



Deposited via The University of Sheffield.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/129111/>

Version: Accepted Version

---

**Article:**

Poluri, N. and De Souza, M.M. (2018) Investigation of the effect of weak non-linearities on P1dB and efficiency of class B/J/J\* amplifiers. IEEE Transactions on Circuits and Systems II: Express Briefs, 65 (9). pp. 1159-1163. ISSN: 1549-7747

<https://doi.org/10.1109/TCSII.2018.2810944>

---

© 2018 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other users, including reprinting/ republishing this material for advertising or promotional purposes, creating new collective works for resale or redistribution to servers or lists, or reuse of any copyrighted components of this work in other works. Reproduced in accordance with the publisher's self-archiving policy.

**Reuse**

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

**Takedown**

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing [eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk) including the URL of the record and the reason for the withdrawal request.

# Investigation of the Effect of Weak Non-Linearities on P1dB and Efficiency of Class B/J/J\* Amplifiers

Nagaditya Poluri and Maria Merlyne De Souza, *Member, IEEE*

**Abstract**—The variation of phase of the current through the non-linear intrinsic capacitances of a high-power RF device caused by the variation of the phase in the continuum of drain voltage waveforms in Class B/J/J\* leads to a reduction of intrinsic drain current when moving from class B to class J\* while the drain current increases from class B to class J. Consequently, a subset of voltage waveforms of the class B/J/J\* continuum can be used to design amplifiers with higher P1dB, and efficiency at P1dB than in Class B. A simple choice of this subset is demonstrated with a 2.6GHz Class B/J/J\* amplifier, achieving a P1dB of 38.1dBm and PAE at P1dB of 54.7%, the highest output power and efficiency at P1dB amongst narrowband linear amplifiers using the CGH40010 reported to date, at a comparable peak PAE of 72%.

**Index Terms**—Class B/J/J\* continuum, non-linear capacitances, Power amplifier, GaN HEMT, linearity, IMD3

## I. INTRODUCTION

Wireless communication systems require power amplifiers with high efficiency and linearity to reduce battery consumption and interference respectively. As a solution, Cripps et. al. [1] proposed a continuum of voltage waveforms from class J\*/B/J, which differ in phase, but achieve constant output power and peak efficiency. These high efficiency, yet linear, waveforms require inductive, short, and capacitive loads for classes J\*, B and J, respectively, at the second harmonic, whilst the reactive component of the fundamental load is adjusted according to the load impedance at the second harmonic. The principle of class B/J/J\* continuum has been applied to classes E, F, and F<sup>-1</sup> to alleviate the need for precise load terminations with the resulting modes referred to as continuous classes E [2], F[3], and F<sup>-1</sup>[4] respectively. The continuum modes demonstrate efficiency above 60% over a wide bandwidth [3]–[7] and allow the drain capacitance to be absorbed into the output matching network thus easing amplifier design [7].

Interestingly, the class B/J/J\* continuum and the continuous class F demonstrate state-of-the-art high efficiencies at P1dB and at back-off power levels, as summarized in Table I. It appears that the improvement of efficiency at back-off in Class B/J/J\* can be attributed to the current generated from intrinsic capacitances. For the case of class J, the improvement over class B is due to the harmonics of current generated from the non-linear output capacitance  $C_{out}$  (a combination of the feedback capacitance ( $C_{gd}$ ) and drain-source capacitance ( $C_{ds}$ )) [8].

Manuscript received September 28, 2017; revised December 20, 2017; accepted February 1, 2018. This work was supported by ENIAC-JU project PARSIMO under Grant 270687. This brief was recommended by Associate Editor D. D.-C. Lu. (Corresponding authors: Nagaditya Poluri and Maria Merlyne De Souza.)

TABLE I  
REPORTED HIGH EFFICIENCIES AT P1dB AND BACK-OFF POWER

Ref.	Mode	Device Technology	P <sub>sat</sub> (dBm)	Merit	Freq. (in GHz)
[9]	Class B/J/J*	GaAs pHEMT	27.4	62% PAE at P1dB	5.25
[10]	Class B/J/J*	GaN HEMT	39.7	50% DE at 5dB backoff	2.13
[11]	Class B/J/J*	GaN HEMT	41.2	50% DE at 5.5dB backoff	2.5
[12]	Class B/J/J*	GaN HFET	26.8	44% PAE at 10dB backoff	2.5
[13]	CCF	GaN HEMT	42.2	42% DE at 6.5dB backoff	2.14

DE and PAE denote Drain Efficiency and Power Added Efficiency respectively. CCF denotes Continuous class F. Freq. denotes Frequency.

The harmonics from non-linear  $C_{out}$  have been shown to improve peak PAE in continuous class F[13].

However, no work, to date, has described conditions to obtain high efficiencies at P1dB and back-off power nor has analysed the influence of the weak non-linearities (non-linear gm and non-linear capacitances) on the performance of a class B/J/J\* amplifier, as addressed in this work. A simple method that relies on an analysis of weak non-linearities on the intrinsic drain current is illustrated for the selection of high-efficiency voltage waveforms in the continuum.

## II. EFFECT OF WEAK NON-LINEARITIES

The device selected for this study is a 10W GaN HEMT, CGH40010F, biased in deep class AB mode ( $V_{dsq}=28V$ ,  $I_{dsq}=150mA$ ) with an optimal loadline resistance ( $R_L$ ) of 38.1Ω. The equivalent circuit of the transistor used for our analysis using ADS is shown in Fig. 1. The values of the extrinsic parasitic elements and intrinsic capacitors of the device are extracted from the Z and Y parameters vendor model using the algorithms presented in [14] and [15] respectively. The non-linear current generator  $I_{gen}$  is implemented via a table look-up as a function of the intrinsic gate ( $V_{gsi}$ ) and drain ( $V_{dsi}$ ) voltages. Analysis of the Intermodulation products and ACPR is undertaken using the vendor model.

### A. Influence of Intrinsic Parasitic Elements on the Intrinsic Drain current

The influence of the intrinsic capacitances on the drain current is analyzed by dividing the intrinsic device into resistive and capacitive cores [16] as shown in Fig. 1. The currents in the

The authors are with the Department of Electrical and Electronics Engineering, University of Sheffield, Sheffield S37HQ, U.K. (e-mail: npoluri1@sheffield.ac.uk; m.desouza@sheffield.ac.uk).

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TCSII.2018.2810944



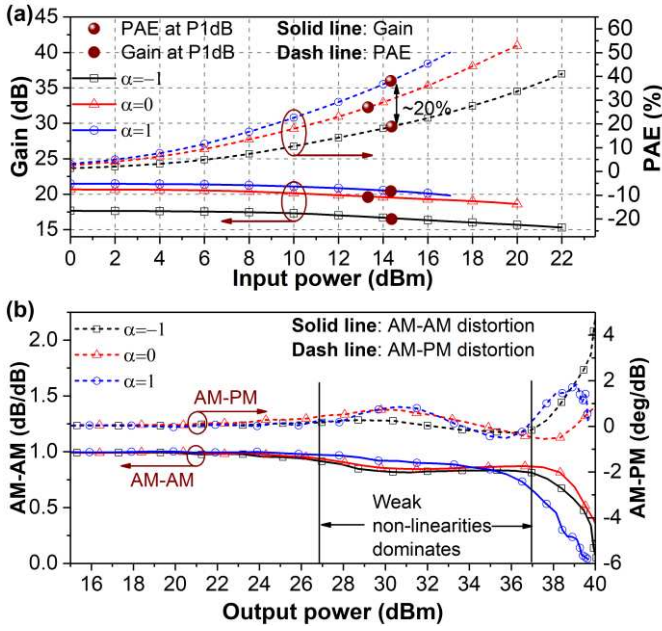


Fig. 3. (a) Gain and PAE as the input power is swept until the minimum of  $V_{dsi}$  grazes the knee voltage, and (b) AM/AM and AM/PM distortion. Both simulated at 2.6 GHz for  $\alpha = -1, 0$  and  $1$  corresponding to classes J\*, B and J respectively

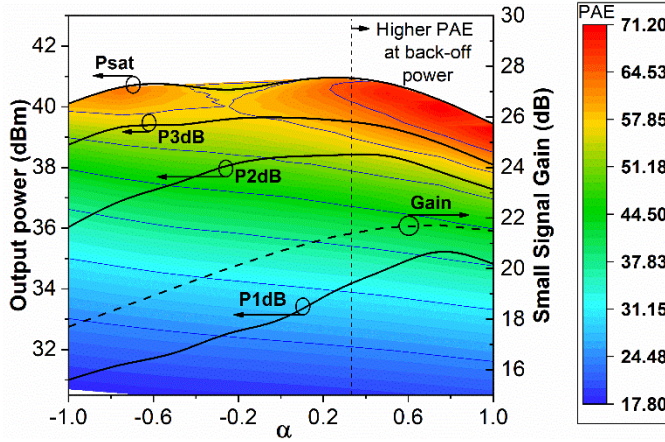


Fig. 4. Simulated P1dB, P2dB, P3dB, Psat (the output power at saturation), and small signal gain for  $-1 \leq \alpha \leq 1$  at 2.6 GHz. Simulated PAE contours as a function of output power and  $\alpha$  are overlaid. The corresponding PAE are indicated by colour.

non-linear  $C_{gs}$  and hence achieved at nearly the same input powers for all values of  $\alpha$ . Since the gain increases with  $\alpha$ , the output power corresponding to 1dB compression (P1dB) increases with  $\alpha$ . The increment in P1dB from  $\alpha = -1$  to  $\alpha = 1$  is 4dB whereas the increment in PAE corresponding to P1dB (PAE at P1dB) is as high as 20%. These provide significant margins of improvement to amplifier designers.

The additional contribution of  $I_{Cgd}$  to the drain current for  $\alpha = 1$  leads to a higher change in output power for a given change of input power, than for  $\alpha = 0$ . Hence AM-AM distortion of class J is lower than for class B (see Fig. 3 (b)). Since the flow of  $I_{Cgd}$  is out of phase with respect to  $I_{dsi}$  for  $\alpha = -1$  (refer Fig. 2 (b) and (c)), the change of phase with input and hence AM-PM distortion is lower for class J\* than for class B, (as shown in Fig. 3 (b)).

The contour plot of PAE with  $\alpha$  and output power in Fig. 4 reveals that PAE at back-off output power increases with  $\alpha$ , due to the increase in gain with  $\alpha$ . The difference in PAE at 5dB back-off output power between classes J\* and J is approximately 6%. The variation of P1dB with  $\alpha$  is greater than that of P2dB, which is greater than P3dB, as seen in Fig. 4. This is because, at higher compression, non-linear effects due to clipping dominate the performance rather than weak non-linearities. It has been shown that clipping of the drain current causes the output power and PAE of the amplifier to remain constant with  $\alpha$  [5]. Consequently, the PAE corresponding to P1dB shows a greater variation than the PAE corresponding to P2dB and P3dB. This observation is in line with literature whereby constant efficiencies over broadband were reported at P2dB [5] or higher compression levels [6], rather than P1dB, while [11] is an exception. In [11], the impedances, which were selected based on extensive load-pull simulations for efficiency near P1dB, in fact, correspond to  $\alpha > 0$  (Fig. 4 in [11]) which corroborates the results of this work.

Furthermore, Fig. 4 reveals that the output power decreases for  $\alpha > 0.5$  even though the power generated by the intrinsic device increases due to increase in drain current with  $\alpha$ . This is because of a reduction of  $R$  and  $|R/X|$  (to less than 1), given in equation (4), causes the power delivered to the load to reduce as  $\alpha$  increases, where  $R$  and  $X$  (shown in Fig. 1) denote the resistance and reactance respectively in parallel with  $C_{ds}$  at the fundamental frequency.

$$R = \frac{R_L}{B^2 + (1 + \alpha B)^2} \cdot \frac{R}{X} = \frac{1}{B(1 + \alpha^2) + \alpha} \quad (4)$$

where  $B = 2\pi f_0 C_{ds} R_L$ .

For  $B < 1$ ,  $|R/X|$  becomes less than 1 for  $\alpha > \alpha_c$ , where,

$$\alpha_c = -\frac{0.5}{B} + \sqrt{\frac{1 - 4B}{4B^2} - 1} \quad (B < 1) \quad (5)$$

For the simulation in Fig. 4,  $B = 0.68$  and  $\alpha_c = 0.26$ . Therefore  $|R/X|$  gradually decreases from 1 at  $\alpha = 0.26$  to 0.5 at  $\alpha = 1$  counteracting the increase in power generated at the intrinsic plane due to the feedback capacitor and voltage gain ( $\delta_f$ ). Hence, the maximum output power and small signal gain are achieved at a balance point between  $\alpha_c$  and 1, in this case  $\alpha \approx 0.65$ . On the other hand,  $|R/X| < 1$  leads to suppression of harmonics of the voltage delivered to the load for  $\alpha > \alpha_c$  [17]. With reducing design frequency (i.e.  $B$ ),  $\alpha_c$  increases whereas the effect of parasitics decreases. For low frequencies ( $B \ll 1$ ), leading to  $R \approx R_L$  and  $|R/X| = |1/\alpha| > 1$ , which implies that the power generated at the intrinsic plane is transferred to the load, independent of  $\alpha$ . This implies that at high frequencies, where  $B$  is close to 1, a subset of the continuum defined by  $\alpha > \alpha_c$  has a constant P1dB and a flat gain response.

Simulated third order intermodulation distortion (IMD3) shows small improvement for  $\alpha > 0.5$  for  $P_{out}$  between 26dBm and 36 dBm, as shown in Fig. 5 (a), because of the lower AM-AM distortion (refer Fig. 3) in this power range, that results in slight improvement in ACPR for average power between 22dBm and 30dBm in Fig. 5 (b). On the other hand, because of the lower AM-PM distortion for  $\alpha < 0$ , (refer Fig. 3), the EVM (Error Vector Magnitude) improves over class B (Fig. 5 (b)).

The higher gain for  $\alpha > 0$  coupled with slight improvement in IMD3 for  $P_{out}$  between 26dBm and 36 dBm, causes PAE corresponding to a given IMD3 (between -30dBc and -20dBc)

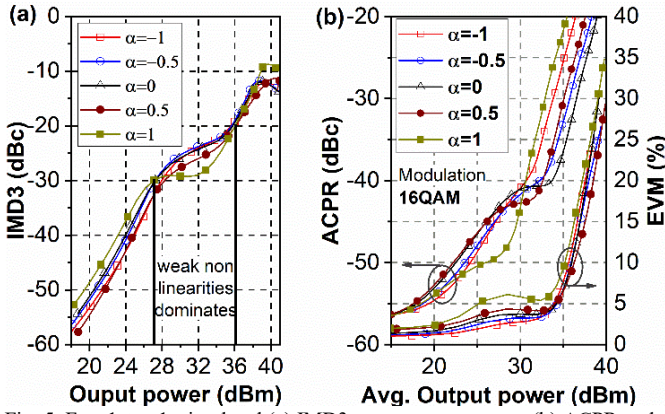


Fig. 5. For  $-1 \leq \alpha \leq 1$ , simulated (a) IMD3 versus output power (b) ACPR and EVM versus average output power for a 16-QAM input signal of peak to average ratio 2dB. Data rate (3.84Mbps) and channel bandwidth (5MHz) are same as in WCDMA.

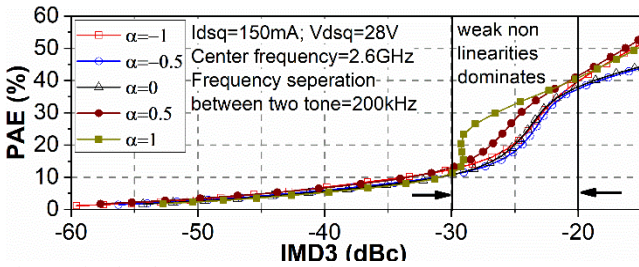


Fig. 6. Simulated PAE versus IMD3 for  $-1 \leq \alpha \leq 1$ .

to improve by 10% and 5% for  $\alpha=1$  and  $\alpha=0.5$  respectively as shown in Fig. 6. For lower IMD3 ( $< -30$  dBc),  $P_{out} < 26$  dBm, PAE is weakly dependent on  $\alpha$  because the drain current is comparable to the bias current and  $I_{Cgd}$  is negligible. Importantly, Figures 4, 5, and 6 reveal that for a set of waveforms in the class B/J continuum, higher P1dB, and higher efficiency at P1dB and at back-off power levels is achievable than class B, without sacrificing IMD3. For the current device, operating at frequency 2.6GHz, this set is defined as  $\alpha \in [0.4, 1]$ . The conclusions of this investigation can be extended to continuous class-F which has a similar variation of the phase of voltage [3].

### III. IMPLEMENTATION AND EXPERIMENTAL RESULTS

#### A. Amplifier design

Based on Fig. 4 an  $\alpha \approx 0.55$  is selected as the optimum value for a high P1dB and efficiency at P1dB without sacrificing the maximum output power. The extrinsic fundamental ( $Z_{L1}$ ) and second harmonic ( $Z_{L2}$ ) impedances for  $\alpha \approx 0.55$  are calculated using the method in section II. The optimal source impedance ( $Z_{S1}$ ) which maximizes P1dB without sacrificing gain, is obtained from source pull simulations of the vendor model. The input and output matching networks are realized using stepped impedance and double stub configurations respectively, as shown in Fig. 7 (a), on a RO4350B substrate of thickness 0.762mm. The output matching network consists of one segment to match  $Z_{L1}$  and another segment to match  $Z_{L2}$ . A parallel RC network in the input matching network is used to ensure unconditional stability [10]. The designed amplifier is shown in Fig. 7 (b).

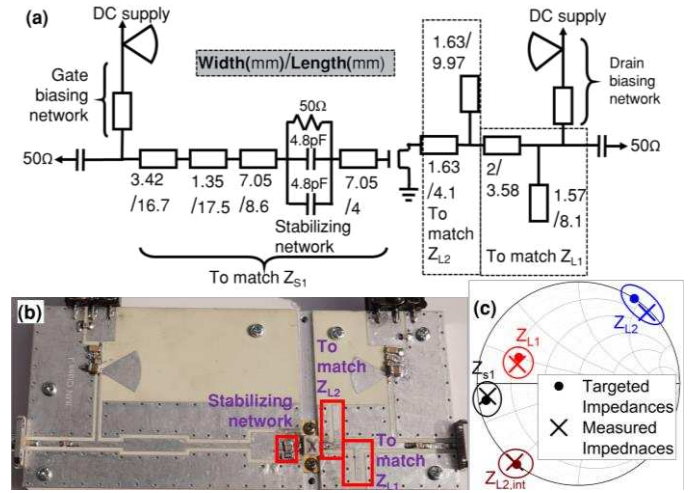


Fig. 7. (a) Schematic of the designed amplifier (b) Photograph of the designed amplifier (c) Measured and targeted source impedances at fundamental frequency ( $Z_{S1}$ ), extrinsic load impedances at fundamental ( $Z_{L1}$ ) and second harmonic frequencies ( $Z_{L2}$ ), and intrinsic load impedances at second harmonic frequency ( $Z_{L2,int}$ )

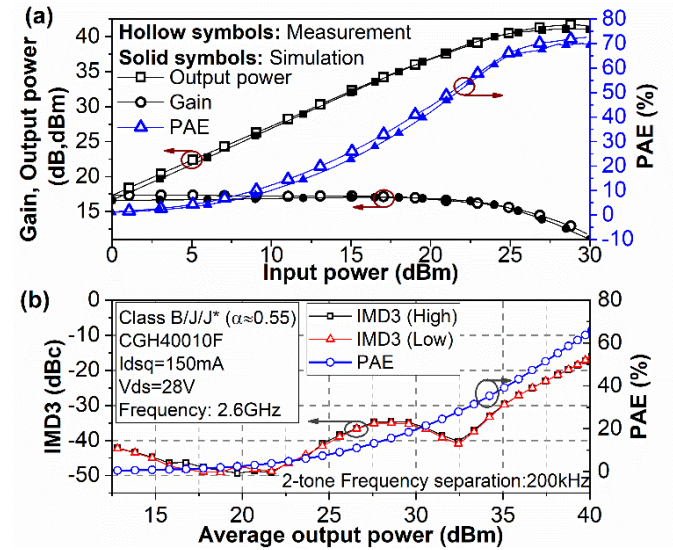


Fig. 8. (a) Measured versus simulated gain, output power and PAE of the designed amplifier. (b) Measured IMD3 and PAE under two-tone excitation centred at 2.6GHz with a frequency separation of 200kHz

#### B. Measurement Results

The fabricated matching networks are measured individually and compared with target values in Fig. 7 (c), which indicates close agreement for  $Z_{S1}$  and  $Z_{L1}$ . The difference between the target and measured  $Z_{L2}$  does not affect the performance of the amplifier as the discrepancy in the corresponding intrinsic impedances ( $Z_{L2,int}$ ), and in turn, in  $\alpha$ , is negligible.

The measured and simulated output power, gain and efficiency of the fabricated class J are plotted in Fig. 8 (a). The peak efficiency achieved is 72.3% and  $P_{sat}$  is 41.72dBm. The output power and efficiency at P1dB are 38.13dBm and 54.7% respectively. Measured IMD3 and PAE with a two-tone signal shown in Fig. 8 (b) reveal that IMD3 remains below -30dBc and -20dBc till 35dBm and 38.7dBm output power respectively and attains PAE of 39% and 58.6% respectively.

The designed amplifier is compared with state-of-the-art

TABLE II  
STATE OF THE ART HIGH EFFICIENCY LINEAR NARROWBAND  
AMPLIFIERS USING CGH40010

Ref.	Mode	Freq. (in GHz)	Peak PAE (%)	Figure of Merit	PAE at P1dB (%)	P1dB (dBm)	Psat (dBm)
[8]	Saturated PA	2.14	77.3	113	42.55*	35.06*	40.6*
[10]	Class J	2.13	64.5	94	47.57*	35.73*	39.7
[17]^	Class J	1.5	87#	106#	55.2#	35.6	39.5*
[18]	Class AB	2.25	45	67.5	32	39	40
<b>This work</b>	<b>Class B/J/J*</b>	<b>2.6</b>	<b>72.3</b>	<b>116</b>	<b>54.7</b>	<b>38.13</b>	<b>41.7</b>

Figure of Merit=Peak PAE\*(Freq. in GHz)<sup>1/2</sup> where Freq. is Frequency  
\*Values are extracted from the figures in the papers; ^ design procedure adopted in [24] does not sacrifice efficiency at the reported frequency whilst achieving broad bandwidth; # Drain efficiency

TABLE III  
COMPARISON OF ACLR/IMD3 AND AVERAGE PAE WITH  
NARROWBAND POWER AMPLIFIER USING CGH40010

Reference	Mode	Freq. (GHz)	ACLR/IM D3 (dBc)	Avg. Output power (dBm)	Avg. PAE (%)
[8]	Saturated PA	2.14	-22.3#	34.2	42.3
<b>This work</b>	<b>Class B/J/J*</b>	<b>2.6</b>	<b>-22.3*#</b>	<b>38.25</b>	<b>55.8</b>
[8]	Saturated PA	2.14	-35#	28	20
<b>This work</b>	<b>Class B/J/J*</b>	<b>2.6</b>	<b>-35*#</b>	<b>28</b>	<b>17</b>
[18]	Class AB	2.25	-21	40	41
<b>This work</b>	<b>Class B/J/J*</b>	<b>2.6</b>	<b>-21</b>	<b>38.3</b>	<b>56</b>

# Bandwidth of input signal is 10MHz. ACLR in [8] is measured at offset 7.5MHz. \* ACLR estimated from measured IMD3 [19] in Fig. 8.

high-efficiency narrowband linear amplifiers using the same device in Table II. Our design shows a higher figure of merit than those reported in terms of output power and PAE at P1dB. The PAE at 5dB back-off is nearly 45%, which is comparable to reported high efficiency at back-off power for the amplifiers with P<sub>sat</sub> close to 40dBm in Table I. As can be seen from Fig. 4, an even higher efficiency can be achieved by choosing a higher value of  $\alpha$  but at the expense of output power and P1dB. A comparison of the fabricated PA with saturated PA, optimized for peak efficiency from [8], in Table III reveals that the designed amplifier achieves PAE lower by 3% at -35dBc ACLR whereas 13% higher PAE is achieved at ACLR of -22.3 dBc than the saturated PA. The designed amplifier achieves 14% higher PAE than class AB at the same IMD3 level as in [18]. This shows that higher efficiencies than class AB and saturated PA can be achieved for a given distortion in the region dominated by the effect of non-linear capacitances, for this device between -30dBc and -20dBc.

#### IV. CONCLUSIONS

A study of the non-linear feedback capacitance shows that the gain, P1dB, and efficiency at back-off power of an amplifier increase from class J\* to class B to class J. This can be attributed to a variation of the phase of the voltage waveforms across its non-linear C<sub>gd</sub>. Based on this knowledge, the trade-off involved with  $\alpha$  are analyzed in this brief. It is shown that a subset of the continuum results in higher PAE at P1dB than Class B (or deep class AB) and these modes can be replaced by the class B/J/J\*, at a higher frequency, without sacrificing

linearity using the methodology presented here. This brief utilizes this hitherto unknown benefit of a remarkable 20% increase in efficiency at P1dB from class J\* to J, to demonstrate a prototype amplifier with 72% PAE, 38 dBm P1dB and 55% PAE at P1dB.

#### V. REFERENCES

- [1] S. C. Cripps, P. J. Tasker, A. L. Clarke, J. Lees, and J. Benedikt, "On the continuity of high efficiency modes in linear RF power amplifiers," *IEEE Microw. Wirel. Components Lett.*, vol. 19, no. 10, pp. 665–667, 2009.
- [2] M. Ozen, R. Jos, and C. Fager, "Continuous class-e power amplifier modes," *IEEE Trans. Circuits Syst. II Express Briefs*, vol. 59, no. 11, pp. 731–735, 2012.
- [3] V. Carrubba, A. L. Clarke, M. Akmal, J. Lees, J. Benedikt, P. J. Tasker, and S. C. Cripps, "On the extension of the continuous class-F mode power amplifier," *IEEE Trans. Microw. Theory Tech.*, vol. 59, no. 5, pp. 1294–1303, 2011.
- [4] T. Sharma, R. Darraji, and F. Ghannouchi, "A Methodology for Implementation of High Efficiency Broadband Power Amplifiers with Second Harmonic Manipulation," *IEEE Trans. Circuits Syst. II Express Briefs*, vol. 63, no. 1, pp. 1–1, 2015.
- [5] P. Wright, J. Lees, J. Benedikt, P. J. Tasker, and S. C. Cripps, "A methodology for realizing high efficiency class-J in a Linear and Broadband PA," *IEEE Trans. Microw. Theory Tech.*, vol. 57, no. 12, pp. 3196–3204, 2009.
- [6] S. Saxena, K. Rawat, and P. Roblin, "Continuous Class-B/J Power Amplifier Using Nonlinear Embedding Technique," *IEEE Trans. Circuits Syst. II Express Briefs*, vol. 1, no. 1, pp. 1–1, 2016.
- [7] K. Mimis, K. A. Morris, S. Bensmida, and J. P. McGeehan, "Multichannel and wideband power amplifier design methodology for 4G communication systems based on hybrid class-J operation," *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 8, pp. 2562–2570, 2012.
- [8] J. Moon, J. Kim, and B. Kim, "Investigation of a class-J power amplifier with a nonlinear Cout for optimized operation," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 11 PART 1, pp. 2800–2811, 2010.
- [9] A. Alizadeh and A. Medi, "A Broadband Integrated Class-J Power Amplifier in GaAs pHEMT Technology," *IEEE Trans. Microw. Theory Tech.*, vol. 64, no. 6, pp. 1–9, 2016.
- [10] K. Mimis, K. A. Morris, and J. P. McGeehan, "A 2GHz GaN Class-J power amplifier for base station applications," in *IEEE Topical Conference on Power Amplifiers for Wireless and Radio Applications (PAWR)*, 2011, pp. 5–8.
- [11] R. Ma, S. Goswami, K. Yamanaka, Y. Komatsuzaki, and A. Ohta, "A 40-dBm high voltage broadband GaN Class-J power amplifier for PoE micro-basestations," *IEEE MTT-S Int. Microw. Symp. Dig.*, pp. 30–32, 2013.
- [12] S. Rezaei, L. Belostotski, F. M. Ghannouchi, and P. Aflaki, "Integrated design of a class-J power amplifier," *IEEE Trans. Microw. Theory Tech.*, vol. 61, no. 4, pp. 1639–1648, 2013.
- [13] N. Tuffly, L. Guan, A. Zhu, and T. J. Brazil, "A simplified broadband design methodology for linearized high-efficiency continuous class-F power amplifiers," *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 6 PART 2, pp. 1952–1963, 2012.
- [14] M. Rasheduzzaman, "Contributing Towards Improved Communications Systems for Future Cellular Networks," PhD thesis, Department of Electronic and Electrical Engineering, University of Sheffield, 2016.
- [15] J. A. Z. Flores, "Device Characterization and Modeling of Large-Size GaN HEMTs," PhD thesis, Department of Electrical Engineering and Computer Science, University of Kassel, Germany, 2012.
- [16] A. Raffo, F. Scappaviva, and G. Vannini, "A New Approach to Microwave Power Amplifier Design Based on the Experimental Characterization of the Intrinsic Electron-Device Load Line," *IEEE Trans. Microw. Theory Tech.*, vol. 57, no. 7, pp. 1743–1752, 2009.
- [17] B. Bukvi and M. I. Milan, "Simple Design of a Class-J Amplifier With Predetermined Efficiency," *IEEE Microw. Wirel. Components Lett.*, vol. 26, no. 9, pp. 699–701, 2016.
- [18] T. Khan and U. Naeem, "10W Power-amplifier design based on passive Load pull," in *17th IEEE International Multi Topic Conference*, 2014, pp. 519–522.
- [19] N. B. Carvalho and J. C. Pedro, "Multi-Tone Intermodulation Distortion Performance of 3rd Order Microwave Circuits," *IEEE MTT-S Int. Microw. Symp. Dig.*, vol. 2, pp. 763–766, 1999.

