A Novel Design Method of Highly Efficient Saturated Power Amplifier based on Self-Generated Harmonic Currents

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***Abstract*— A novel design method without requiring the special harmonic termination circuit for a highly efficient power amplifier (PA) is proposed. The proposed PA is driven into saturated operation, from the linear to knee region, by adjusting the only fundamental load, and the saturated operation induces self-generated harmonic currents. The current and voltage waveforms can be shaped easily by the harmonic currents, and efficiency of the PA is maximized. From the proposed design concept, a PA is implemented using 45-W GaN HEMT device at 2.655 GHz. The designed PA has a maximum drain efficiency of 71.5% at a saturated output power of 46.8 dBm for CW signal. The PA can be linearized to –46 dBc using the WDFBPD technique for a mobile WiMAX 2FA signal.**

I. Introduction

High efficiency of power amplifiers (PAs) is an important design issue because it is directly related to the cost, reliability, and thermal management. Among the highly efficient PA topologies, a class-E PA is the most popular one and operates the active device as a switch but not a gm source. The current and voltage waveforms of the class-E PA do not have any overlap, i.e, no internal power consumption, and provide high efficiency [1]. However, the class-E PA topology suffers from large output capacitance C_{DS} of a high-power device at high frequencies, where the appropriate solution for the zero voltage switching cannot be found.

A class-F PA has been developed to reduce the dissipated power at the device also by minimizing overlap between the current and voltage waveforms, which is accomplished by employing the waveform shaping using an appropriate harmonic control circuit [2]. However, it requires high impedance terminations at the current source for odd harmonics. The terminations are difficult to be realized because the high-order harmonic components are shorted by the large output capacitance C_{DS} of the high-power device. The inappropriate terminations generate a non-ideal waveform shaping, and the efficiency is also degraded.

For highly efficient PAs at a high frequency, the most effective approach is to control the second harmonic control using a simple matching topology. Class-G and class-J PAs increase the fundamental voltage and reduce the overlap between the waveforms through a quasi half-sinusoidal voltage waveform shaping, which is accomplished by the specific second harmonic termination [3], [4].

We have extended the class-G and class-J PA topologies to a new PA topology with a high efficiency. The novel design method induces the saturated operation, driving into saturated region. The saturated operation produces a large amount of the self-generated harmonic current components, which are dependent on the fundamental resistive load. The harmonic control can be easily realizable due to the harmonic currents manipulated by the load. This design method has been employed to construct 10-W saturated PA with a PAE of approximately 75% at 2.655 GHz [5]. In this paper, we have designed the saturated PA using a 45-W high-power device which has a four times large output capacitance, and explored the operational behavior for the high-power device. The efficiency and nonlinearity of the PA are also investigated using CW and mobile WiMAX 2FA signals. It is demonstrated that the proposed design method is well suitable for high-power/efficiency PA topology.

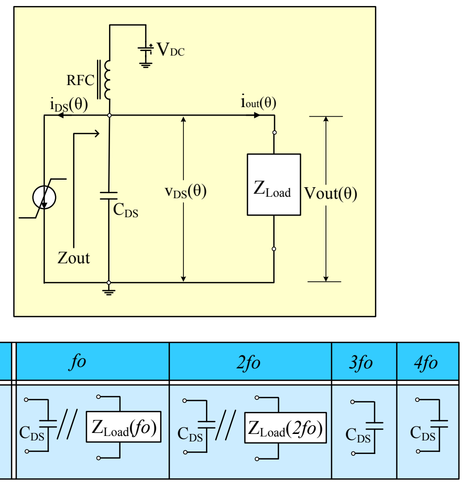
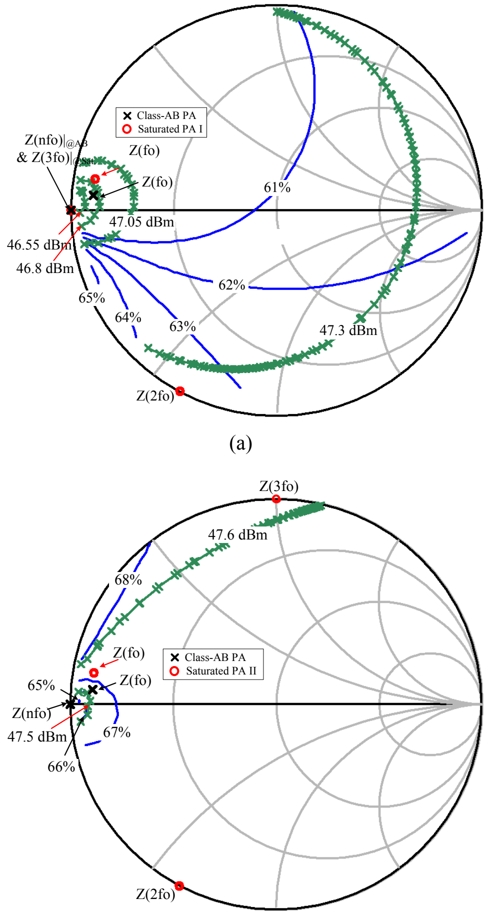


Fig. 1. Simplified schematic diagram and output load impedances of the proposed saturated power amplifier.

II. Operational Behavior and Design Method

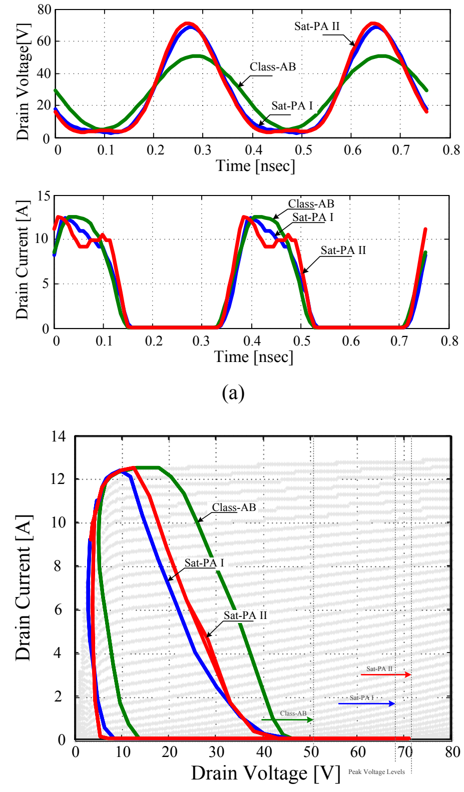
A design method of a saturated PA, that can be realized by a simple harmonic termination topology and deliver a high efficiency, is described. Fig. 1 shows the simplified schematic diagram of the proposed saturated PA. In this design, the fundamental resistive load controls the amplitude and phase of self-generated harmonic currents. With the appropriate choice of the load, the desired voltage waveform can be generated by the harmonic load mainly of C_{DS} fine-tuned by an additional



(a)

(b)

Fig. 2. Loadpull contours of the output power and PAE, and fundamental load and harmonic impedances for the class-AB and saturated PAs. (a) Second order impedance. (b) Third order impedance.



(a)

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Fig. 3. Simulated: (a) time-domain current and voltage waveforms and (b) load lines of the class-AB and saturated PAs.

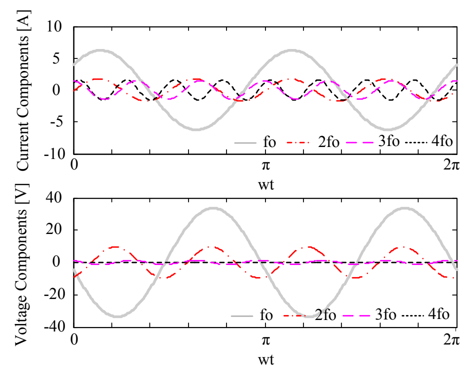


Fig. 4. Simulated fundamental and harmonic waveforms of the saturated PA II.

load. Therefore, the added harmonic impedances have a high tolerance. The output capacitance creates like a short circuit at high-order harmonic frequencies. In the saturated operation, the PA generates a large amount of the self-generated harmonic currents, which can be utilized for the waveform shaping. The currents at the current source of the device are expressed as

$$i_{\mathrm{DS}}(\theta) \quad = \quad I_{\mathrm{DC}} + I_1 \cos(\theta + \alpha_1) + \sum_n I_n \cos(n\theta + \alpha_n) \tag{1}$$

where

$$\sum_n I_n \cos(n\theta + \alpha_n) = f\left[Z_{\mathrm{L}}(f_0)\right]$$

and I_{DC}, I_1, and I_n are the dc, fundamental, and harmonic current amplitudes, respectively, and α_1 and α_n are the fundamental and harmonic current phases, respectively. $Z_{\mathrm{L}}(f_0)$ is the fundamental load impedance to generate the harmonic currents. Since the harmonic voltages at the current source of the device depends on the harmonic impedances, the voltage components are given by

$$V_n \angle \beta_n \quad = \quad Z_{\mathrm{L}}(nf_0) I_n \angle \alpha_n \tag{2}$$

where V_n and β_n are the harmonic voltage amplitude and phase, respectively. $Z_{\mathrm{L}}(nf_0)$ are harmonic load impedances. The self-generated currents create the fundamental and harmonic voltages described in [3]. As a result, the current and voltage waveforms become quasi rectangular and half-sinusoidal, respectively, similar to the class-F^{-1} waveforms. These shaped waveforms minimize the overlap between the current and voltage waveforms, and efficiency of the PA is maximized.

The saturated PAs are designed using the Cree CGH40045 device model in the ADS simulator. Fig. 2 illustrates the loadpull contours of the output power and PAE according to the second and third harmonic impedances for the designed fundamental load. The second and third harmonic impedances that can provide the high efficiency are widely located so that the harmonic load impedances after C_{DS} can be easily achieved. The saturated PA I is designed with the fundamental load and the second harmonic termination of –j30 Ω. Moreover, to explore the saturated PA for the third harmonic termination shown in Fig. 2(b), the saturated PA II is designed

TABLE I

SIMULATED PERFORMANCES FOR THE DESIGNED PAS

	P_{out} [dBm]	Drain Efficiency [%]	PAE [%]	V_P [†] [V]	I_P [‡] [A]
Class-AB Amp.	47.9	55.3	52.5	50.9	12.5
Saturated Amp. I	47.4	68.9	63.7	68.5	12.4
Saturated Amp. II	47.6	72.8	67.6	71.2	12.5

[†] V_P is the peak voltage.
[‡] I_P is the peak current.

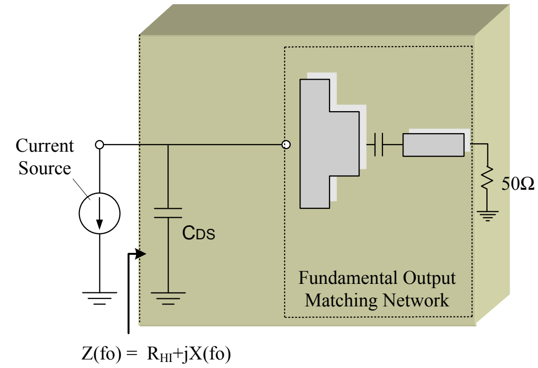
with the third harmonic of j50 Ω along with the fundamental load and second harmonic termination of the saturated PA I. In the saturated PA design, the fundamental load and harmonic impedances induce both quasi half-sinusoidal voltage with an additional voltage peaking of 20 V and quasi rectangular current shapings, as shown in Fig. 3(a). The load line trajectory of the class-AB PA is changed to a load line trajectory with the saturated operation including the knee region, as depicted in Fig. 3(b). The current waveform can be built by the third and fourth harmonic components which have almost the same amplitude compared to the second harmonic amplitude, and the voltage waveform can be constructed by the second and third harmonic components, while maintaining the appropriate phase relationships, as shown in Fig. 4. Also, it is worth while to be notice that the fundamental components of voltage and current are exactly 180° off, indicating that the fundamental load is purely resistive. The drain efficiency improvement greater than 15% is achieved by the proposed design method, and the simulated performances are summarized in Table. I.

III. IMPLEMENTATION AND EXPERIMENTAL RESULTS

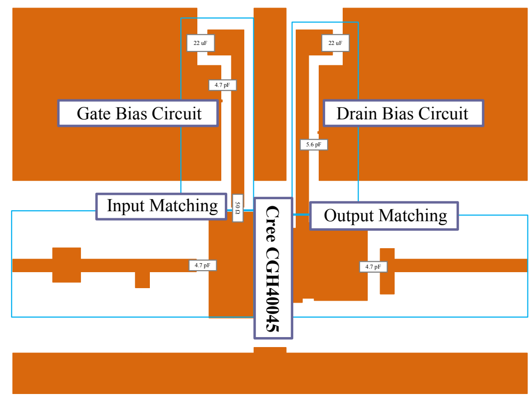
Based on the analysis and design in Section II, the proposed PA is implemented using the same device for 2.655-GHz mobile WiMAX application. The output matching circuit is realized on the fundamental impedance matching, as shown in Fig. 5(a), because the self-generated harmonic currents mainly depend on the fundamental impedance and then harmonic terminations have a large tolerance for the harmonic control. The PCB layout of the proposed saturated PA is shown in Fig. 5(b). The PA is biased at I_{DSQ} = 0.2 A and a drain voltage of 28 V (deep class-AB bias). The measured and simulated results are similar, and the PA delivered a maximum drain efficiency of 71.5% at saturated output power of 46.8 dBm, as shown in Fig. 6. Fig. 7 illustrates the measured output power, drain efficiency, and PAE over frequencies. The drain efficiency greater than 70% is obtained over approximately 100 MHz between 2.6 GHz and 2.7 GHz, and the output power is decreased as the frequency is increased.

Compared to comparable high-power PAs using a packaged GaN HEMT, operating at the frequency of 2 GHz–3 GHz and producing the saturated output power of 30 W–100 W, the proposed PA delivers a high efficiency performance at a high operating frequency without having any harmonic control circuit and special device fabrication [9]. The performances are compared to the published data in Table II.

To demonstrate the potential of the proposed PA as a main block of a wideband linear PA system, we have employed the wideband digital feedback predistortion (WDFBPD) technique for mobile WiMAX 2FA signal with 20 MHz bandwidth and 8.5 dB PAPR at the 0.01% level of the CCDF [10].



(a)



(b)

Fig. 5. (a) Simplified schematic diagram of the proposed output matching network and (b) PCB layout of the proposed saturated power amplifier.

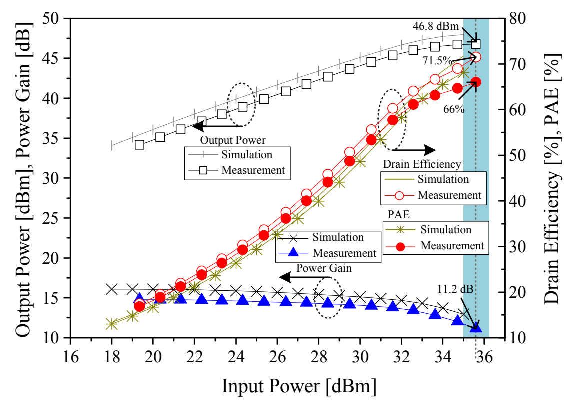


Fig. 6. Measured and simulated output power, drain efficiency, PAE, and power gain for 2.655-GHz CW signal.

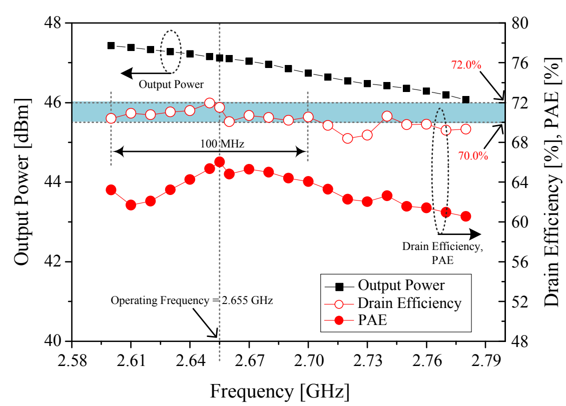


Fig. 7. Measured output power, drain efficiency, and PAE as a function of frequency.

TABLE II

PERFORMANCE COMPARISON WITH REPORTED COMPARABLE PAs USING A PACKAGED GaN HEMT DEVICE

Refs	f_o* [GHz]	P_{sat} [W]	DE† [%]	Class	Drain Voltage [V]
[6]	2.000	48	68.0	B	40
[7]	2.140	100	61.4	AB	48
[8]	2.800	100	58.0	AB	50
[9]‡	2.140	100	75.0	E	50
This work	2.655	47.9	71.5	Sat.	28

*f_o denotes the operating frequency.
†DE denotes the drain efficiency.
‡PA is optimized by the internal circuit in the package.

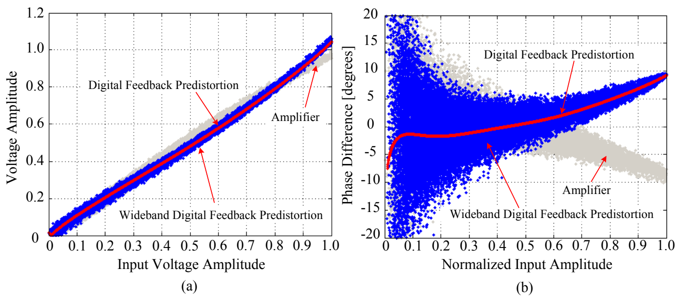


Fig. 8. Measured predistorted signals of the DFBPD and WDFBPD techniques and amplifier output signal before linearization for the mobile WiMAX 2FA signal. (a) AM/AM. (b) AM/PM.

Fig. 8 illustrates the AM/AM and AM/PM characteristics before linearization and after predistortion by the DFBPD and WDFBPD techniques. The DFBPD technique provides the memoryless PD signal, while the WDFBPD technique generates the memory PD signal which linearizes the instantaneous nonlinearity of the PA. Fig. 9 shows the measured WiMAX 2FA spectra before and after DFBPD and WDFBPD linearization at an average output power of 38 dBm. The ACLR at an offset of 5.32 MHz and RCE for the WDFBPD technique is approximately –46 dBc and –38 dB, respectively, which are an improvements of approximately 14 dB and 8 dB, and then the drain efficiency is 30%. The measurement results are summarized in Table III.

IV. CONCLUSION

A novel design method for a highly efficient PA is developed. The PA is driven into a saturated region by a fundamental resistive load to generate appropriately phased harmonic currents. Due to the self-generated harmonic current,

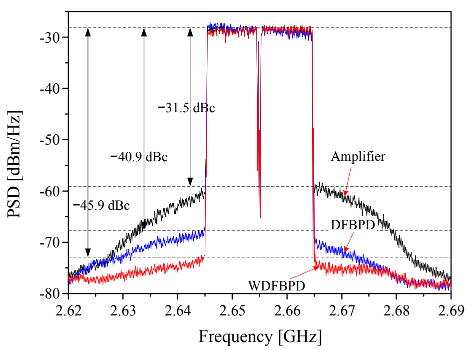


Fig. 9. Measured mobile WiMAX 2FA spectra of amplifier output signals.

TABLE III

MEASURED PERFORMANCE BEFORE AND AFTER LINEARIZATIONS AT AN AVERAGE OUTPUT POWER OF 38 dBm (30%) FOR WiMAX 2FA SIGNAL

	ACLR [dBc] at –/+ 5.32 MHz	ACLR [dBc] at –/+ 6.05 MHz	RCE [dB]
Amplifier	–33.0/ –31.5	–33.9/ –32.2	–29.8
DFBPD + Amp.	–40.9/ –42.2	–41.1/ –43.3	–35.9
WDFBPD + Amp.	–45.9/ –47.0	–46.5/ –47.1	–38.2

the waveform shaping is possible with the fundamental output matching circuit and large C_{DS}. Based on the design concept, the saturated PA is implemented at 2.655 GHz, delivering a drain efficiency of 71.5% at a saturated output power of 46.8 dBm for a CW signal. The proposed design method is very useful to achieve high-power/efficiency PA at a high frequency.

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REFERENCES

[1] N. O. Sokal and A. D. Sokal, "Class-E: A new class of high-efficiency tuned single-ended switching power amplifiers," *IEEE J. Solid-State Circuits*, vol. SC-10, pp. 168–176, Jun. 1975.

[2] F. H. Raab, "Class-F power amplifiers with maximally flat waveforms," *IEEE Trans. Microw. Theory Tech.*, vol. 45, no. 11, pp. 2007–2012, Nov. 1997.

[3] P. Colantonio, F. Giannini, G. Leuzzi, and E. Limiti, "Multi harmonic manipulation for highly efficient microwave power amplifiers," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 11, no. 6, pp. 366–384, 2001.

[4] S. C. Cripps, *RF Power Amplifiers for Wireless Communications*. Norwood, MA: Artech House, 2006.

[5] J. Kim, J. Moon, J. Kim, and B. Kim, "Efficiency optimized saturated power amplifier operation using self-generated harmonic currents," unpublished.

[6] T. Kikkawa, M. Nagahara, N. Adachi, S. Yokokawa, S. Kate, M. Yokoyama, M. Kanamura, Y. Yamaguchi, N. Hara, and K. Joshin, "High-power and high-efficiency AlGaN/GaN HEMT operated at 50 V drain bias voltage," in *IEEE Radio Frequency Integrated Circuits (RFIC) Symp. Dig.*, Jun. 2003, pp. 167–170.

[7] R. Vetury, Y. Wei, D. S. Green, S. R. Gibb, T. W. Mercier, K. Leverich, P. M. Garber, M. J.Poulton, and J. B. Shealy, "High power, high efficiency, AlGaN/GaN HEMT technology for wireless base station applications," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Jun. 2005, pp. 487–490.

[8] A. Maekawa, M. Nagahara, T. Yamamoto, and S. Sano, "A 100 W high-efficiency GaN HEMT amplifier for S-band wireless system," in *Proc. European Gallium Arsenide and Other Semiconductor Application Symp.*, Oct. 2005, pp. 497–500.

[9] N. Ui and S. Sano, "A 100W class-E GaN HEMT with 75% drain efficiency at 2GHz," in *Proc. European Microwave Conference*, Sep. 2006, pp. 72–74.

[10] J. Kim, Y. Y. Woo, J. Moon, and B. Kim, "A new wideband adaptive digital predistortion technique employing feedback linearization," *IEEE Trans. Microw. Theory Tech.*, vol. 56, no. 2, pp. 385–392, Feb. 2008.