A Novel Highly Efficient Broadband Continuous Class-F RFPA Delivering 74% Average Efficiency for an Octave Bandwidth

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Abstract — **A novel, highly efficient and broadband RF power amplifier (PA) operating in "continuous class-F" mode has been realized for first time. The introduction and experimental verification of this new PA mode demonstrates that it is possible to maintain expected output performance, both in terms of efficiency and power, over a very wide bandwidth. Using recently established continuous class-F theory, an output matching network was designed to terminate the first three harmonic impedances. This resulted in a PA delivering an average drain efficiency of 74% and average output power of 10.5W for an octave bandwidth between 0.55GHz and 1.1GHz. A commercially available 10W GaN HEMT transistor has been used for the PA design and realization.**

Index Terms — **Microwave measurements, microwave theory and techniques, power amplifiers, power transistors, wideband.**

I. INTRODUCTION

The overall efficiency of wireless communication networks is predominantly determined by the power amplifier (PA) stage. Low efficiency generally translates into increased running costs for base stations and reduced battery life for mobile handsets. Linearity is an equally important performance target as it refers to the fidelity of the signal. Once the expected performance is achieved in terms of efficiency and output power, the next step is to address the requirement of increased bandwidth. Wireless communication networks work for different ranges of frequencies, which depend on application and location. The development of emerging 4G (Fourth Generation) multi-purpose wireless communication networks, such as LTE (Long Term Evolution) that provide higher data-rates (downlink peak rates of at least 100Mbit/s and uplink of at least 50Mbit/s) motivates the microwave community to improve PA performance also in terms of bandwidth. In these new communication systems, bandwidth is very important, specifically as it is needed in order to transfer large amount of data over finite communications channels.

Reported results on efficient class-F or inverse class-F power amplifiers [1] have shown that high efficiency states can be achieved for narrow bandwidths, typically less than 10%. In these cases, deviation from the center frequency will degrade efficiency and output power due to the high-Q resonant tuning conditions usually associated with the narrow band modes. In the continuous class-F mode presented here [2], it is shown that it is possible to have multiple impedance solutions, maintaining the expected output performance over a wider design space and hence bandwidth. Critically, this means that it is now possible to achieve the high efficiency associated with conventional class-F designs, without the requirement of presenting narrow band short and open harmonic terminations. As these new solutions provide higher peaks in the voltage waveforms, GaN devices have been used. In recent years, GaN technologies have become very interesting for the development of broadband applications due to the advantages of high voltage operation in comparison with other technologies.

The class-J power amplifier [3] has demonstrated that starting from the class-B mode, it is possible to achieve high efficiency states for a wideband of frequencies when controlling the first two harmonic impedances. The continuous class-F approach demonstrates that starting from the standard narrow band class-F mode and varying the first two harmonic impedances (while keeping the third harmonic termination open-circuited) it is possible to achieve higher efficiency and output power over an even wider bandwidth than class-J mode.

Design has been conducted using the now well-established and accurate non-linear model for the CGH40010 10W GaN (gallium nitride) HEMT (high electron mobility transistor) device from CREE. Based on simulations results, a PA has been realized yielding a very broadband amplifier operating at high efficiency and at output power levels normally associated with the narrow band class-F mode.

II. THE CONTINUOUS CLASS-F MODE ANALYSIS

Recent investigations into this new PA mode [2] have demonstrated that with constant open-circuited third harmonic impedance, the shorted second harmonic termination is not a unique solution for the achievement of optimum efficiency and output power. The required voltage waveforms are defined by equation (1), [2], which has been derived from the generic factorial representation of voltage waveforms, originally derived by Cripps [4]:

$$v(\vartheta)=\left(1-\frac{2}{\sqrt{3}}\cos\vartheta\right)^2\cdot\left(1+\frac{1}{\sqrt{3}}\cos\vartheta\right)\cdot\left(1-\gamma\sin\vartheta\right) \qquad (1)$$

Expanding the first two brackets in (1) gives:

$$v(\vartheta)=\left(1-\frac{2}{\sqrt{3}}\cos\vartheta+\frac{1}{3\sqrt{3}}\cos 3\vartheta\right)\cdot(1-\gamma\sin\vartheta) \qquad (2)$$

The first bracket of (2) is the standard voltage formulation for the conventional class-F mode (i.e. with γ=0), which has no second harmonic component. The last bracket of (1) and (2) is a defining term (1-γsinϑ) that characterizes the new design space. The variation of γ must result in an entirely positive voltage waveform. Zero crossing or negative voltage waveforms will result in interaction with the knee region, and highly non-linear behavior, usually accompanied by reduced power and efficiency. Varying the γ parameter between -1 and 1, a family of voltage waveforms that provide multiple solutions to maintain constant output performance in terms of power and efficiency can be obtained [2]. Over this range of γ, at the device current-generator plane (Igen-plane) the fundamental impedance varies on a circle of constant resistance whilst the second harmonic impedance remains purely reactive, as shown in Fig. 1(a) [2]. The third harmonic impedance is maintained as an open-circuit. A constant half-wave rectified current waveform has also been assumed for all values of γ.

For the conventional class-F mode (γ=0) at 0.9GHz, the simulated input power was swept in order to identify the target 2dB of gain compression. For this compression point (where P_{IN}=20.5dBm) a peak drain efficiency of 86.4% has been obtained with 40.7dBm device output power at a drain voltage of 28V. In accordance with (1) and for the input power previously achieved (P_{IN} @ P2dB), the first three harmonic terminations have been computed at the Igen-plane and then shifted to the device-package measurement plane for γ varying from -1 to 1, as shown in Fig. 1(b).

Equations (3) and (4) represent the continuous class-F fundamental and second harmonic impedances at the Igen-plane in order to maintain constant output power and drain efficiency.

$$Z_{F_0}=R_L+j\cdot X_L\,, \qquad (3)$$

$$Z_{2F_0}=0-j\cdot\frac{\pi}{2}\cdot X_L \qquad (4)$$

For the 10W GaN HEMT device the fundamental real component impedance is R_L=44.8Ω. To keep a positive voltage waveform, X_L=±38.8Ω are the minimum and maximum values allowed for the reactive fundamental component. Beyond those values of X_L non-linear behavior will be presented. The third harmonic impedance is kept open-circuited at the Igen-plane, resulting in $1\angle 120°$ at the package measurement plane.

Fig. 2 shows simulated engineered current and voltage waveforms at the Igen-plane for first three harmonic terminations, for the conventional class-F mode and for the continuous class-F mode for γ =-1.

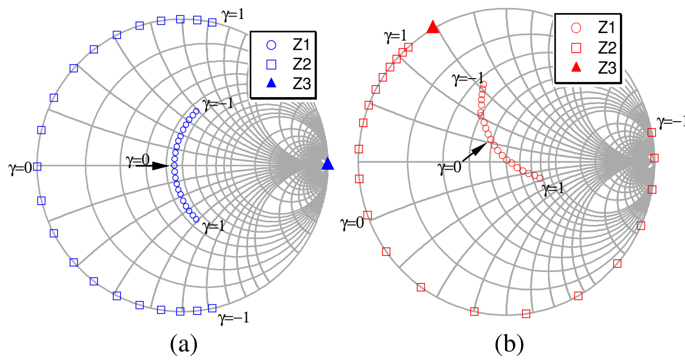

Fig. 1. First three harmonic target impedances for the 10W GaN HEMT device at the Igen-plane (a) and at the device-package measurement plane (b).

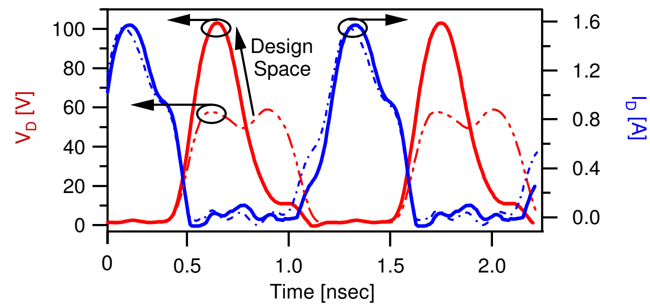

Fig. 2. Simulated current and voltage waveforms at the Igen-plane for a 10W GaN HEMT device for the standard Class-F mode (dotted lines) and "Continuous Class-F" mode (solid lines) for γ=-1.

It can be seen that the current waveform is maintained as half-wave rectified sinusoidal whilst the voltage waveform presents a significantly higher peak value for the continuous mode, which must be accommodated. The approach does however provide a much wider design space where output power and efficiency are maintained constant [2].

III. Design of Broadband Continuous Class-F PA

The PA has been designed using a 10W GaN HEMT transistor and a non-linear CAD approach with the aim of maximizing the drain efficiency whilst delivering the expected output power over significant bandwidth. As efficiency is related to the input bias voltage, drive power level and harmonic terminations, an iterative procedure has been applied to rapidly find these parameters [5]. In this case, bias voltage V_G=-4.6V, available input power P_{AVS}=29dBm and harmonic terminations at the package plane shown in section II have been presented.

A. Output matching network design

Target harmonic impedances have been obtained for a single frequency of 0.9GHz with varying γ through the use of equation (1). In PA design, the aim of the output matching network is generally to present the requested terminations over

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a specified range of frequencies. Fig. 3 shows the broadband output matching network used for the continuous class-F design.

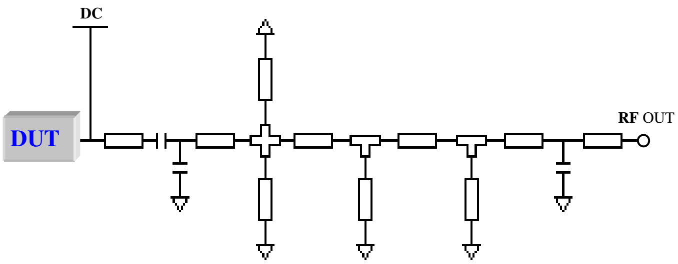

Fig. 3. Continuous class-F output matching network schematic

Fig. 4 shows the target loads and the behavior of the output matching network over a bandwidth of 0.5-1.2GHz. The fundamental component is shown as a solid blue line. The required second harmonic reflection coefficient needs to change rapidly to quickly present high reflection necessary for the continuous class-F mode (green solid/dotted line), whilst the third harmonic component varies around the edge of the Smith chart (black dotted line).

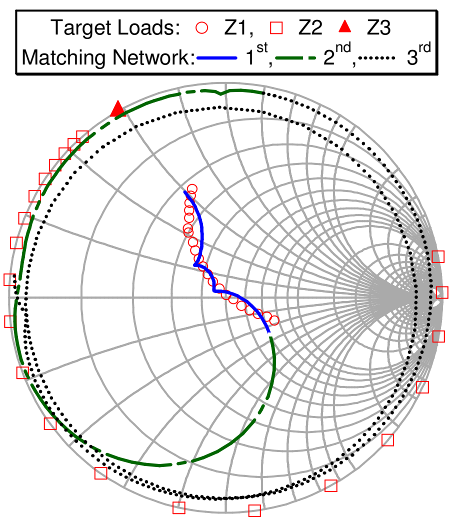

Fig. 4. Target loads and S-parameters for the Continuous Class-F output matching network.

It is important to highlight that the complexity of the matching network (Fig. 3) is mainly due to two aspects: the importance of fitting the network behavior over frequency to the target loads and the accuracy of controlling the third harmonic component. Theoretically the third harmonic impedance should be considered as a constant point (red triangle in Fig. 4), but when designing the matching network for first two harmonics it obviously varies significantly on the Smith chart. To keep expected output performance over the bandwidth, it has been found that the third harmonic termination has to stay as close as possible to the edge of the Smith chart, as shown in Fig. 4.

B. Theoretical Second Harmonic termination inside the Smith chart

When designing and realizing PAs, it is not possible to devise ideal matching networks that present purely reactive impedances, as shown in Fig. 4. This is mainly due to the influence of the assumed broadband 50 Ohm termination. For this reason it is important to establish a target efficiency for which the second harmonic impedance can present a real component without losing too much output performance in terms of power and efficiency.

Equation (5) represents a more general formulation for the continuous class-F mode:

$$v(\vartheta) = (1 - \alpha \cos \vartheta)^2 \cdot (1 + \beta \cos \vartheta) \cdot (1 - \gamma \sin \vartheta) \qquad (5)$$

In this case, varying the parameters α, β and γ it is possible to present second harmonic impedances inside the Smith chart and achieve the correspondent fundamental impedance for which efficiency and output power are maximized. This explains why it is possible to have high efficiency and output power over the bandwidth without perfect short terminations. This is counter-intuitive, but represents an important advance in PA theory. Again, it is important that the voltage waveform is kept above zero to avoid non-linear behavior of the device. Fig. 5 shows the theoretical fundamental and second harmonic impedances as a function of α, β and γ in accordance with (5).

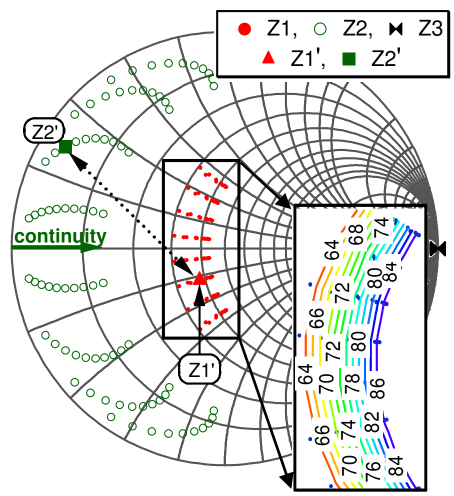

Fig. 5. Extended continuous class-F mode with second harmonic impedance inside the Smith chart with $\beta=\alpha/1.9$ when varying α between 0.6 and 1.5 and γ between -0.7 and 0.7, inset efficiency contour for fundamental load points.

It can be seen that varying the second harmonic termination inside the Smith chart and varying fundamental load in accordance with (5), high efficiency states greater than 64% can still be achieved (i.e. Z1' and Z2' is one optimum combination). The third harmonic impedance is kept open circuited.

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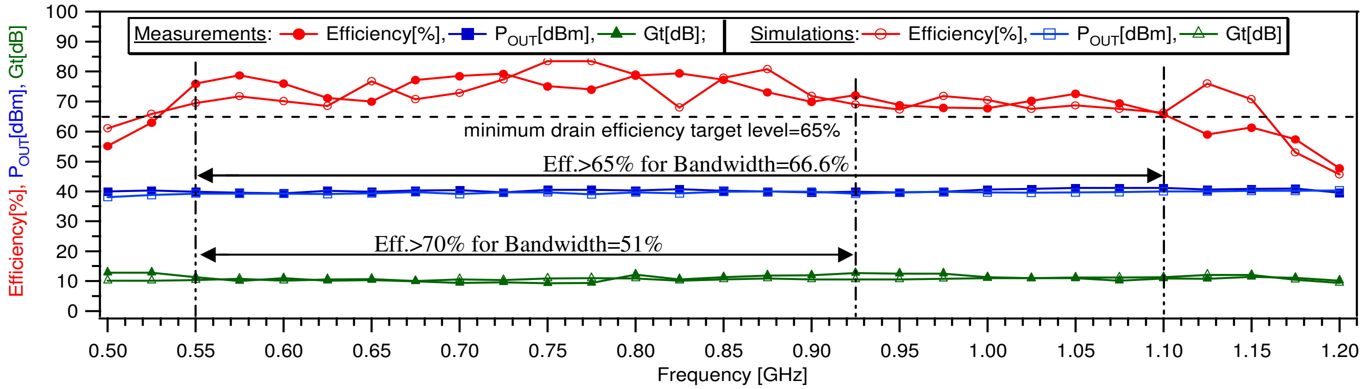

Fig. 6 Measured and simulated drain efficiency, output power and transducer power gain for the realized continuous class-F PA across the bandwidth from 0.5GHz to 1.2GHz.

IV. Realization and Measurements of the Broadband Continuous Class-F PA

The physical implementation of the continuous class-F power amplifier is shown in Fig. 7. Fig. 6 shows the simulated and measured behavior of drain efficiency, output power and transducer power gain over frequencies ranging between 0.5GHz and 1.2GHz. It can be seen how measured results fit well with simulated results. A minimum target efficiency of 65% was chosen.

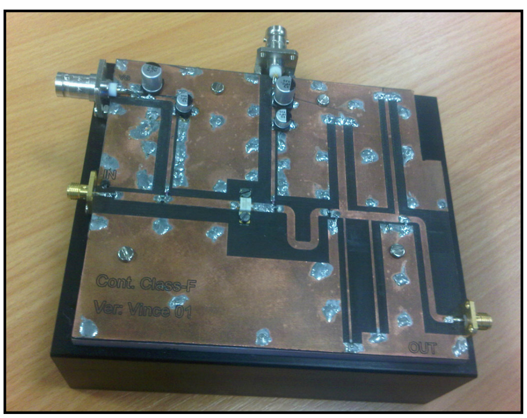

Fig. 7. Realized Continuous Class-F 10W power amplifier.

The realized continuous class-F PA delivers efficiency greater than 65% with maximum peak up to 80% (average efficiency of 74%) over a wide band of frequencies from 0.55GHz to 1.1GHz resulting in an octave (66.6%) bandwidth. In this range of frequencies output power is greater than 39.3dBm with a maximum value of 41.2dBm (average power of 40.2dBm=10.5W). The average transducer power gain is around 11dB, from 9.5dB to 12dB, across the bandwidth. Besides, the PA performance shows that for a smaller range of frequency, ranging from 0.55 to 0.925GHz, higher efficiency greater than 70% is obtained resulting in around 51% of bandwidth.

V. Conclusion

This paper has presented for first time the realization of the "continuous class-F" power amplifier. Using a systematic design process the theoretical identification of continuous class-F fundamental and second harmonic terminations have been carried out over the wide design space. It has been shown that the fabricated continuous class-F PA delivers the expected output power of around 10.5W for a very wide band of frequencies from 0.55GHz to 1.1GHz, resulting in an octave bandwidth. Very high efficiency state from 65% up to 80% (average efficiency of 74%) across the octave bandwidth, and greater than 70% over 51% bandwidth has been obtained. In this work the realization of a highly efficient and broadband PA has demonstrated the validation of the continuous class-F theory.

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