Hybrid EER transmitter using Highly Efficient Saturated Power Amplifier for 802.16e Mobile WiMAX application

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***Abstract*— We have demonstrated a highly efficient Hybrid Envelope Elimination and Restoration transmitter for IEEE 802.16e Mobile WiMAX application using a highly efficient saturated Power amplifier (PA). For the optimum H-EER operation, the PA has been designed to have a maximum PAE at the average V_{ds} region by using 10 W (P_{3dB}) GaN High Electron Mobility Transistor. The maximum Power-added efficiency (PAE) is a 74.07 % at the 14 V V_{ds}. The bias modulator designed using a Hybrid Switching Amplifier (HSA) has a 73.3 % of efficiency. In the interlock experiment, the transmitter has shown an excellent PAE performance of 45.9 % at an average output power of 33.07 dBm with drain efficiency (DE) of 48.86 %. By using digital predistortion technique, the Relative Constellation Error (RCE) has been satisfied the specification of –30 dB with –36.88 dB. When considering the saturated PA with constant drain bias, the average PAE of the proposed transmitter has been hugely improved, about 13.64 %. These results clearly show that the H-EER transmitter using the saturated PA can deliver the excellent PAE performance.**

I. Introduction

Modern wireless communication systems usually apply the time-varying envelope modulation schemes, such as QPSK and QAM, to achieve higher spectrum efficiency. For the high peak-to-average power ratio (PAPR) in these modulation signals, it is hard to achieve the high efficiency and linearity at the same time. Recently, it is shown that the hybrid envelope elimination and restoration (H-EER)/polar transmitter can be a solution when the digital predistortion technique is assisted [1]. For the maximum efficiency of the transmitter, a highly efficient power amplifier (HEPA) is very important. The HEPA is generally designed using a switch or saturated mode power amplifier (PA), such as D, E, F, and F^{-1}. But the large size power device for the base station application has a large C_{ds} capacitance, and it is very difficult to obtain the high impedance required harmonic frequencies. On the other hand, the class-J and class-G topology reported by S. C. Cripps [2], and P. Colantonio [3], respectively, have employed the harmonic control circuit including the device's output capacitance. The class-J is designed with a simple 2nd harmonic control and is easily realizable at a high frequency, but it provides a moderate efficiency comparable to that of an ideal class-B PA. The class-G delivers a high efficiency with proper 2nd and 3rd harmonic terminations, but the power density is reduced.

In this paper, a new saturated PA [4], which is similar to the class-G approach, can be achieved a highly efficient H-EER transmitter shown in Fig. 1. For the verification, the

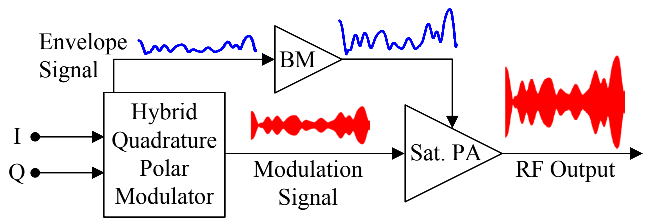


Fig. 1. Architecture of Hybrid EER(H-EER) transmitter.

802.16e Mobile World Interoperability for Microwave Access (WiMAX) signal with 8.5 dB peak-to-average power ratio (PAPR) is used.

II. Design of Saturated Power Amplifier for H-EER Operation

For the proper waveform shaping of the saturated PA, enough harmonic voltage have to be generated at the current source. Since the harmonic voltage components are dependent on the harmonic load impedances, the components are defined as

$$V_n\angle\beta_n = Z_L(nf_0)I_n\angle\alpha_n \quad (1)$$

V_n and I_n are the harmonic voltage and current amplitudes and β_n and α_n are the fundamental and harmonic voltage and current phases, respectively. $Z_L(nf_0)$ is the harmonic load impedances. When the PA is driven into the saturated state for the high PAE with an acceptable power gain, it generates large amounts of harmonic component currents. Due to the large self-generated harmonic currents, the saturated PA can use low enough harmonic loading circuit for the voltage waveform shaping. With the complex fundamental load impedance appropriately determined for the maximum efficiency, the harmonic voltages can be shaped through the C_{ds} with a miner help. The maximum PAE performance with reasonable peak power can be achieved for a broad impedance range of the harmonics. Accordingly, the proposed PA has a very simple architecture with a high tolerance [4]. The simulated load lines and time-domain waveforms are shown in Fig. 2. By employing the proper 2nd and 3rd harmonic terminations, the saturated PA has been shown a half-sinusoidal voltage and a quasi-rectangular current waveform similar to class-F^{-1}. The simulation results including knee effect have been shown that

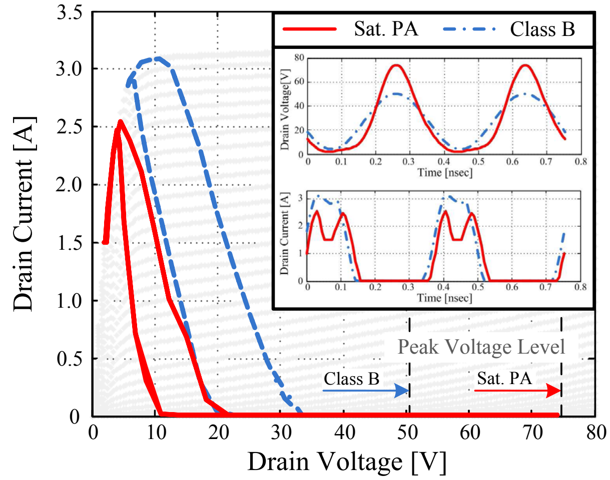


Fig. 2. Simulated load lines, time-domain current and voltage waveforms of Class B and saturated PA.

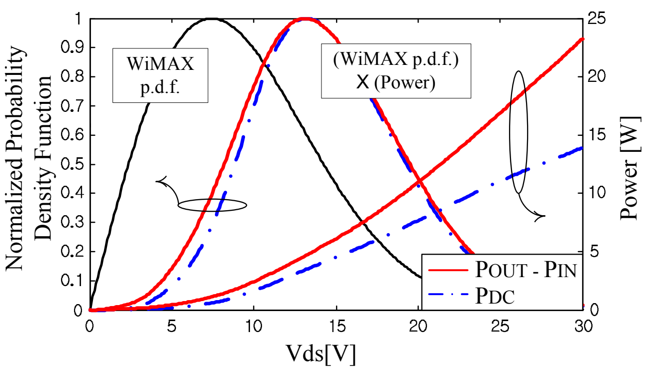


Fig. 3. Probability density function and power distribution versus V_{ds} of the H-EER transmitter.

the saturated PA has 78 % of efficiency compared with a class-B with 63 % of efficiency.

The saturated PA has been designed at 2.655 GHz for the Mobile WiMAX signal using Cree's 10 W (P_{3dB}) GaN HEMT device, and the gate bias for the PA was set to –2.14 V (I_{DQ}=167 mA). For the proper harmonic termination, the decoupling capacitance and quarterwave bias line with the fundamental output matching network has been optimized. For the optimum H-EER operation, the proposed PA has been re-designed to have maximum PAE at the average V_{ds} region. In Fig. 3, the calculated power added probability density function (PDF) is illustrated [5]. The measured performance under H-EER operation for CW signal is summarized in Fig. 4. By minimizing nonlinear C_{ds} mismatch, the output power and power gain at the average V_{ds} region has been significantly increased. The proposed PA has 74.07 % of PAE at the 14 V V_{ds}, which is the 40.5 % improvement over the PA optimized at the peak V_{ds}.

III. Implementation of the Bias Modulator for Mobile WiMAX signal

The bias modulator has been implemented using a hysteretic controlled hybrid switching amplifier(HSA) [1]. The HSA has a high efficiency because the most of current is supplied by the highly efficient current source, DC–DC buck converter, and the voltage signal is linearly amplified by the voltage source. The

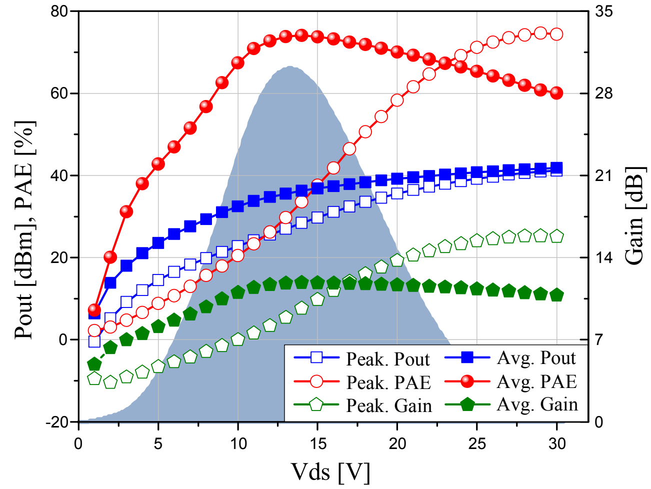


Fig. 4. Characteristics of the saturated PAs for CW signal.

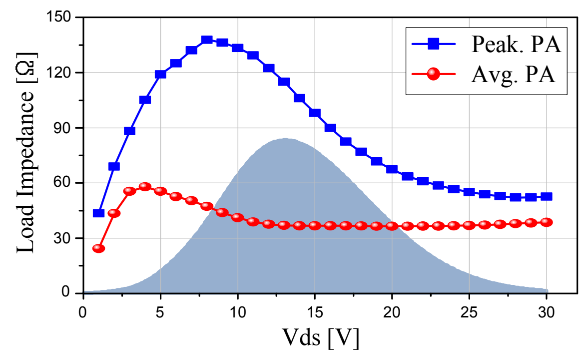


Fig. 5. Measured load resistances of the bias modulator versus V_{ds} for each PA.

calculated load impedance of the HSA is presented in Fig. 5, and the measured efficiency are summarized in the Table I. Its peak output voltage is 30 V and a 73.31 % of efficiency has been obtained for the envelope signal with 8.5 dB PAPR. The output spectra and time-domain waveforms are depicted in Fig. 6. It has been shown enough bandwidth up to 8.75 MHz for the linear drain bias modulation of the saturated PA.

IV. The Interlock Experiment

The hybrid EER transmitter has been evaluated for the 802.16e Mobile WiMAX signal with 5 MHz signal bandwidth. For interlock experiment of the H-EER transmitter, Agilent's E8267D and E4438C have been used as master and slave units, respectively, for the baseband and RF signal generators. The source signals are generated by the Agilent's Advanced Design System simulator. The measured results are summarized in Table II. The H-EER transmitter using the PA optimized at the average V_{ds} region has an output power of 33 dBm with a PAE

TABLE I
Summarized Performance of the Hybrid Switching Amplifier for IEEE 802.16e Mobile WiMAX envelope signal with 8.5 dB PAPR

R_{LOAD}	V_{PEAK}	P_{OUT}	P_{DC}	$Eff.$
37.2 Ω	30 V	2.952 W	4.027 W	73.31 %

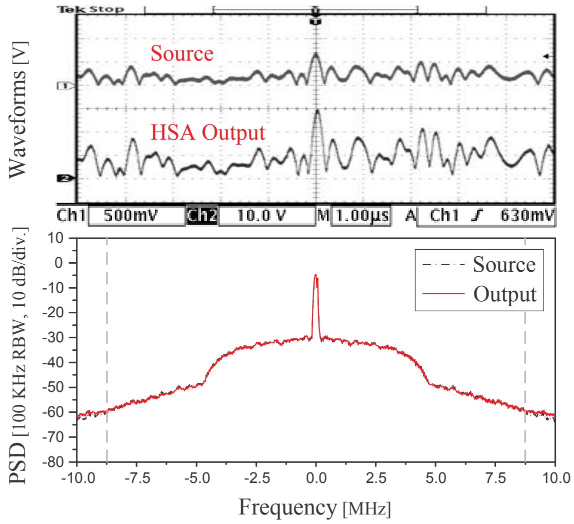
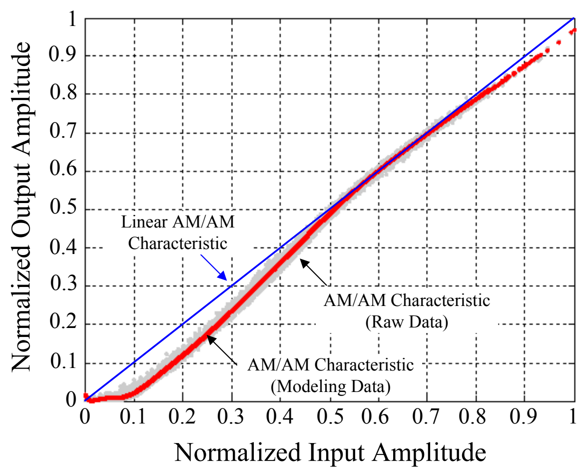
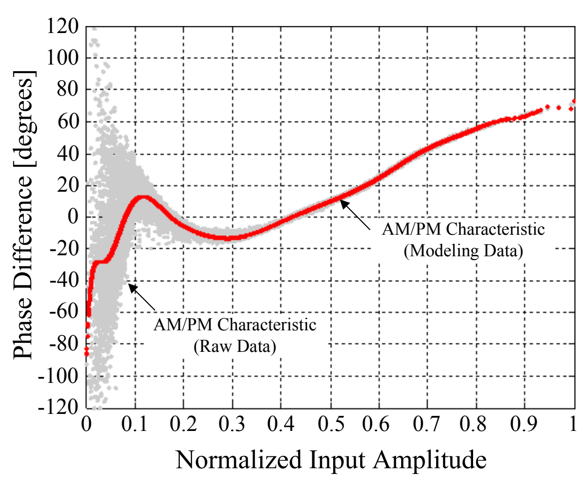


Fig. 6. Time-domain waveforms and output spectra of the bias modulator for IEEE 802.16e Mobile WiMAX envelope signal.



(a)



(b)

Fig. 7. Measured : (a) AM/AM and (b) AM/PM characteristics of the H-EER transmitter at an average output power of 33 dBm.

TABLE II

SUMMARIZED PERFORMANCES OF THE H-EER TRANSMITTER USING DIFFERENT PAS FOR IEEE 802.16e MOBILE WIMAX SIGNAL WITH 8.5 dB PAPR

–	$[Peak.PA]$ $HEER$ $beforeDPD$	$[Avg.PA]$ $HEER$ $beforeDPD$	$[Avg.PA]$ $HEER$ $afterDPD$
P_{OUT}	$31.19\ dBm$	$33\ dBm$	$33.07\ dBm$
$Gain$	$9.9\ dB$	$11.57\ dB$	$12.17\ dB$
DE	43.5 %	50.94 %	48.86 %
PAE	39 %	47.39 %	45.9 %
$ACLR$ @$3.572MHz$	–15.9 dBc	–13.7 dBc	–39.1 dBc
RCE	–16.1 dB	–13.5 dB	–36.88 dB

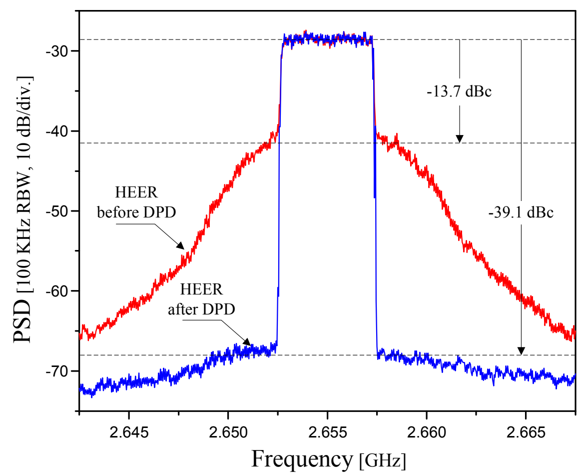
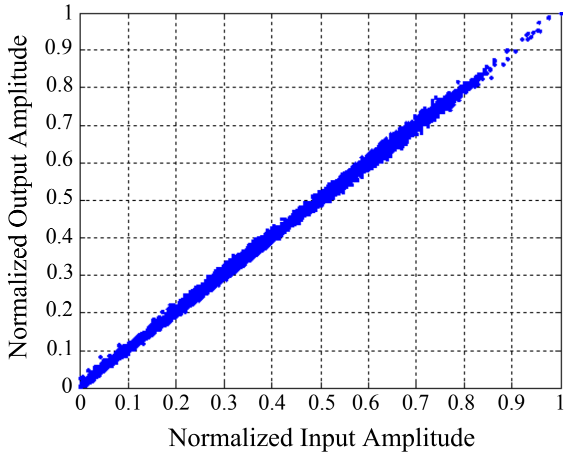


Fig. 8. Measured Output spectra of the H-EER transmitter before and after the linearization for IEEE 802.16e Mobile WiMAX signal.

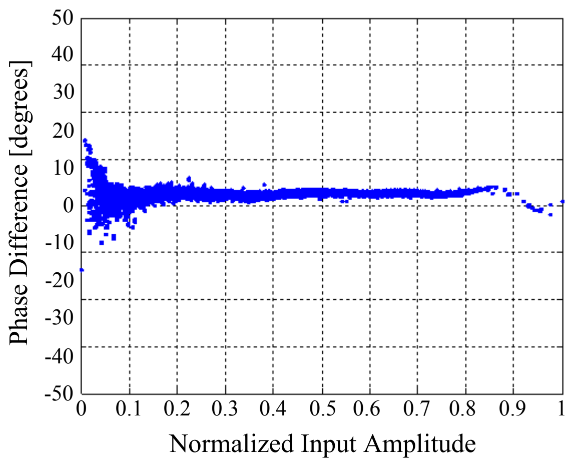
of 47.39 % before linearization. When considering the transmitter using the PA optimized at the peak V_{ds}, a 1.8 dB, 8.4 % of output power and PAE has been successfully improved, respectively. The AM/AM and AM/PM characteristics of the transmitter using the proposed PA optimized at the average V_{ds} region are investigated in Fig. 7. The gain compression has been mainly shown at the low power level in Fig. 7(a). A little saturated operation at the high power region has been shown as expected. The serious AM/PM characteristic due to the saturated operation is illustrated in Fig. 7(b).

The relative constellation error (RCE) performance before linearization is –13.5 dB. To satisfy RCE specification, we have linearized the H-EER transmitter by applying digital feedback predistortion (DFBPD) technique with a simple and fast convergence algorithm [6]. The measured output spectra before and after the linearization are shown in Fig. 8. The ACLR at an offset of 3.572 MHz has been measured to be –39.1 dBc, which is an improvement of approximately 25.4 dB at an average output power of 33.07 dBm with PAE of 45.9 %. After the linearization, the H-EER transmitter has been successfully satisfied the RCE specification of –30 dB with –36.88 dB. The linearized AM/AM and AM/PM characteristics are illustrated in Fig. 9, and the Fig. 10 shows the constellation diagram before and after the linearization.

Table III summarizes a comparison of this work. The H-



(a)



(b)

Fig. 9. Measured : (a) AM/AM and (b) AM/PM characteristics of the transmitter after linearization at an average output power of 33.07 dBm.

EER transmitter using the saturated PA has 5.51 % and 6.32 % enhanced drain efficiency (DE) and PAE, respectively, than the H-EER transmitter using F^{-1} PA under the same backed off output power level [5]. Considering the unit PA with constant drain bias operation, a 13.64 % of PAE has been successfully improved. These results clearly show that the highly efficient H-EER transmitter can be realized by using the proposed PA.

V. Conclusions

In this paper, we have demonstrated the highly efficient H-EER transmitter using the proposed saturated PA for IEEE 802.16e Mobile WiMAX application. The saturated PA has been implemented using the Cree's 10 W (P_{3dB}) GaN HEMT device at 2.655 GHz, and has been optimized at the average V_{ds} region for the optimum H-EER operation. The HSA has been implemented as a bias modulator and the 73.3 % of efficiency has been obtained. For the interlock experiment, the transmitter has shown the excellent PAE performance of 45.9 % at an average output power of 33.07 dBm with drain efficiency (DE) of 48.86 %. By using DFBPD, the Relative Constellation Error (RCE) has been successfully satisfied the specification of –36.88 dB. These results clearly show that the H-EER transmitter can deliver the excellent PAE performance by using the proposed PA.

TABLE III
Performance comparison of the H-EER Transmitters

–	[ref.[5]] [Avg.PA] HEER afterDPD	[Thiswork] [Peak.PA] alone	[Thiswork] [Avg.PA] HEER afterDPD
Signal @frequency	WCDMA @ 1 GHz	WiMAX @ 2.655 GHz	WiMAX @ 2.655 GHz
Bandwidth	5 MHz	5 MHz	5 MHz
PAPR	9.8 dB	8.5 dB	8.5 dB
PA	F^{-1}	Sat.PA	Sat.PA
Back−off	8.8 dB	7.83 dB	8.76 dB
DE	43.35 %	32.65 %	48.86 %
PAE	39.58 %	32.26 %	45.9 %
EVM	1.47 %	6.77 %	1.43 %

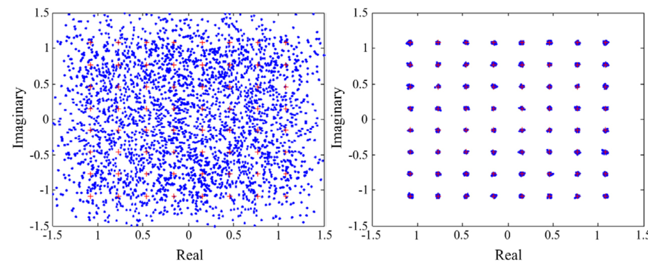


Fig. 10. Measured signal constellation diagrams of the H-EER transmitter before(left) and after(right) linearization.

Acknowledgements

The authors would like to thank to Cree Inc. for providing the GaN HEMT transistors used in this work. This work was supported by the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korea government (MOST) (No. R01-2007-000-20377-0), the Ministry of Knowledge Economy, Korea, under the ITRC(Information Technology Research Center) support program supervised by the IITA(Institute of Information Technology Advancement)" (IITA-2008-C1090-0801-0037), and partially sponsored by ETRI SoC Industry Promotion Center, Human Resource Development Project for IT SoC Architect.).

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