

Novel High Efficiency Power Amplifier Mode Using Open Circuit Harmonic Loading

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Abstract—This paper introduces the Class O² power amplifier (PA) with high power-density and drain efficiency. A new waveform engineering-based design approach is proposed to realize a reliable high-efficiency PA operation while tuning both second and third harmonic impedances to open-circuit termination. The proposed theory derives the intrinsic current and voltage waveforms as a function of input second-harmonic tuning which is adopted to enable the realization of reliable Class O² PA operation. A multi-harmonic vector load-pull system is used for the practical validation that is carried out using a 10-W gallium nitride (GaN) transistor. On load-pull, the Class O² mode demonstrates a drain efficiency of 87% at an output power of 39.8 dBm with a gain of 10 dB at a frequency of 1.0 GHz.

Keywords—class O², gallium nitride, high efficiency, harmonic load-pull, input harmonics, open circuit, power amplifier.

I. INTRODUCTION

Today, harmonically tuned power amplifiers (PAs) are well-established for increasing the efficiency of the power amplification stage of radio frequency (RF) wireless transceivers. These PA classes manipulate the waveforms at the current generator plane of the device to minimize the overlap between drain current and voltage waveforms. The legacy of RF harmonically tuned PAs dates to 1974 with one of the first works on Class F by F. Raab [1], followed by inverse Class-F (F⁻¹) by C. Kanmuri in 1983 [2]; and, most recently Class J by S. Cripps in 2009 [3]. All the aforementioned classes mainly rely on a specific combination of a second (Z_{2L}) and third (Z_{3L}) harmonic to be either short- or open-circuited. Starting from tuned-load Class-B with both harmonics short-circuited, the Class-F tunes Z_{2L} and Z_{3L} to short- and open-ended terminations, respectively. Conversely, the Class F⁻¹ tunes Z_{2L} and Z_{3L} to open- and short-circuited terminations, respectively. With advancements in waveform engineering, Class-J and other continuous-mode PAs exploit sweeping of second-harmonic impedance around short or open circuit to achieve broadband operation [3]–[11].

This paper presents an addition to the harmonically tuned PA family. The analysis is focussed on realizing a PA operation with both second and third harmonics to be at open-circuited terminations. Such mode of operation, denoted herein as class O² (open-open), has not been reported previously. Unlike other PA classes that are typically focused on output loading, the Class-O² amplifier exploits both input

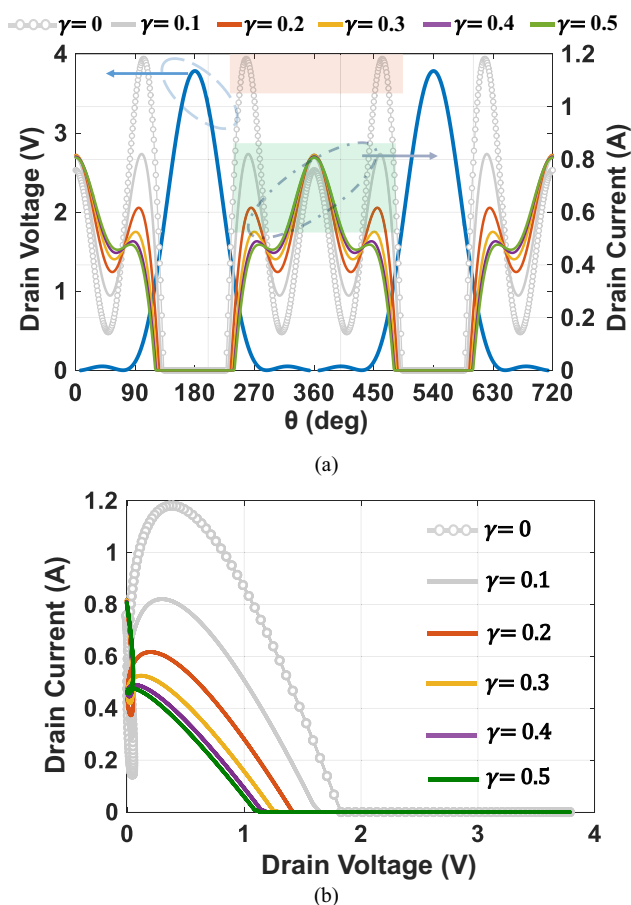


Fig. 1. (a) Class O² drain voltage and current waveforms as function of γ for Class-B bias mode (b) Class O² PA load line as function of γ .

and output harmonics of a transistor. This is proven to help shaping voltage and current waveforms in a way that enhances the efficiency while maintaining high power density.

II. CLASS O² PA WAVEFORM SYNTHESIS

High-efficiency PAs exploit the voltage waveform shaping by addition of suitably phased harmonic components to increase the fundamental voltage swing and minimize the overlap with the current. The voltage waveform, V_{ds,O^2} for

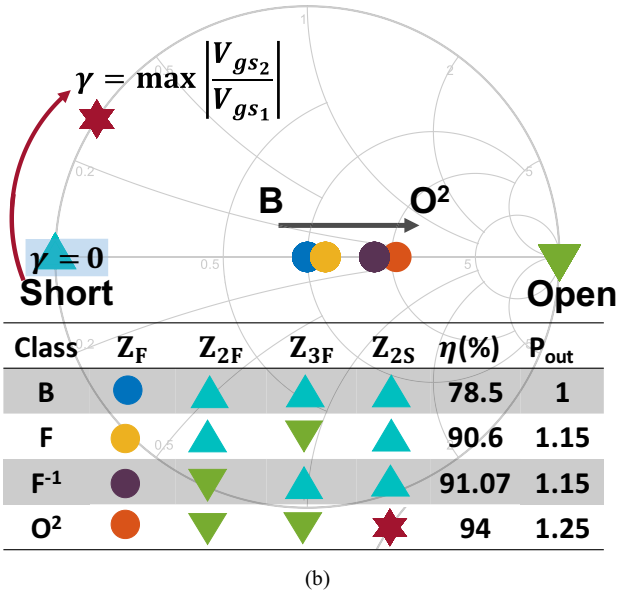
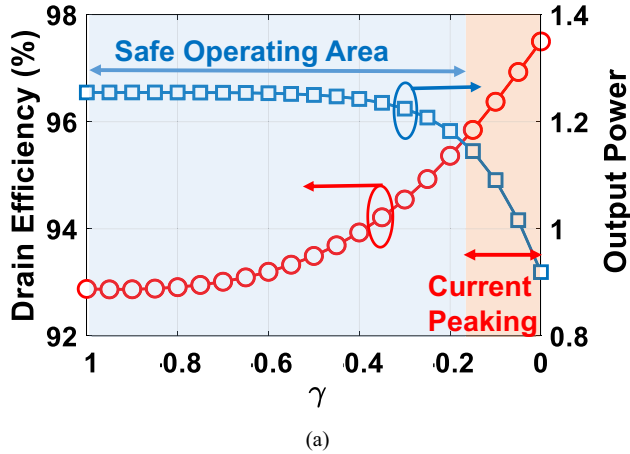


Fig.2. Class O² PA mode (a) Theoretical drain efficiency as a function of γ (b) Design space and performance comparison for different harmonically tuned PAs.

second and third harmonic tuned amplifier can be expressed [5] as

$$V_{ds,O^2}(\theta, V_k, V_{dc}) = V_{dc} - (V_{dc} - V_k)(1.62 \cos \theta - 0.89 \cos 2\theta + 0.275 \cos 3\theta) \quad (1)$$

where θ is angular frequency, V_k is the knee voltage, and V_{dc} is the drain bias-voltage.

The drain voltage given in (1) has the highest achievable fundamental component amongst any harmonically tuned class. Since the voltage has both second and third harmonic components, the total voltage swing peaks as high as $3.7 V_{dc}$ as shown in Fig. 1(a), which, in principle, leads to higher output power. However, there is no known current waveform equation that can satisfy the appropriate relationship that leads to positive and realizable impedance terminations at both second and third harmonics.

In previous attempts, bias tuning was exploited to correct the phase relationship but with no explicit definition of the drain current waveform [6], [8]. The Class O² mode proposed

in this paper solves the problem of phasing relationship between voltage and current waveforms by forcing both second harmonic (Z_{2F}) and third harmonic (Z_{3F}) terminations to open-circuit conditions.

While controlling up to three harmonics and assuming class-B bias mode, the drain current waveform of class O² amplifier can be shown to be expressed as

$$I_{ds,O^2}(\gamma) = I_{dc}(\gamma) + \sum_{n=1}^{\infty} I_n(\gamma) \cos n\theta \quad (2)$$

where

$$I_{dc}(\gamma) \cong 0.2357 - 0.5895\gamma - 1.289\gamma^2 - 1.018\gamma^3 \quad (3)$$

$$I_1(\gamma) \cong 0.2841 - 0.6645\gamma - 1.544\gamma^2 - 1.255\gamma^3 \quad (4)$$

$$I_2(\gamma) = I_3(\gamma) = 0 \quad (5)$$

and γ is the input second harmonic tuning factor which is defined as a ratio of second harmonic to fundamental input voltage component i.e. $|V_{gs2}/V_{gs1}|$ [5], [9].

From (5), it is noteworthy that second and third harmonic current components are zero for any second harmonic tuning condition. As seen in Fig. 1(a), the drain current varies as a function of γ with a current peaking when second harmonic source impedance is short circuited (i.e., = 0), meaning that a reliable Class-O² operation is not recommended with no manipulation of input second harmonic termination. Besides, selecting a second harmonic source (Z_{2s}) that provides maximum input nonlinearity ($\gamma = \max |V_{gs2}/V_{gs1}|$) enables Class-O² operation and yields a high efficiency performance with both Z_{2F} and Z_{3F} at open circuit. The drain current waveform limits itself below maximum current providing both high efficiency and reliable PA solution. Using (1) and (2) the drain efficiency for Class O² amplifier can be computed as

$$\eta_{O^2} = \frac{1.62}{2} \left(1 - \frac{V_k}{V_{dc}}\right) \left[\frac{I_1(\gamma)}{I_{dc}(\gamma)} \right] \quad (6)$$

The theoretical drain efficiency (DE) is plotted as a function of γ for $V_k=0$ in Fig. 2(a). As seen the DE decreases with increase in γ . It is noteworthy, however, that for a Gallium Nitride (GaN) device, γ is typically within $0 \leq \gamma \leq 0.5$, thereby setting the highest achievable efficiency to 94%. In addition, for device reliability and high-efficiency operation the, selection of Z_{2s} yielding maximum γ ensures a lower value of peak current and yet provides high output power because of fundamental voltage swing.

Considering a design example with $\gamma = 0.4$, the design space at fundamental and harmonic frequencies for a Class O² PA can be computed using (1)-(5) as

$$Z_F = \frac{1.62 (V_{dc} - V_k)}{I_1(\gamma = 0.4)} = \frac{1.62 (V_{dc} - V_k)}{0.76 (I_m/2)} = 2.13 R_{opt} \quad (7)$$

where

$$R_{opt} = \frac{(V_{dc} - V_k)}{(I_m/2)} \quad (8)$$

$$Z_{2F} = \infty ; Z_{3F} = \infty \quad (9)$$

$$Z_{2s} = \text{Impedance for } (\max (|V_{gs2}/V_{gs1}|)) \quad (10)$$

The design space is depicted in Fig. 2(b) showing the impedance terminations for source and load matching for a reliable PA operation. In addition, Fig 2(b) shows that, Class O² provides higher output power and efficiency in comparison to other classes of amplifiers when simultaneously exploiting input and output harmonics.

III. EXPERIMENTAL AND WAVEFORM VALIDATION

For the practical validation, Vector Load Pull (VLP) is carried out using Focus Multi-Purpose Tuner (MPT) at the load and MPT-Lite at the source [12] on a 1.95mm GaN device at a frequency of 1.0 GHz. The measurement set-up is shown in Fig. 3(a). The proposed Class O² mode was realized and studied using a procedural load-pull methodology described below:

1. The VLP setup is calibrated with Focus 8-term calibration procedure which consists of a 12-term VNA calibration followed by a power calibration using Focus Device Characterization Suite (FDCS) [12]. The vector parameters (A1, B1, A2, B2) measured by the VLP setup provide information about the device input impedance and ensures accurate and reliable device performance measurements.
2. The intrinsic impedances at the current generator plane for second and third harmonics i.e. Z_{2F} and Z_{3F} are set to short circuit. With the fundamental load impedance, Z_F ,

set to R_{opt} , a second harmonic source pull is performed to select Z_{2s} corresponding to the maximum γ i.e. $\max(|V_{gs2}/V_{gs1}|)$. This impedance is often the impedance of minimum efficiency under Class B PA operation.

3. After fixing Z_{2s} , the harmonic load impedances, Z_{2F} and Z_{3F} under Class O² PA mode are remapped to the extrinsic plane using device parasitic information ($Z_{2L}=0.1+j44$ and $Z_{3L}=0.1+j24$ at extrinsic plane) as shown in Fig. 3(a) and 3(b), respectively.
4. Under the input and output harmonic loading conditions set in step 3, a fundamental load pull is performed. The maximum power (MXP) and maximum efficiency (MXE) contours are shown in Fig. 3(b) and 3(c).

Using steps (1)-(4), measured contours show maximum output power of 42.5 dBm at $Z_{F, MXP} = 50 \Omega$ and maximum efficiency of 87% at $Z_{F, MXP} = 63+j30$. The device is biased at drain supply voltage, $V_{dc} = 28$ V and quiescent current, $I_{dq} = 21$ mA at a frequency of 1.0 GHz. For maximum efficiency impedance, the Class O² PA exhibits DE of 87% with output power of 39.8 dBm and a gain of 10 dB as shown in Fig 3(d). The intrinsic drain waveforms are shown in Fig. 3(e) with a voltage swing of more than $3.5V_{dc}$ (98V). The de-embedded design space and waveforms reported in Fig. 3 are in close harmony with the proposed theory of Class O² PA mode presented in Section II, confirming the proposed mode of operation.

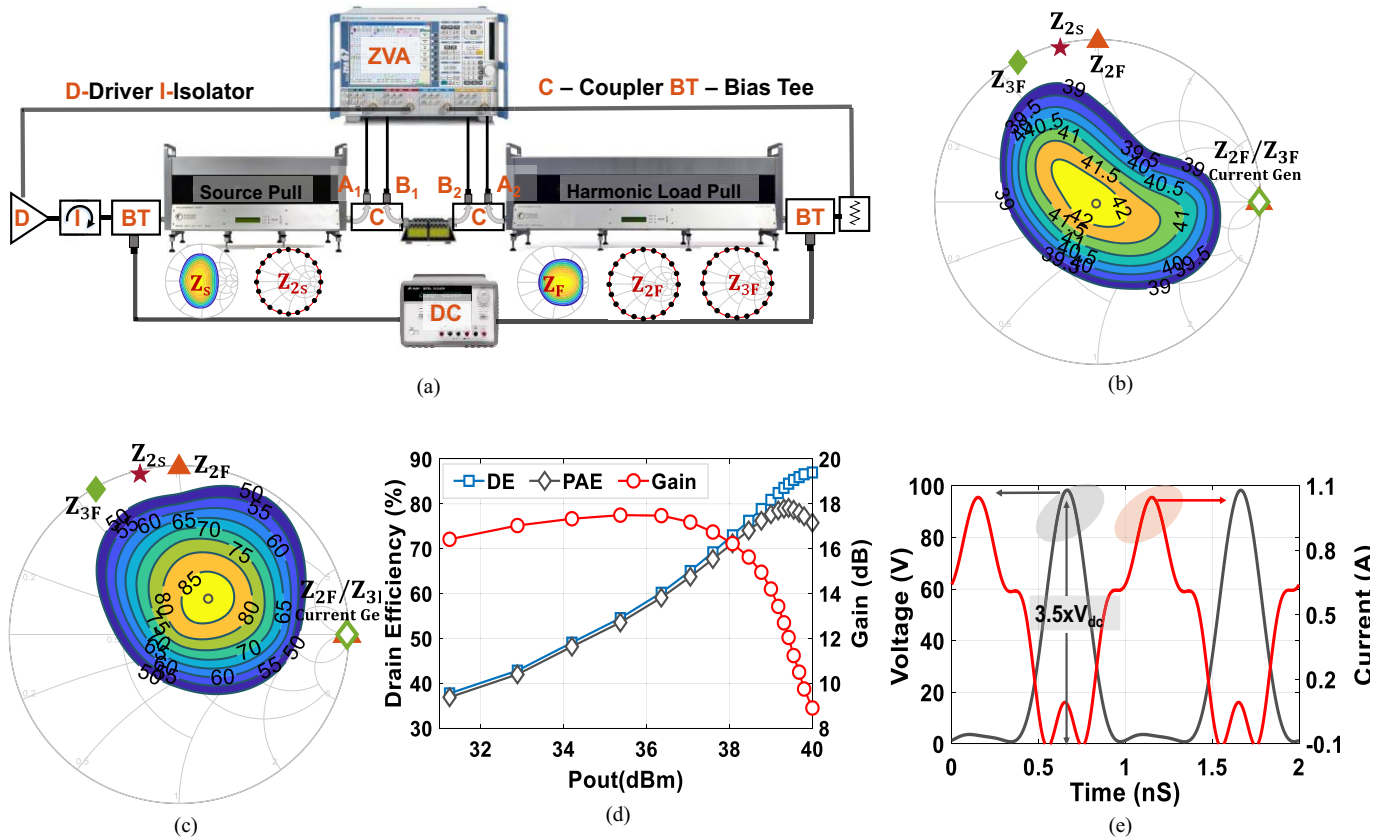


Fig. 3. Class O² power amplifier mode (a) Vector load-pull setup with harmonic source and load pull. (b) Fundamental load-pull contours for maximum power (MXP). (c) Fundamental load-pull contours for maximum drain efficiency (MXE). (d) Measured gain, DE and PAE at a frequency of 1.0 GHz. (e) Intrinsic drain voltage and current waveforms at 1.0 GHz.

IV. CONCLUSIONS

The paper presents for the first time a Class O² PA which provides high-efficiency operation. A novel mathematical framework for waveforms and design space is proposed in the paper. Class O² PA completes the harmonic tuned PA family by providing a design methodology with both second and third harmonic at open impedance. The proposed theory is validated using multi-harmonic load pull for realizing PA operation under Class O². At a frequency of 1.0 GHz, Class O² PA mode provides a drain efficiency of 87% with an output power of 39.8 dBm and gain of 10 dB. It is anticipated that the theory of Class O² PA will be thoroughly explained in the extension of this work.

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