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Novel Realisation of a Broadband High-Efficiency Continuous Class-F Power Amplifier

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Abstract— This work outlines the analysis and design procedure employed for the realisation of a broadband Continuous Class-F power amplifier. Waveform analysis is used in determining the most sensitive parameters for maintaining high efficiency over a desired bandwidth. A design methodology is then employed for control of the dominant parameters over the band of interest, while preserving maximum fundamental output power. By using a commercially available GaN Cree 10W HEMT transistor, an amplifier was fabricated which is operational over a 20% bandwidth. Greater than 11.4W of output power is found with efficiencies between 65-76% measured over the band from 2.15-2.65GHz. An average drain efficiency of 70.5% and PAE of 65% is obtained with a corresponding average output power of 13.5W.

Keywords- Power Amplifier, Class-F, broadband, high efficiency

I. INTRODUCTION

Switch-mode amplifiers have received extensive attention recently due to the push for greater efficiency in power amplification. By exploiting the non-linear nature of a saturated device, the resultant harmonics can be manipulated to produce highly efficient current and voltage waveforms. Class-F [1] operation defines a simple set of load harmonic impedances which produce square-wave voltage and half-sinusoidal current drain waveforms. Theoretical analysis of the Class-F mode reveals 100% efficiency but in practice a limited number of harmonics are controlled, with an associated reduction in the maximum obtainable efficiency. Class-F amplifiers have been well demonstrated as a feasible solution at RF by absorbing package parasitics and output capacitance to present the high efficiency waveforms at the current generator plane. Realisation typically incorporates the use of band-limited $\lambda/4$ harmonic stubs for providing the required precise harmonic terminations. The inherent narrowband performance of the Class-F amplifier (typically $\leq 5\%$) restricts its potential for integration within wideband systems.

Recently, a new amplifier mode known as the Continuous Class-F was published [2], which extended the work on the Class-J amplifier [1] to the Class-F case. The Continuous Class-F enhances the bandwidth potential of the Class-F by exploiting a family of solutions which can be utilised over a desired band. This is achieved by introducing suitable reactive fundamental and 4th harmonic components, as the 2nd harmonic deviates away from the ideal short position and becomes reactive. Open-circuit terminations must also be provided at the internal drain across the 3rd harmonic band for obtaining maximum power and efficiency.

In this work the Continuous Class-F mode is analysed using waveform analysis, with specific emphasis on understanding the efficiency reduction mechanisms. It is shown that the key to maintaining highly efficient switch-mode operation across a band lies in the 2nd harmonic and fundamental reactive impedance components presented at the drain of the device. By careful tuning of the critical frequency components while maintaining an approximate open-circuited 3rd harmonic band, the designer can achieve minimal efficiency degradations over the band of interest.

For implementing the methodology, narrowband harmonic load-pull has been performed on a Cree 10W GaN HEMT transistor to determine the optimal package plane impedances for Class-F operation at the chosen centre frequency. Package and intrinsic de-embedding were then implemented to acquire the corresponding current generator impedances. Using fundamental loadpull data across a 500MHz bandwidth, a broadband fundamental match was designed using the Simplified Real Frequency Technique (SRFT) synthesis algorithm [3]. Upon conversion to microstrip, the 2nd harmonic reactance was tuned over the band in response to the reactive fundamental component while simultaneously producing high impedance at the 3rd harmonic band. Measurements reveal greater than 11.4W of output power over a 20% bandwidth from 2.15-2.65GHz. Across this band, drain efficiency is between 65-76% resulting in obtained PAE of 61-71%.

II. CLASS-F THEORY

A. The Class-F Amplifier

Practical Class-F amplifier design approximates the ideal waveforms at the drain of the device by producing a short-circuit at the 2nd harmonic ($2F_0$) and an open-circuit at the 3rd harmonic ($3F_0$). The drain current waveform then tends toward a half-sinusoid with the drain voltage waveform inclined towards a square-wave. The drain voltage waveform, derived from the Rhodes singularity condition [4], is expressed in equation (1) with a corresponding efficiency of 90.7%.

$$v_{ds} = 1 - \frac{2}{\sqrt{3}} \cos \theta + \frac{1}{3\sqrt{3}} \cos 3\theta \quad (1)$$

The above waveform represents a unique set of coefficients which deliver maximum power and efficiency. There usually is only a single frequency for which these precise coefficient values can be satisfied, which results in rapid efficiency degradation over a band.

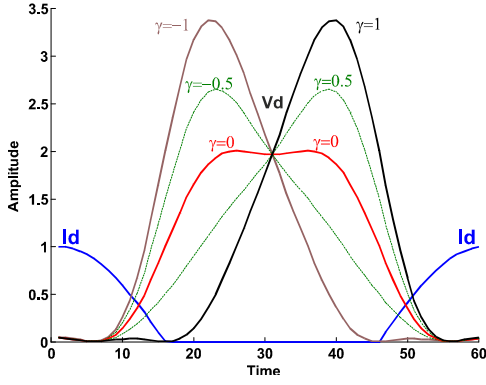


Figure 1. Continuous Class-F voltage and current waveforms

B. The Continuous Class-F Amplifier

The Continuous Class-F voltage waveform equation is shown in (2) and provides solutions, dependent on a variable γ , which maintain the performance of the conventional Class-F over the range $-1 \leq \gamma \leq 1$ [2].

$$v_{ds} = \left(1 - \frac{2}{\sqrt{3}} \cos \theta\right)^2 \left(1 + \frac{1}{\sqrt{3}} \cos \theta\right) (1 - \gamma \sin \theta) \quad (2)$$

A continuous family of solutions can then be manipulated over a frequency band by dynamically updating the voltage waveform to deliver maximum power at 90.7% efficiency. The trade-off for such performance comes in the form of increased maximum amplitude of the drain voltage waveform as shown in Fig.1. Although, by utilizing high voltage breakdown device technologies such as GaN, such large voltage waveform excursions can be sustained.

III. CONTINUOUS CLASS-F EFFICIENCY ANALYSIS

In practice, preserving the optimum coefficient values over the range $-1 \leq \gamma \leq 1$ will be not viable. This arises due to realisable passive matching networks only producing clockwise phase rotation on the Smith Chart [5]. In the search for the sub-optimum solution it becomes necessary to perform an efficiency sensitivity analysis on the waveform. By identifying the most sensitive coefficients, it was then a case of prioritising the progression of their associated impedances over the band. To gain insight into the frequency components involved, it was necessary to multiply out the factorisation given by (2), which is shown in (3).

$$v_{ds} = 1 - \gamma \sin \theta - \frac{2}{\sqrt{3}} \cos \theta + \frac{7\gamma}{6\sqrt{3}} \sin 2\theta + \frac{1}{3\sqrt{3}} \cos 3\theta - \frac{\gamma}{6\sqrt{3}} \sin 4\theta \quad (3)$$

It can be seen that control of up to the 4th harmonic is essential to maintaining the optimum solution over a bandwidth. Also, the 3rd harmonic is seen to be independent of γ , which implies the 3rd harmonic drain impedance must provide a constant open-circuit across the band. From this, three potential sources of efficiency degradation were identified:

- Neglecting the 4th harmonic requirement from a practical standpoint

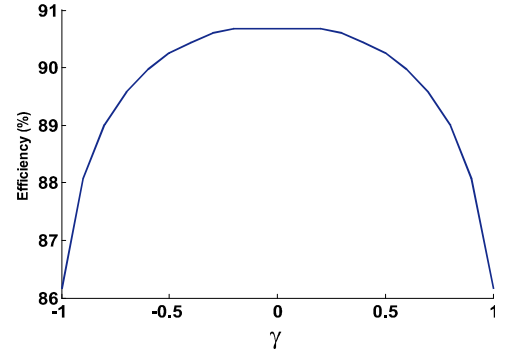


Figure 2. Efficiency against γ without 4th harmonic voltage component

- Imperfect open-circuit termination across the 3rd harmonic band
- Non-optimum fundamental and 2nd harmonic reactive components

By analysing the three established sources of efficiency deterioration separately, the most important components were distinguished and given precedence in the design process.

A. Neglecting the 4th Harmonic

The potential impact of neglecting the 4th harmonic over a band of interest can be seen in Fig.2. Since from (3) the 4th harmonic component is dependent on γ , it is seen that when $|\gamma| = 1$ a maximum efficiency degradation of about 4.5% occurs. The case for neglecting the 4th harmonic is approximately justified by C_{ds} offering small enough impedance at $4F_0$ to produce minimal 4th harmonic presence in the drain voltage waveform.

B. Imperfect Open-circuit across the 3rd Harmonic Band

Referring again to (3), it can be seen that the 3rd harmonic voltage component must be kept at a constant open-circuit over the frequency band for achieving maximum efficiency. This will have an adverse effect on efficiency over the band of interest as it will not be practical to maintain a consistent open-circuit across the band.

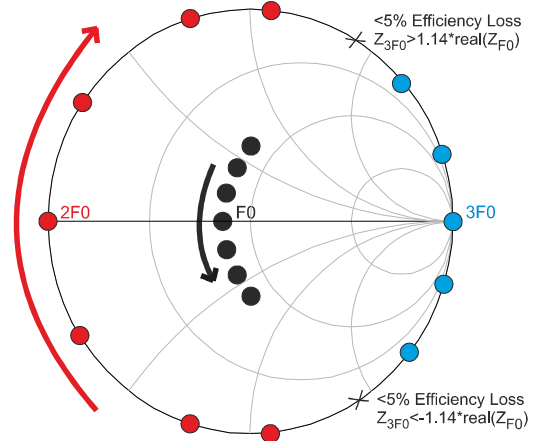


Figure 3. Smith Chart bounds for $3F_0$ to obtain $< 5\%$ efficiency drop

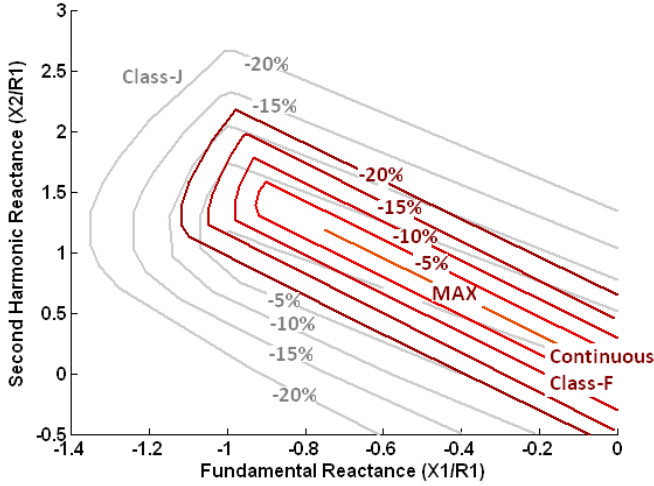


Figure 4. Continuous Class-F and Class-J efficiency contours

By manipulating the current and voltage drain waveforms, 3rd harmonic movement across the Smith Chart was simulated with the results shown in Fig.3.

It is seen that if the 3rd harmonic impedance remains within the specified bounds of $|Z_{3F_0}| > |1.14 \times Re(Z_0)|$ then a degradation of less than 5% can be expected. Although it is of paramount importance to attain high impedance at $3F_0$, there exists a well defined region of the Smith Chart for 3rd harmonic band placement for which minimal efficiency degradation occurs.

C. Non-optimum Fundamental and 2nd Harmonic Reactances

Finally, efficiency sensitivity was addressed by varying the reactive fundamental and 2nd harmonic components. This traced out a set of efficiency contours in the harmonic reactance plane as shown in Fig.4. For comparison purposes, the Class-J reactance plane is shown in the background. It is evident that the Continuous Class-F exhibits far greater sensitivity to sub-optimum reactive terminations than its quasi-linear counterpart. This highlights the crux of Class-F narrowband behaviour and demonstrates the difficulty in practical broadband switch-mode design. By observing the fundamental reactance across the desired band, it will then be possible to obtain high efficiency operation with 2nd harmonic reactance fine tuning provided a near open-circuited $3F_0$ is maintained.

IV. CONTINUOUS CLASS-F DESIGN PROCEDURE

The identification of the key parameters in the previous section allowed priorities to be placed on certain harmonic impedance components to aid in the design process. The primary concern was given to the fundamental and 2nd harmonic reactive terminations, with secondary considerations given to 3rd harmonic high impedance. The approach taken was to utilize a synthesis algorithm to provide fundamental load impedances within a pre-determined, high-power region of the Smith Chart. The resulting lumped circuit was then converted to microstrip, with topological considerations given for optimal 2nd harmonic reactance and 3rd harmonic impedance placement within the designated < 5% efficiency loss region.

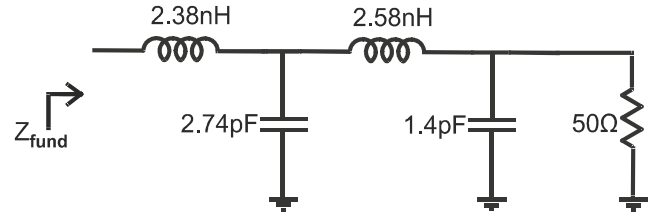


Figure 5. Lumped output broadband fundamental matching network

A. Lumped Fundamental Output Matching Network

The Simplified Real Frequency Technique (SRFT) [3] was used to present the required fundamental impedances across a wide bandwidth, determined by fundamental loadpull. For a passive, reciprocal LC network its S-parameters can be defined as a function of the polynomials $g(s)$, $h(s)$ and $f(s)$, known as the Belevitch form [6]. The transducer power gain (TPG) can be represented as shown in (4).

$$TPG(\omega) = \frac{f \cdot f^* [1 - |\Gamma_L|^2]}{h \cdot h^* [1 + |\Gamma_L|^2] + f \cdot f^* - 2Re[\Gamma_L \cdot h \cdot g^*]} \quad (4)$$

By initialising the coefficients of $h(s)$ and choosing $f(s)$, the coefficients of $g(s)$ can be determined by (5), which is given by the lossless condition [3].

$$g(s) \cdot g(-s) = h(s) \cdot h(-s) + f(s) \cdot f(-s) \quad (5)$$

By setting $f(s) = 1$, a low pass LC network is obtained without the need for a transformer. Careful numerical construction of the strictly Hurwitz polynomial $g(s)$ is formed by the left half plane (LHP) roots of $g(s) \cdot g(-s)$. The TPG is then unique and can then be maximized across the band by non-linear optimization of the coefficients of $h(s)$. When the optimum $h(s)$ coefficients are found, S_{11} is then calculated by the relationship $S_{11} = h(s)/g(s)$. The element values for the LC network may then be determined by standard synthesis methods. The algorithm was employed for the design of broadband input and output fundamental match. The resultant output lumped circuit is shown in fig.5.

B. Microstrip Output Matching Network

Upon conversion of the lumped circuit to microstrip, optimal

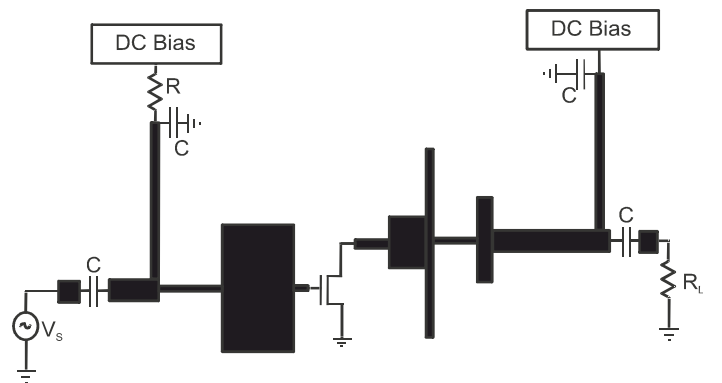


Figure 6. Layout of complete Continuous Class-F Amplifier

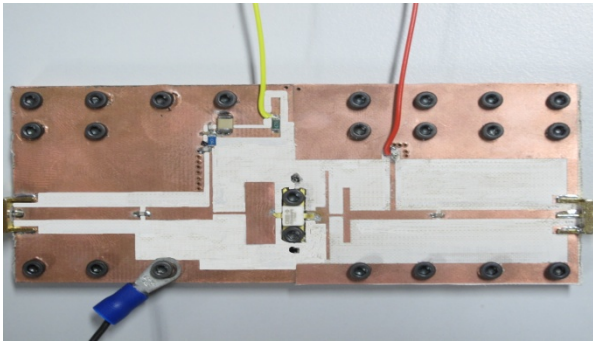


Figure 7. Fabricated Continuous Class-F PA

2nd harmonic reactive terminations were sought, coupled with the need for 3rd harmonic high impedance. Commercial 3D EM software was used for greater accuracy at determining the harmonic impedances presented to the device. Optimisation and sensitive tuning was employed for conversion of each lumped element to give a high-efficiency trajectory on the reactance plane of Fig.4, while maintaining the optimum fundamental impedances for maximum power delivered across the band. Precise placement of a $\lambda/4$ line can offer extra flexibility in tuning the 2nd harmonic while also providing a convenient DC feed point. The PA layout is shown in Fig.6.

V. MEASUREMENT RESULTS

The Continuous Class-F PA was implemented on Taconic RF-60A substrate with $\epsilon_r = 6.15$ and thickness of 1.6 mm. The final fabricated amplifier is shown in Fig.7. The Cree CGH40010FE device was biased near cut-off at -3V with 28V chosen on the drain to allow for large amplitudes of the voltage waveforms without device breakdown. The fabricated PA was tested using continuous wave (CW) excitation from 2.15-2.65GHz. Drain efficiency, PAE and gain were determined over the 20% bandwidth. Results are shown in Fig.8.

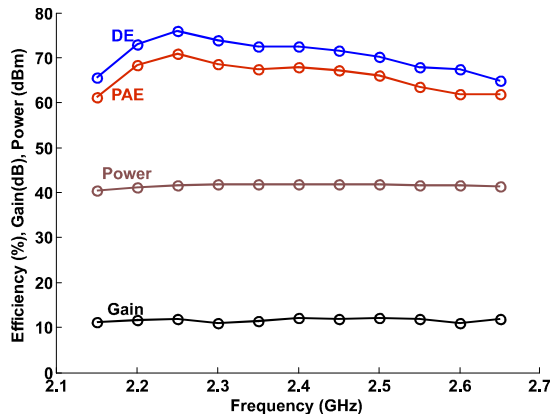


Figure 8. Measured PA efficiency, power and gain from 2.15-2.65GHz

Between 11.4-15W of output power was delivered across the band with drain efficiency between 65-76%. 11-12.5dB of gain was obtained, corresponding to PAE from 61-71% with the peak PAE of 71% occurring at 2.25GHz. Comparisons of this work with a selection of current state-of-the-art results are shown in Table 1. It is evident that when comparing PAE and

bandwidth for maximum delivered power, this work surpasses similar switch-mode broadband PA design results.

TABLE I. SWITCH-MODE AMPLIFIER PERFORMANCE COMPARISON

	<i>Class Of Operation</i>	<i>BW (GHz)</i>	<i>Power (W)</i>	<i>PAE (%)</i>	<i>Peak PAE (%)</i>
[7]	Class-E	1.9-2.4	< 7.4	> 50	57
[8]	Class-E	2.1-2.7	9.3-12.7	> 53	63
[9]	Class-E	2.05-2.25	< 20	> 60	71.3
[10]	Class-F	1.8-2.1	< 1	> 48	54
This Work	Continuous Class-F	2.15-2.65	11.4- 15	> 61	71

VI. CONCLUSIONS

A fully realised Continuous Class-F high efficiency PA has been demonstrated over a 20% bandwidth. Initially, a lumped element fundamental match was designed using the Simplified Real Frequency Technique (SRFT) synthesis algorithm. While converting to microstrip, the fundamental band reactance is observed for suitable fine tuning of the most efficiency sensitive 2nd harmonic reactance. By also presenting high 3rd harmonic band impedances the key criteria for Continuous Class-F operation were satisfied. Measurements show efficiency between 65-76% with 11.4-15W of output power over the 2.15-2.65GHz band.

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