synthesis at the injection port. It is important to note that the reduction in IMD5$_L$ results from mixing of IMD3$_L$ and distortion products caused due to second order nonlinearities. Fig.3 shows the optimal amplitude and phase for injected second harmonic tone ($2f_1$) in order to achieve low IMD3$_L$ power levels for a fundamental input drive of P_{in} = 16 dBm. It is seen that the minimum obtained for IMD3$_L$ is sensitive to both the amplitude and phase of the injected second harmonic. Similarly, a minimum for IMD5$_L$ is also a function of $P_{inj}(2f_1)$. The minima for IMD3$_L$ and IMD5$_L$ occur at somewhat different values for amplitude and phase of the injected second harmonic, differing by about 0.3 dB in amplitude and 20° in phase, as shown in Fig. 4.

For lower input power levels, the two amplitude and phase values differ from each other on the order of 5-

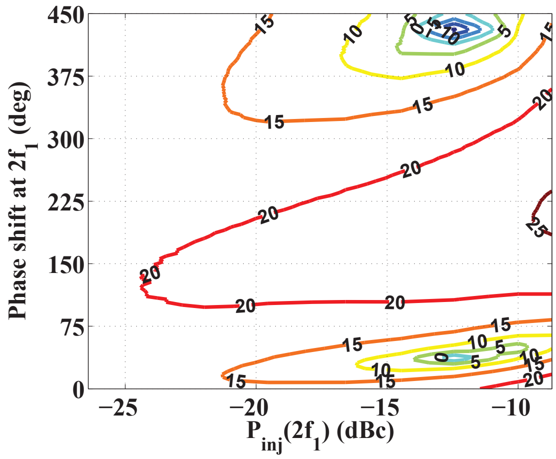

Fig. 3. Power level of IMD3$_L$ ($2f_1$-f_2) as a function of the amplitude and phase of the injected second harmonic tone $2f_1$.

10 dB in amplitude and around 100° in phase. The optimal

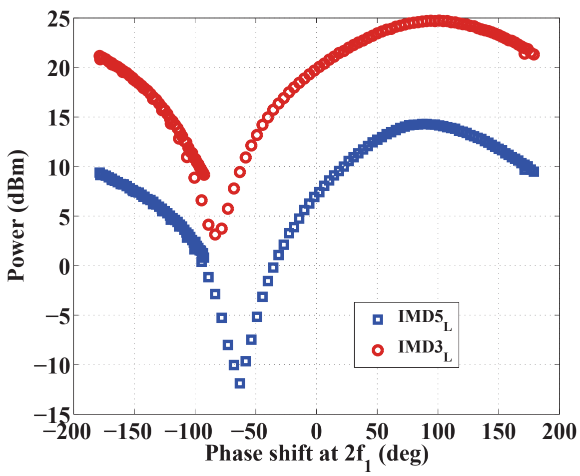

Fig. 4. Power levels for IMD3$_L$ and IMD5$_L$ with harmonic injection at $2f_1$ and P_{in} = 16 dBm. The minima for IMD3$_L$ and IMD5$_L$ are obtained for $P_{inj}(2f_1)$ = -9.25 dBc and -8.95 dBc, respectively.

injected 2^{nd} harmonic power which results in minimum IMD3$_L$ is shown in Fig.5 as a function of the input drive level. It is seen that the reduction in IMD3$_L$ using external second harmonic injection is greater than 15 dB for different input drive levels, whereas IMD3$_H$ at $2f_2$-f_1 and IMD5$_H$ at $3f_2$-$2f_1$ remain unaffected. The total drain efficiency of the PA which takes into account the amount of injected second harmonic as explained in [6] is improved from 53% for the two-tone class-A mode to 58% using harmonic injection at one tone. The total output power is seen to reduce by 0.5 dB along with 1 dB lower gain as compared to the class-A PA. The maximum efficiency improvement is seen to be 8% but this results in a trade-off between high efficiency and linearity.

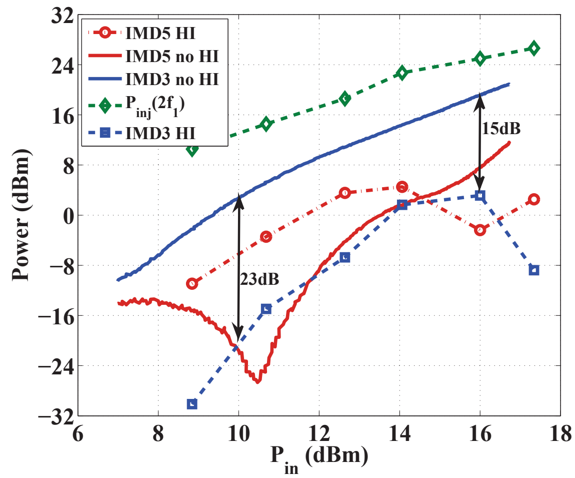

Fig. 5. Comparison of power at IMD3$_L$ ($2f_1$-f_2), IMD5$_L$ ($3f_1$-$2f_2$) for HI-PA and PA without harmonic injection as a function of input drive level. The graph also shows the power injected at the second harmonic tone ($2f_1$) to achieve lowest IMD3$_L$.

The measurements presented here are for the lower IMD3/5 sidebands, but the same results are obtained for the higher sidebands at tone spacing upto 5 MHz for injected harmonic at $2f_2$. In order to achieve symmetrical reduction corresponding to increased linearity, harmonics at both tones need to be injected at the output of the PA.

IV. Acknowledgment

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