Novel Wide Band High-Efficiency Active Harmonic Injection Power Amplifier Concept

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***Abstract* — This paper introduces a novel approach for the realization of wide band (>octave) high-efficiency (>95%) high Power Amplifiers (PAs). The proposed concept utilizes active harmonic injection to achieve the appropriate waveform shaping of the voltage/current waveforms necessary to deliver simultaneously both high power and high efficiency operation. The new PA structure thus consists of two parallel PAs where the main PA generates fundamental power and an auxiliary PA injects a harmonic signal at the output of the main PA to perform waveform shaping. An active harmonic injection PA circuit designed around the 10 W GaN transistor is demonstrated, along with the basic mathematical analysis and computer simulation of this new mode of operation. The measured performance of the PA demonstrator realized at 0.9 GHz provided a drain efficiency of 74.3% at P1dB, validating the concept and its potential.**

***Index Terms* — Broadband amplifiers, high efficiency, injection amplifiers, microwave amplifiers, power amplifiers.**

I. Introduction

In many communication and radar systems there is an increasing need to improve the functionality of the Power Amplifier (PA) to meet new system specifications; definitely in terms of output power, bandwidth, efficiency and often also linearity. For example, wireless communication systems consume significant electric power with the component consuming the largest amount of power being the Power Amplifier (PA), thus the importance of improving their efficiency.

Fundamentally the only way to improve the efficiency of a Power Amplifier is to use harmonic injection to provide for wave shaping of the RF output voltage/current waveforms. This harmonic injection is typically achieved by presenting appropriate passive reactive output load terminations at the harmonics. Power Amplifiers operating in the traditional class B (78.5%) and F (100%) modes are all examples of this approach. Generally these modes, since they require high Q-factor short and/or open circuit terminations, provide solutions that are inherently narrow band.

More recently and alternative mode of operation, class J (78.5%), was introduced that requires only reactive second harmonic terminations [1]. Additionally by exploiting the newly highlighted design continuum combining both the Class B and J modes this bandwidth limitation can be partially overcome. Recently a PA demonstrating high efficiency (>60%) over a 60% bandwidth has been demonstrated [2]. However, the maximum theoretical efficiency of this approach is only 78.5% and it cannot address systems requiring over an octave bandwidth.

This paper introduces a novel power amplifier approach, which utilizes active rather than passive second harmonic injection, to address these theoretical limitations on efficiency and bandwidth associated with passive second harmonic injection. The paper starts with an investigation of optimum waveforms that would deliver best performance in terms of efficiency and power. Next, the active load pull system developed by Cardiff University [3] was used to experimentally investigate whether the 10 W GaN transistor can support these optimum waveforms. Finally, a prototype amplifier test structure based on this new topology is designed, simulated, built and measured to demonstrate its feasibility.

II. Theoretical Analysis

1. Passive Second Harmonic Injection

In Class B and J amplifiers the transistor is initially biased so that, ideally, the resulting current waveform is shaped to provide a half rectified sinusoid. The key feature of the half rectified sinusoid is that over the same maximum current swing it provides for same fundamental signal as the sinusoidal waveform but importantly it has a reduced $(2/\pi)$ DC component, hence providing for an increase of $(\pi/2)$ efficiency. In Class B a short circuit at the second harmonic is used to shape the voltage waveform to a simple sinusoid. While in class J an appropriate fundamental and second harmonic reactive termination is used to shape the voltage waveform into a band limited half rectified sinusoid. In both these cases it is assumed that all higher harmonics are passively terminated into low impedance, in which case they both have a maximum theoretical efficiency of 78.5%.

2. Active Second Harmonic Injection

On close inspection it is observed that the performance potential of the Class J current and voltage waveforms is limited by the constraint of requiring passive harmonic injection. The two half rectified waveforms are offset by 135 rather than the optimum 180 case; the value required for a real only fundamental load (maximum output power) and to minimize current and voltage waveforms overlap (maximum efficiency).

The voltage and current waveforms in the optimum case are given by the following equations:

$$v(\theta) = V_{dc}\left[1 - \sqrt{2}\cos(\theta) + 0.5\cos(2\theta)\right] \quad (1)$$

$$i(\theta) = I_{max}\left[\frac{1}{\pi} + \frac{\cos(\theta)}{2} + \frac{2}{3\pi}\cos(2\theta) + \cdots\right] \quad (2)$$

Indicated that the required optimum fundamental load is given by;

$$R_f = 2\sqrt{2}V_{dc}/I_{max} \quad (3)$$

Analysis of these waveforms indicates the following output power and efficiency performance.

$$P_{dc} = 2V_{DC}I_{max}/\pi = 2V_1/\pi R_f = 2\sqrt{2}V_{DC}^2/\pi R_f \quad (4)$$

$$P_{out} = V_1^2/2R_f = V_{dc}^2/R_f \quad (5)$$

$$\eta_{Drain} = P_{out}/P_{dc} = \pi/2\sqrt{2} = 111\,\% \quad (6)$$

Obviously efficiency greater than 100% is not theoretically possible. Further analysis of the current and voltage waveforms indicates that the required load impedance at the second harmonic is negative and is given by;

$$R_{2f} = -\frac{3\pi}{4}V_{dc}/I_{max} \quad (7)$$

While this is not possible with passive second harmonic injection it is achievable if active second harmonic injection is utilized. However, in this case the efficiency calculation must be modified, as follows, to include the addition of this energy input.

$$\eta_{IPA\ Drain} = P_{out}/(P_{dc} + (P_{dc0}/\eta_0)) \quad (8)$$

where P_{dc0} and η_0 are the DC power and efficiency of the generated harmonic power. The modified drain efficiency calculation shows that the efficiency of the second harmonic PA is important for achieving high overall efficiency. Table (1) shows the predicted theoretical performance when the efficiency of the second harmonic PA is 100% and 50% respectively.

For $V_{dc} = 1$ V and $I_{max} = 2$ A;

TABLE 1
PERFORMANCE PARAMETERS

	$P_{dc}(W)$	$P_{out}(W)$	$PUF^1(dB)$	$V_{max}(V)$	$\eta_{Drain}(\%)$
$ClassB$	$2/\pi$	$1/2$	0	2	78.5
IPA^{2nd} 100%	$\frac{2}{\pi}+\frac{2}{6\pi}$	$1/\sqrt{2}$	1.5	2.9	95.2
IPA^{2nd} 50%	$\frac{2}{\pi}+\frac{4}{6\pi}$	$1/\sqrt{2}$	1.5	2.9	83.3

The results show that even when the second harmonic power is fully accounted for and with realistic efficiency values for the second harmonic power generator that the active injection second harmonic Power Amplifier (IPA) has the potential to provide for efficiencies over 80%. The bandwidth advantage expected is inherently associated with such mode of operation since the fundamental matching can be broadband covering multiple octaves and harmonic impedances can be actively adjusted using broadband PAs such as multi octave class-A PA design. Moreover, the expected power of IPA will be around 50% enhanced relative to class-B equivalent.

[1] This is Power Utilization Factor [1] which shows the power capability of a device referenced to class-B output power

III. TRANSISTOR VALIDATION

To validate these theoretical results experimental transistor investigations were undertaken using the previously developed waveform measurement and engineering system at Cardiff University. Since these measurements system utilized active harmonic load-pull they can provide the negative impedances necessary to experimentally demonstrate the IPA mode of operation on the selected 10W packaged GaN device. For the appropriate comparison with theory the V/I waveforms at the current generator plane of the packaged device are required, hence a package parasitic de-embedding process [4] was used.

A. Measurement and Results

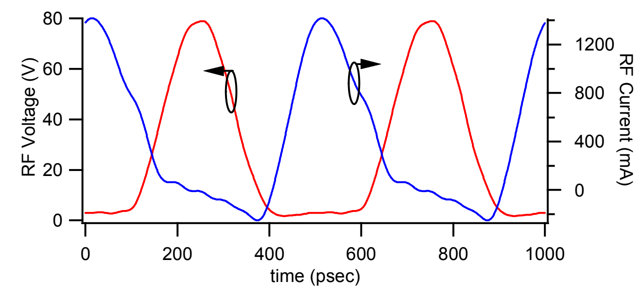

Fig. 1 Voltage/Current waveforms de-embedded to the current generator plane

In order to achieve the required half rectified class-B current waveform the 10 W GaN device was biased around pinch-off at a 28V drain voltage. The active load pull measurement started from inverted class-F optimum fundamental loading condition [5]. The active second harmonic loop was then used to inject energy at the second harmonic to appropriately shape the voltage waveform; targeting a band-limited half rectified waveform offset by 180 from the current waveform. The measured V/I waveforms achieved at the current generator plane are shown in Fig.1. It clearly demonstrates that transistor can support this mode of operation. The required optimum load reflection coefficient of the second harmonic measured is 4 with a phase of 178° relative to the fundamental load reflection coefficient.

The dynamic RF load line for this IPA mode is shown in Fig. 2 and is compared to that achieved for class-B operation; passive harmonic injection into the same fundamental load at the same drive level. In the Class-B case the transistor is clearly overdriven in contrast to the IPA mode. In the IPA the active injected second harmonic voltage component allowing the fundamental voltage component to be increased without forcing the current into a clipping regime and consequently as theoretically predicted both the RF output power and efficiency increases.

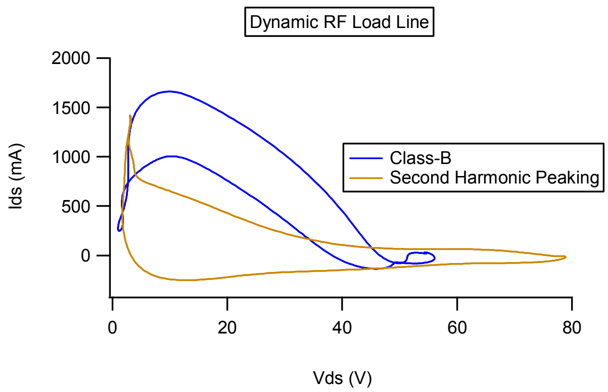

Fig. 2 RF load line of class-B and IPA de-embedded to the current generator plane

B. Discussion

The measured efficiency, taking into account the RF energy injected at the second harmonic is 92%. This is very close to that predicted theoretically which is 95.2% (correspond to that predicted for a 100% efficient second harmonic generator). The reduction of efficiency can be associated with the knee effect which will limit the minimum voltage value. Considering knee effect in drain efficiency calculation predicts an efficiency of 90.4%:

$$\eta_{\mathrm{IPA\ Drain}} = P_{RF}/\left(P_{dc}(1 + V_k/V_{dc}) + (P_{dc0}/\eta_0)\right) \quad (9)$$

$$= 90.4\%$$

where $V_k = 1.74$ V is the measured minimum voltage value. The measured efficiency is slightly higher than the theoretical value and possibly this is the advantageous effect of the higher harmonic voltage components produced by the system impedance.

Also as theoretically predicted the measured output power in this IPA mode has increased by 2 dB. This is in part due to the injected second harmonic power contributing around 1 dB of the change. This outcome highlights an alternative interpretation of how this amplifier works. The resulting waveform shaping allow for the conversion of RF power injected at the second harmonic to a RF power at the fundamental frequency [6]. These results show that significant advantages can be gained from second harmonic injection in terms of efficiency, power and possibly bandwidth.

IV. PA Demonstrator

A. Proposed Topology

The proposed Injection Power Amplifier (IPA) consists of two paths where the upper one (Fig. 3) generates the main fundamental radio frequency (RF) signal and a lower path with a voltage source/auxiliary PA to control the V/I waveforms of the main PA by injecting the even harmonics of the fundamental signal, resulting in the V/I waveforms being shaped for better PA performance in terms of power, efficiency and bandwidth. The baseband information (BB) are up converted by Local Oscillator (LO) through this constant LO power and the fundamental signal is up converted to second harmonic by a doubler. This solution of generating the second harmonic is just a suggestion and could be realised by other circuit topologies.

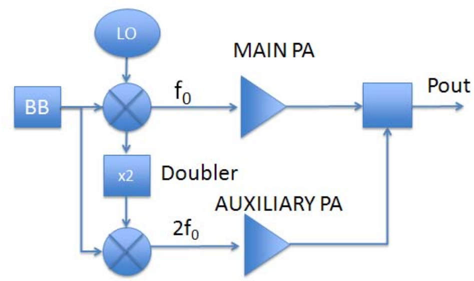

Fig. 3 Proposed topology

B. PA Demonstrator Design

For the purpose of proof of concept and simplicity, the actual realized PA demonstrator consists of two 10 W GaN HEMT (High Electron Mobility Transistor) devices (CGH40010F) biased at class-B and an output matching network consisting of a simple multiplexer and impedance transformers. The devices have been chosen since they are commercially available; nonlinear model exist and provide relatively high output power levels. The board used is a high frequency laminate board (TMM3) from Rogers Corporation. Input drive is achieved using two ESGs (Electronic Signal Generators); hence one is used to generate the second harmonic signal instead of a doubler and thus feeds the auxiliary PA directly.

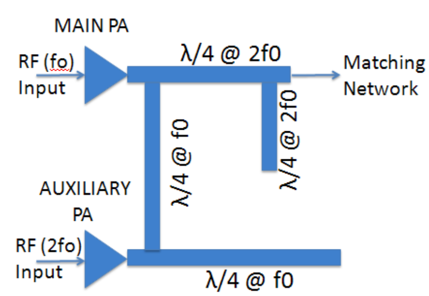

Fig. 4 Multiplexer

The design starts with a multiplexer (Fig.4) where the main PA fundamental signal sees only constant load while the auxiliary PA, active second harmonic injection, sees only the main PA. Therefore, the RF fundamental signal finds its way to the load and the auxiliary PA performs the required waveform shaping.

The output matching network was designed for optimum performance according to load pull measurement while the auxiliary PA's matching network was designed based on ADS simulation for maximum efficiency. Next, an optimization process in ADS has been used and the simulated results showing a drain efficiency of around 75 % at P1dB.

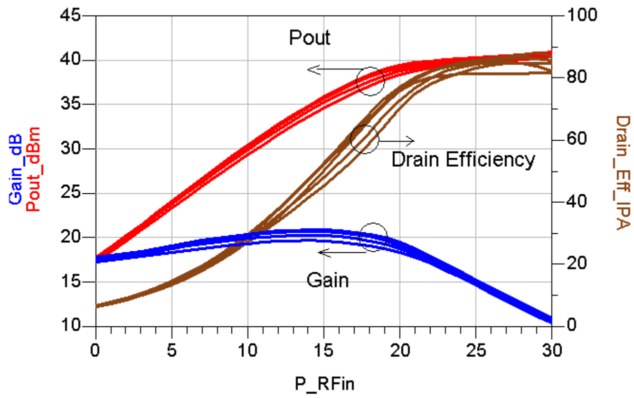

Fig. 5 IPA Simulation results for an increasing phase offset between the two input signals

It is believed that with further investigations/optimization that this value can be further increased using an optimised drive strategy as can be seen in Fig.5. However, it was felt that this design performance was sufficient to demonstrate the potential of the IPA mode of operation, hence demonstrate the feasibility of using this concept in PA design for high efficiency wide band applications. Moreover, this topology has interesting drain efficiency behaviour. It does not decrease but continues to increase as the PA is driven hard into saturation, a result that can be utilized in some applications. The predicted efficiency is 88% at 11W.

C. Realized PA Demonstrator

The demonstrator PA (Fig.6) has successfully fabricated and characterized. It achieved the expected efficiency at P1dB with IPA drain efficiency of 74.3 % at 900 MHz for a yet not optimised drive strategy. The highest drain efficiency was 85.7% at the saturated output power of 10W. (Fig.7)

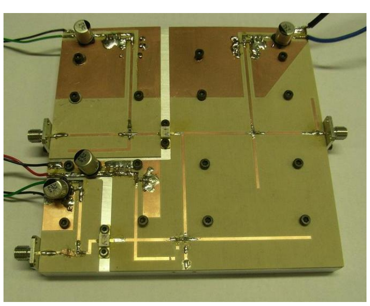

Fig. 6 Realized IPA

V. CONCLUSION

A novel approach for wide band high efficiency high power amplifier has been introduced. The approach is based on the concept of using active second harmonic injection to wave shape the transistor output V/I waveforms. Theoretical analysis indicated that this concept is capable of delivering very high, >95%, efficiencies.

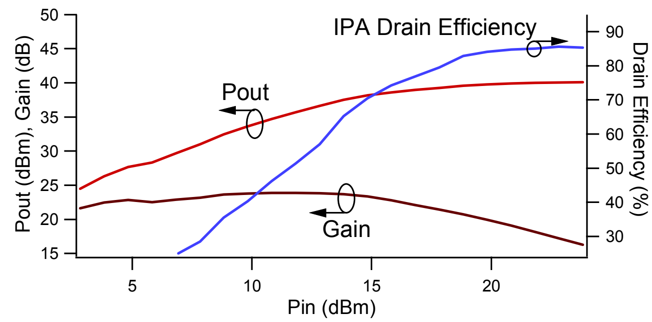

Fig. 7 IPA measurement results for a constant (and hence not yet optimized) magnitude and phase offset between the two drive signals.

This analysis fully takes into account the input energy component at the second harmonic and was confirmed by initial experimental measurements. These measurements involved both active load-pull measurements on the transistor and on a proof of concept PA structure.

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