An Efficient Linear Power Amplifier with 2^{nd} Harmonic Injection

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***Abstract*— A 2.3 GHz hybrid GaN power amplifier (PA) with 2^{nd} harmonic injection (HI) in the output is studied in terms of efficiency and linearity enhancement under a two-tone signal input. The 2^{nd} harmonic signal is obtained by frequency doubling of the main RF signal but with opposite phase for IMD_3 cancellation. The HI-PA demonstrates a peak drain efficiency of 80% (assuming 100% efficient $2f_0$ injection) at 14.1 W output power and more than 10 dB reduction in IMD_3 when the injected harmonic phase and amplitude are adjusted for a compromise between efficiency and linearity.**

***Index Terms*— Power amplifier, harmonic injection, linearity, efficiency.**

I. Introduction

To improve efficiency of microwave power amplifiers (PAs), the active device is driven into saturation and the generated harmonics are reflected by the output matching network in such a way that voltage and current waveforms are shaped for minimal overlap during a period [1]. When sufficient harmonic content is available for waveform shaping, the device is operated in a strongly non-linear regime and needs to be linearized for low-distortion signal amplification. Typically digital pre-distortion is required, adding complexity especially for wideband signals. Harmonic injection (HI) at the input has also been investigated for improving linearity for both tube [2] and solid-state [3] amplifiers. In [4], the phase and amplitude of the 2^{nd} harmonic were chosen to optimize efficiency without regard for linearity. HI was also used to improve linearity without regard for efficiency [5]. Both efficiency and linearity improvement of a PA operating in CW mode are discussed in [6]. This improvement, however, is compared to a PA that does not include harmonic terminations.

To demonstrate the advantages of an HI-PA, this work directly compares PA performance with passive and active 2^{nd} harmonic terminations. A harmonically-terminated PA is designed to maximize power-added efficiency (PAE) and then measured under load-side harmonic injection (Fig. 1) to demonstrate an improvement in linearity while maintaining high efficiency. The phase and amplitude of the injected signal are dynamically adjusted during power sweeps showing reduction in AM/AM distortion. With a two-tone input signal of varying separation, a reduction in third-order intermodulation distortion (IMD_3) by more than 10 dB is achieved while maintaining drain efficiency $\eta_D = 93\%$ at peak power. For this operating point, the total efficiency is measured to be 80%, and includes the input powers at the fundamental and 2^{nd} harmonic.

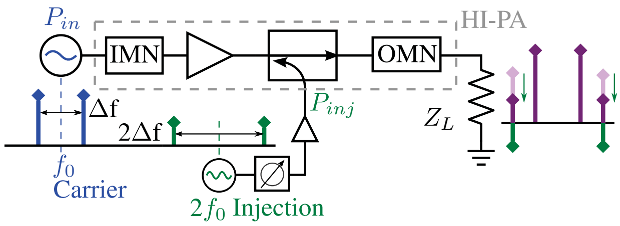

Fig. 1. Block diagram of the HI-PA. When driven into compression with a two-tone signal, the PA operates efficiently but not linearly. By injecting into the output a two-tone signal with a doubled carrier frequency ($2f_0$) and tone spacing ($2\Delta f$), IMD_3 can be reduced while maintaining efficiency through waveform shaping.

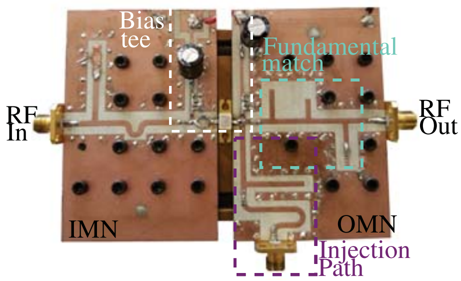

Fig. 2. Photograph of the fabricated 2.3-GHz HI-PA on Rogers 4350B substrate and copper baseplate. The board size is 106 mm × 76 mm.

II. HI-PA Design

The main PA at 2.2875 GHz is designed with a packaged Wolfspeed 10-W GaN HEMT CGH40010F. We consider a 6-MHz signal bandwidth for the target application NASA's S-Band Space Network channel. The device is biased in Class AB ($V_{DD} = 28$ V, $I_{DQ} = 67$ mA) and the output matching is designed as a trade-off between PAE and output power using load-pull. A 3-port injection network is integrated into the HI-PA matching network to allow $2f_0$ injection without affecting f_0 impedance, Fig. 2. The PA was tested alone and with the $2f_0 = 4.575$ GHz injection path enabled and the results compared in experiment.

Considering the significant $2f_0$ content in the drain circuit, the bias network (Fig. 3) is designed to have a high-impedance at both f_0 and $2f_0$. Furthermore, for minimal impact on the injected signal, the impedance at $2f_0$ is close to an open, achieved with inductor L_b between the bias and RF paths with a parallel resonance at $2f_0$. Shunt capacitor C_b with a series resonance at f_0 serves to short any fundamental content beyond the RF choke. The

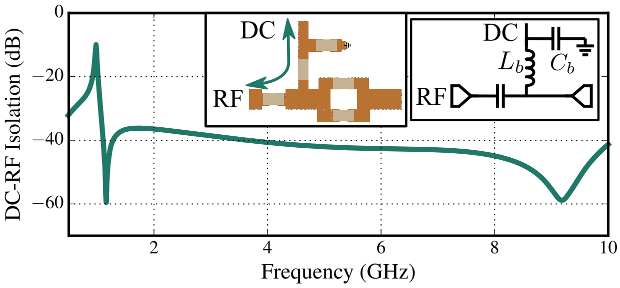

Fig. 3. Isolation between the DC and the RF path from 0.5 to 10 GHz, showing a high bias-line impedance across a bandwidth of greater than 10 GHz (including up to $3f_0$).

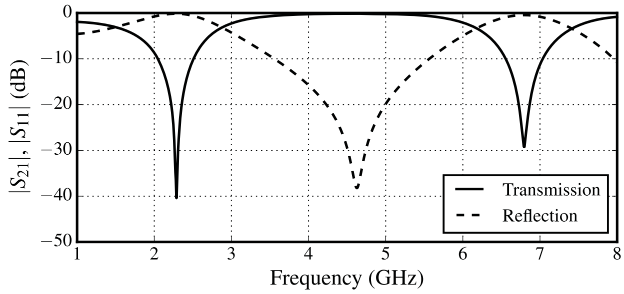

Fig. 5. S-parameters of the injection path showing diplexing characteristic of the OMN. The injection path presents an open at f_0 and $3f_0$, while presenting $50\,\Omega$ at $2f_0$.

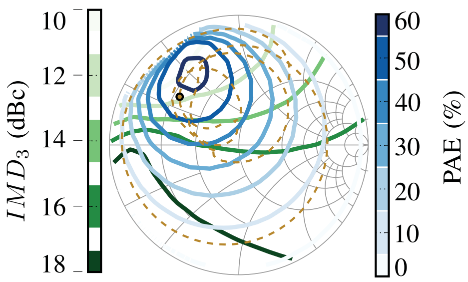

Fig. 4. Simulated 10-MHz spaced two-tone LP *PAE* and IMD_3 contours at the reference plane between the bias-tee and the PA output. The S_{11} of the EM-simulated matching network is also plotted from 1-8 GHz (gold dashed) with a marker (gold circle) at the design carrier frequency.

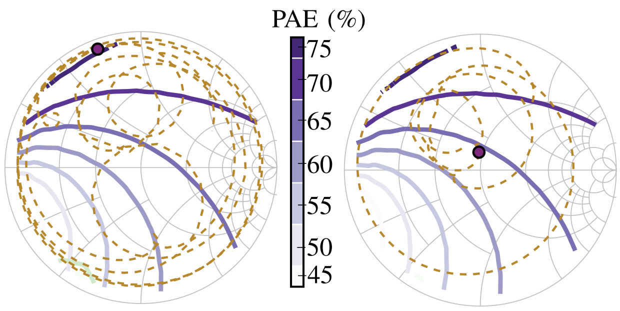

Fig. 6. The $2f_0$ PAE contours are plotted with a continuous line (purple). The impedance presented by the output network including the injection port SMA connector when the injection port is unloaded (left) and loaded (right) is plotted from 2-8 GHz (gold, dashed trace), with Γ_{2f_0} marked by a circle (purple).

DC-RF isolation of the designed bias network, Fig. 3, is achieved through careful layout with electromagnetic co-simulations.

Simulated source-pull (SP) and load-pull (LP) are performed in Keysight ADS with the manufacturer-provided nonlinear model. Since the bias network affects the fundamental impedance, a two-tone 10-MHz load-pull is performed with a reference plane located after the bias tee and the results for PAE and IMD_3 are shown in Fig. 4. The matching network is implemented on microstrip Rogers 4350B 30-mil substrate and the input is matched for gain.

The $2f_0$ is injected through a diplexing network that presents an open at f_0 and a passive $2f_0$ terminated at the device drain. The microstrip network together with an unloaded (open) SMA connector is designed to terminate the 2^{nd} harmonic in a high-efficiency region of the load-pull contours. Therefore, by disconnecting the $2f_0$ injection source, a direct comparison can be made between a PA with passive and active harmonic terminations. With $50\,\Omega$ connected to the injection path, the 2^{nd} harmonic is pre-matched to $47\,\Omega$ during $2f_0$ injection. The injection path includes a DC block, and is meandered to fit the OMN within a 2”×3” form factor. The *S*-parameters of the injection path are plotted in Fig. 5. The 2^{nd} harmonic must be introduced as close to the device as possible to minimize injection signal attenuation and therefore the required injected power. The simulated impedance of the entire drain network under both conditions (loaded and unloaded injection port) is shown in Fig. 6, also showing the impedance at $2f_0$. The 3^{rd} harmonic is terminated for peak efficiency and the injection path does not affect its impedance.

III. HI-PA Measurements

A setup based on two synchronized National Instruments VSTs is used to characterize the HI-PA. An external RF source (HP 83650A) generates the f_0 carrier, which is locked to the local oscillator of a VST. The first VST is locked at $2f_0 = 4.575\,\text{GHz}$, derived from f_0 with a frequency multiplier (Mini-Circuits ZX90-2-36+) and an high-pass filter (Mini-Circuits VHF-3800+). In this way, two carriers, f_0 and $2f_0$, are phase-coherent and phase-aligned. The RF generation and acquisition (after calibrating the VSTs), are synchronized with a trigger and a 10 MHz reference clock. An instrumentation driver (Mercury Systems SM0825-40) amplifies the f_0 signal up to 29.5 dBm at the PA input. The second signal at $2f_0$ is amplified by a bench-top driver (Keysight 83020A). The measured CW performance with the injection port unloaded (passive $2f_0$ termination) is plotted from 2 to

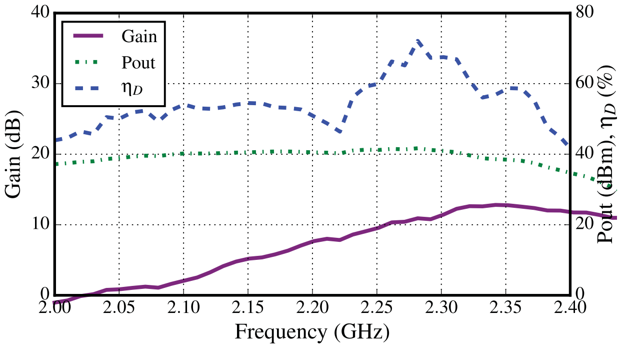

Fig. 7. Measured CW gain, P_{OUT}, and η_d of the PA. The efficiency of the PA is fine-tuned to peak at the targeted frequency $f_0 = 2.2875\,\text{GHz}$.

2.4 GHz in Fig. 7, demonstrating $G = 12\,\text{dB}$, $P_{out} = 41.5\,\text{dBm}$, and $\eta_D = 72\%$ at the design frequency.

To account for the input DC power, as well as the powers at f_0 and $2f_0$, we define a total efficiency η_{total} as:

$$\eta_{total} = \frac{P_{out}(f_0)}{P_{dc} + P_{inj}/\eta_{inj}} \quad (1)$$

where P_{inj} is the injected $2f_0$ power and η_{inj} is the drain efficiency of the injection path active components. With injection enabled, the measured η_{total} as a function of injected phase and amplitude is shown in Fig. 8 for two values of injection-path efficiency: $\eta_{inj} = 100\%$ and 50%. For a 50 point reduction in η_{inj}, total efficiency reduces by seven points and the maximum η_{total} contour is achieved at a lower P_{inj}.

Referring to Fig. 1, a two-tone signal at f_0 with Δf spacing is input to the PA, while a second two-tone signal, centered at $2f_0$ and with $2\Delta f$ spacing, is concurrently injected at the HI port. In this case, both the main and injected signals are amplitude modulated with a 3-dB peak-to-average ratio (PAR), resulting in higher efficiencies when compared to CW measurements because of the lower PA temperatures. The large signal performance, with and without HI, is shown in Fig. 9. With HI, gain is shown to be linearized with a maximum variation of ~0.3 dB, while η_D and η_{total} at higher output power also improve as a result of waveform shaping. Measurements are also performed with the injection path unloaded, when it presents a passive $2f_0$ termination as indicated by Fig. 6. Additionally, the PA is characterized for the case when the path is loaded with 50 Ω and presents near-50 Ω at $2f_0$ to the device. These two passive harmonic loading conditions are compared directly to HI in Fig. 9.

The HI-PA linearity is studied with the normalized AM/AM plot of Fig. 10. Here, the compressing behavior of the PA is significantly reduced with HI as also visible in the residual AM/AM distortion. Note that the injected signal at $2f_0$, identical to the signal at f_0 but with

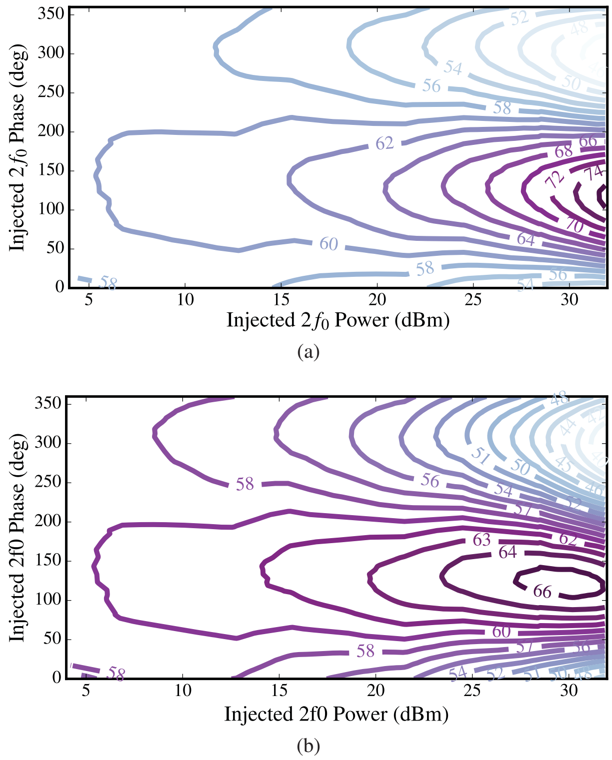

Fig. 8. Measured contours of constant η_{total} assuming an injector efficiency of (a) 100% and (b) 50%, with swept injected phase and power at a fixed CW input signal at 30 dBm. Note that lower injected power is necessary to reach the maximum η_{total} when considering a non-ideal $2f_0$ injection.

twice the bandwidth, reduces most of the compression, but injection of the 3^{rd} harmonic is required to remove the residual distortion. Linearity is also verified in the frequency domain, Fig. 11, where the IMD_3 products are reduced more than 10 dB while the IMD_5 products remain below 35 dBc. Similar results are obtained for tone spacing from 100 kHz up to 10 MHz.

A high-efficiency GaN PA is designed with harmonics terminated passively using traditional elements such as microstrip lines and stubs. An unloaded SMA connector at an edge of the PA board is included in the design of the $2f_0$ impedance that is terminated in a high-efficiency region of the Smith chart. The drain network is designed such that when the connector is loaded with a 50 Ω system (e.g., another PA), the $2f_0$ impedance returns to near-50 Ω, serving as a $2f_0$ pre-match for active impedance tuning. Under injection, an actively synthesized $2f_0$ impedance is presented to the device. By designing the drain network to present either a passive or active $2f_0$ termination, the advantages and disadvantages of an HI-PA can be directly observed.

Although the scope of this work does not include the design of the active components which generate the $2f_0$ injection, the theoretical efficiency of this path is consid-

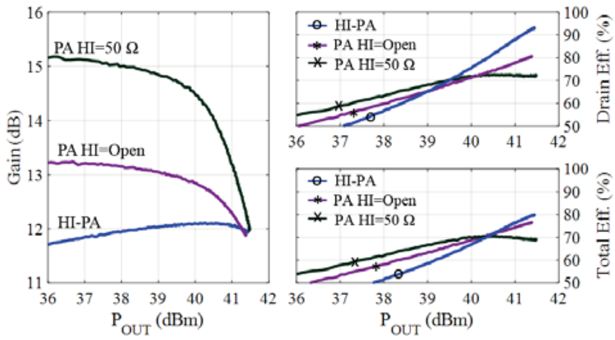

Fig. 9. Measured modulated gain, drain and total efficiency of the amplifier at f_0 with and without 2^{nd} harmonic injection (open and $50\,\Omega$ load on the HI port). Both the main and injected signals are amplitude modulated. When HI is employed, the gain is flatter while the efficiency is also improved as a result of waveform shaping with 2^{nd} harmonic.

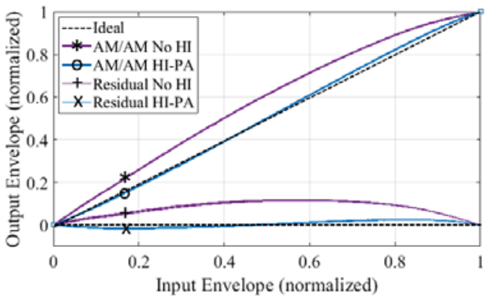

Fig. 10. Normalized AM/AM characteristics of the PA with and without HI. The significant AM/AM distortion can be mitigated by 2^{nd} harmonic injection. After HI, the residual distortion shows an odd-order nonlinearity that can be reduced with injection of higher order harmonics.

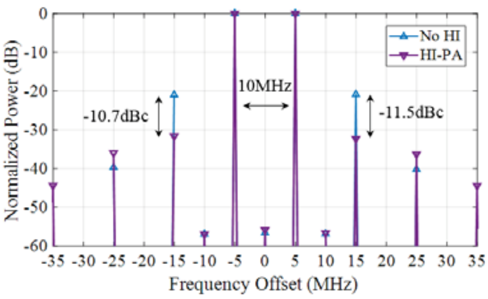

Fig. 11. Normalized spectra showing a two-tone test at f_0 with 10 MHz spacing and $P_{OUT,MAX} = 41.5$ dBm. More than 10 dB improvement in the IMD_3 is demonstrated by injecting a two-tone signal with 32 dBm power at $2f_0$ while the upper IMD_5 is below 30 dBc.

ered in the calculation of the total HI-PA efficiency where it is seen that reducing n_{inj} from 100% to 50% reduces η_{total} by only 7 points while reducing the P_{inj} required for maximum η_{total} from 32 dBm to 29 dBm (3 dB reduction).

With an active $2f_0$ termination, 2 dB greater gain and 3 points greater η_{total} are measured at peak power, assuming $\eta_{inj} = 50\%$. With a passive termination, the efficiency is greater at > 3 dB backoff, however IMD_3 is 10 dB greater. The AM/AM distortion is significantly reduced in the HI case, and any further reduction in distortion would require injection of the 3^{rd} harmonic in addition to the 2^{nd}. It has been shown that with harmonic injection, it is possible to achieve significantly lower IMD_3 and AM/AM distortion for a two-tone modulated signal while maintaining the high efficiency of a harmonically-terminated PA.

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