Doherty Amplifier with Envelope Tracking for High Efficiency

Junghwan Moon[1], Junghwan Son[1], Jungjoon Kim[1], Ildu Kim[1],
Seunghoon Jee[1], Young Yun Woo[2], and Bumman Kim[1]

[1]*Department of Electrical Engineering, Pohang University of Science and Technology (POSTECH), Gyeongbuk, 790-784, Republic of Korea, Tel: +82-54-279-5584, Fax: +82-54-279-8115*
E-mail: {jhmoon, bmkim}@postech.edu
[2]*Network Systems Division, Samsung Electronics Co., LTD, Suwon, Gyeonggi, Republic of Korea*

***Abstract*— A Doherty amplifier assisted by a supply modulator is presented using 2.14 GHz GaN HEMT saturated power amplifier (PA). A novel envelope shaping method is applied for high power-added efficiency (PAE) over a broad output power range. Experimental comparison with the Doherty and saturated PAs with the supply modulator is carried out. For the 8 dB crest factor WCDMA 1FA signal, the Doherty PA supported by the modulator presents the improved PAE over the broad output power region compared to the standalone Doherty PA. In addition, it achieves better PAE than the saturated PA with the supply modulator due to the lower crest factor envelope signal applied to the Doherty PA. At the maximum average output power, back-off by 8 dB from the peak power, the Doherty amplifier employing bias adaptation shows the PAE of 50.9%, while the comparable saturated PA with supply modulator and standalone saturated Doherty amplifier and saturated PA provide the PAEs of 42.3%, 49.7%, and 35.0%, respectively.**

***Index Terms*— Bias adaptation, Doherty amplifier, envelope tracking, saturated power amplifier.**

I. Introduction

High efficiency is an important design issue for power amplifiers (PAs), reducing the system size, lowing cost, and improving reliability. It is challenging to maintain a high efficiency during operation over the wide instantaneous dynamic range of the signal required for modern wireless communication signals such as WCDMA and LTE, or over the broad average power range for both mobile and base-station applications, while meeting the stringent linearity requirement of the systems [1], [2]. Recently, to provide a high efficiency at the back-off region, the Doherty PA and envelope tracking (ET)/envelope elimination and restoration (EER) transmitter become the most popular architectures. Doherty amplifier shows a good efficiency at the back-off power level, but the high efficiency is restrained around the 6 dB back-off region [3]. In ET/EER architecture, efficiency drop of the PA at a low supply voltage and inefficient operation of the supply modulator for the high crest factor signal limit the high efficiency operation for the wide instantaneous power range or broad average power level [4], [5].

In our early work on the Doherty ET transmitter [4], we have demonstrated the high efficiency capability of the transmitter for the mobile application. However, since the signal used in the work has a large crest factor of 10.75 dB, the efficiency degradation caused by the peaking PA is not considered. For the signal with a crest factor of more than

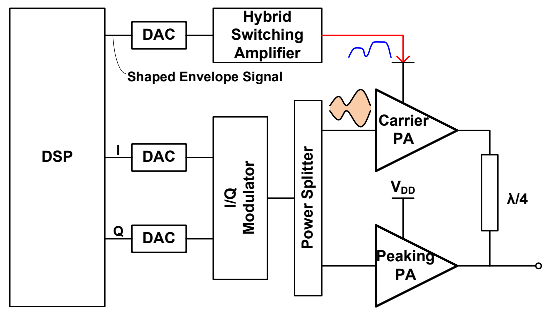


Fig. 1. Block diagram of the saturated Doherty amplifier with supply modulator.

10 dB, above 98 percentage RF power of the Doherty PA is generated by the carrier PA even at the maximum average output power. Moreover, although the envelope signal shaping method in [4], depicted in Fig. 5, prevents the serious nonlinearity generated by the operation below or near the knee region, it does not consider the gain degradation problem caused by the low supply voltage, which is directly related to a drop of the PAE. In this paper, the Doherty ET transmitter is implemented and optimized for the base-station application. To verify the highly efficient operation of the transmitter when the peaking PA affects the overall efficiency of the Doherty PA, the moderate crest factor signal of 8 dB is used. Moreover, the novel envelope shaping function is adopted to improve the linearity as well as the PAE. Finally, we experimentally demonstrate better efficiency of the ET Doherty PA than that of conventional ET/EER transmitter.

II. Design of Doherty Amplifier with Supply Modulation

Fig. 1 shows the architecture of Doherty amplifier with supply modulator. As an unit cell PA of the Doherty structure, saturated amplifiers are employed to provide higher efficiency over a broad output power level compared to the general Doherty PA. Highly efficient operation of the saturated PA is carried out by nonlinear output capacitor, generating a large amount of harmonic voltage, especially second harmonic component [6]. Thus, it delivers the high efficiency comparable to the conventional high efficiency PA, such as Class-F^{-1}, without any special harmonic control circuitry. For a fixedsupply voltage of 30 V, the implemented saturated PA achieves the power-added efficiency (PAE) of 78.5% at the P_{sat} of 40.5 dBm with the gain of 16.2 dB at 2.14 GHz. The Doherty amplifier consisting of the saturated PAs delivers the maximum output power of 43 dBm with the PAE of 70%, while the PAE at the 6 dB back-off power is 58%, as depicted in Fig. 4(a). Due to the loss of the Doherty combiner and low gate bias of the peaking cell, the maximum efficiency and output power are slightly degraded with respect to the saturated PA.

Fig. 2(a) shows the ideal efficiencies of the Doherty, carrier, and peaking amplifiers and the power generation distributions (PGDs) of the carrier and peaking PAs for the 8 dB WCDMA 1FA signal at the maximum average output power [5]. For the modulation signal, the efficiency of the Doherty amplifier is expressed by

$$\eta = \frac{\int pdf(v_{\rm in}) \cdot [P_{\rm RF,c}(v_{\rm in}) + P_{\rm RF,p}(v_{\rm in})]\, dv_{\rm in}}{\int pdf(v_{\rm in}) \cdot [P_{\rm DC,c}(v_{\rm in}) + P_{\rm DC,p}(v_{\rm in})]\, dv_{\rm in}}$$
$$= \frac{\overline{P_{\rm RF,c}} + \overline{P_{\rm RF,p}}}{\overline{P_{\rm DC,c}} + \overline{P_{\rm DC,p}}} = \frac{\overline{P_{\rm RF,c}}\,(1+\alpha)}{\overline{P_{\rm DC,c}}\,(1+\beta)} = \eta_{\rm c} \times \gamma \qquad (1)$$

where

$$\alpha = \frac{\overline{P_{\rm RF,p}}}{\overline{P_{\rm RF,c}}},\ \beta = \frac{\overline{P_{\rm DC,p}}}{\overline{P_{\rm DC,c}}},\ \text{and}\ \gamma = \frac{1+\alpha}{1+\beta}.$$

P_{RF}, P_{DC}, $\overline{P_{RF}}$, and $\overline{P_{DC}}$ are instantaneous and average RF and DC powers, respectively, and η_c is the efficiency of the carrier PA. PGD means the multiplication of the power and *pdf* of the modulation signal. Since integration of the PGD represents the average power for the modulation signal, most of RF and DC powers of Doherty PA are generated by the carrier PA at the maximum average output power region, as shown in Fig. 2(a). In particular, for a 8 dB crest factor WCDMA 1FA signal, 90 percentage RF power of the Doherty PA is produced by the carrier PA. Moreover, below 6 dB back-off level, only the carrier PA generates the power. Thus, α and β are 0, and γ is 1. It presents that the carrier PA assisted by the supply modulator is more effective than the peaking PA or both PAs assisted by the architecture because overall efficiency of the Doherty amplifier is mainly determined by the carrier amplifier for the operation under the modulation signals with a large crest factor.

Fig. 3(a) represents the ideal case efficiencies of the standalone Doherty PA, ET Doherty amplifier, and conventional EER transmitter employing the Class-B PA for a CW signal. In spite of the fact that the Class-B amplifier delivers the maximum efficiency for the whole power level, the Doherty amplifier shows a slightly degraded efficiency after the half of the input voltage because only the carrier PA is supported by the supply modulator. However, in real environment, the overall efficiency of the ET Doherty transmitter is better than that of the conventional EER for the WCDMA 1FA signal with the crest factor of 8 dB, as depicted in Fig. 3(b). For the load modulation characteristic of the Doherty amplifier, the output fundamental voltage of the carrier amplifier maintains the maximum voltage of V_{DD} when the peaking amplifier is

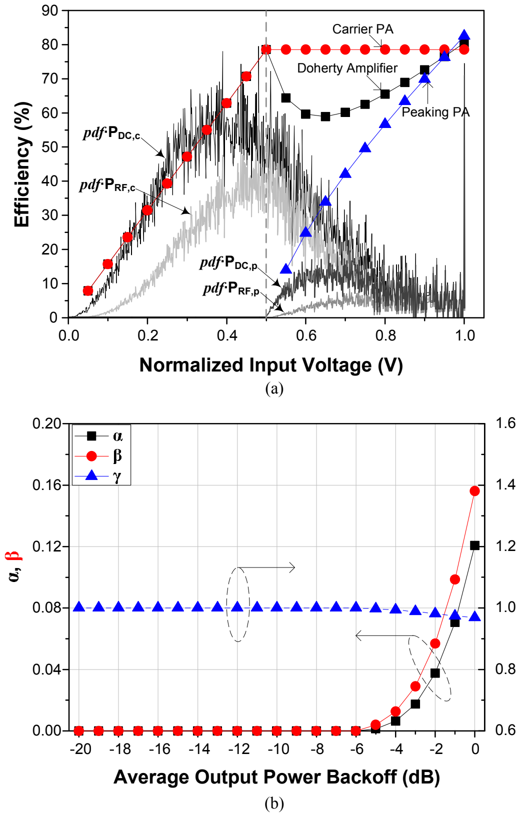
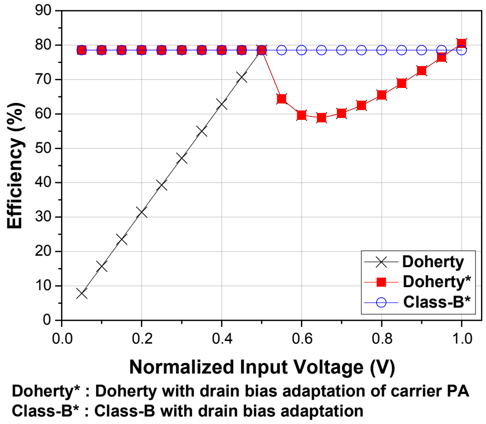


Fig. 2. (a) Efficiencies of the Doherty, carrier, and peaking amplifiers and PGDs of the carrier and peaking amplifiers for the 8 dB WCDMA 1FA signal at the maximum average output power. (b) Fundamental and DC power ratios of the carrier to peaking amplifiers and the efficiency degradation factor for the 8 dB WCDMA 1FA signal according to the average output power back-off level.

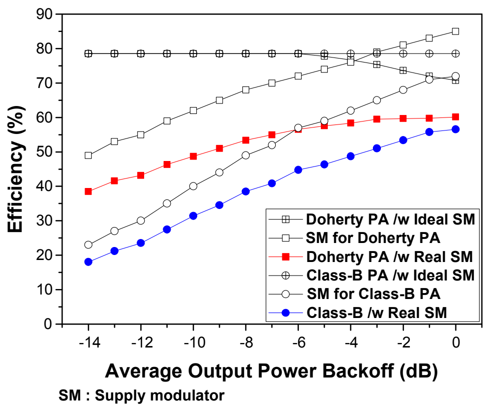
turned on. Thus, the crest factor of the envelope signal applied to the Doherty amplifier can be reduced by 6 dB because only the carrier amplifier below the 6 dB back-off region is supported by the supply modulator. It results in a significant improvement of the supply modulator efficiency. Compared to the efficiency of the supply modulator delivering to the Class-B amplifier, over the broad output power range, more than 15% of the efficiency is enhanced at the same average output power level, as shown in Fig. 3(b). The efficiencies of the supply modulators for the ET Doherty and conventional EER is refered to [4]. Above investigation shows the ET Doherty amplifier consisting of the saturated PA is the suitable transmitter architecture for the highly efficient operation across a broad power range.

III. Implementation and Experimental Results

The Doherty PA consisting of the saturated PA for each unit cell is implemented at 2.14 GHz using Cree GaN HEMT CGH40010s. It shows a very high PAE for a 8 dB crest factor WCDMA 1FA signal. At the maximum average output power level, back-off by 8 dB from the peak power, the PAE of 49.7% is obtained. For modulating the supply voltage of the carrier PA, a hybrid switching amplifier consisting of a parallel linear

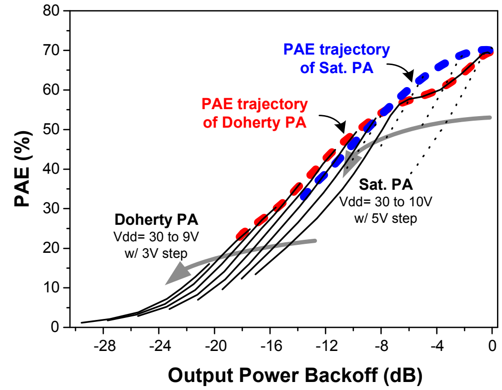


(a)

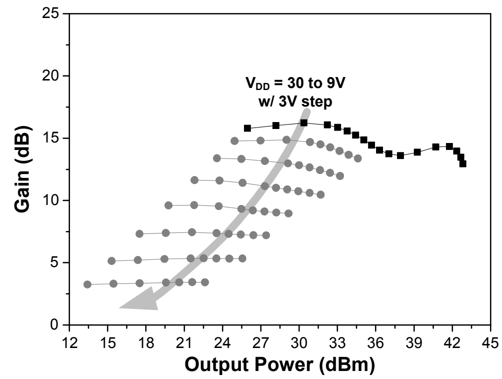


(b)

Fig. 3. (a) Efficiencies of the standalone Doherty, the ET Doherty PA, and conventional EER transmitter employing Class-B PA with the ideal supply modulator for a CW signal. (b) Estimated efficiencies of the ET Doherty and conventional EER transmitters under the ideal and real supply modulators for the WCDMA 1FA signal.



(a)



(b)

Fig. 4. (a) Measured PAEs of the implemented Doherty and saturated amplifiers with various supply voltage. (b) Measured gain of the implemented Doherty amplifier with various supply voltage.

stage and an efficient switcher stage is implemented [5]. A buck converter is employed as a switch stage, which efficiently provides most of the current required for the amplifier. In the linear stage, an OP amplifier and class AB output buffer linearly amplify the envelope voltage signal applied to the saturated carrier cell.

The supply voltage of the saturated carrier cell is swept from 9 V to 30 V, and that of the saturated amplifier is also similarly modulated, as shown in Fig. 4. Due to the $2R_{opt}$ operation of the carrier cell at a low power region, the PAE trajectory of Doherty PA is higher than that of the saturated PA at this region. However, as the efficiency of the peaking amplifier is low when the peaking PA starts to be turned on, the PAE is slightly degraded at the high power region, as depicted in Fig. 4(a). Fig. 4(b) shows the measured gain of the implemented saturated Doherty amplifier with various supply voltage. By modulating the supply voltage of the carrier amplifier, serious gain degradation appears due to the operation in the small g_m-region. It results in a significant reduction of the PAE. To prevent the gain degradation and nonlinear characteristics from operation at the low supply voltage region and below knee voltage, the novel envelope shaping method shown in Fig. 5 is employed. In the case of the carrier PA, for the average output power back-off level from 0 to 6 dB, the applied envelope signal is the same as the shaping function #1 [4]. Below the 6 dB back-off level, the offset voltage V_{offset} and the maximum value are enlarged, following #2 shaping, to avoid the severe gain reduction, resulting in the good PAE.

For the 8 dB crest factor WCDMA 1FA signal, the designed saturated ET Doherty amplifier provides a PAE of 50.9% at the maximum average output power, while those of the standalone saturated PA, saturated Doherty PA, and ET transmitter employing the saturated PA are 35%, 49.7%, and 42.3%, respectively, at the same average output power back-off level, and the results are summarized in Table. I. For a broad range of the average output power level, the PAE of the ET Doherty transmitter is better than those of other PAs, as depicted in Fig. 6(a). For the ET transmitter with the saturated PA, the envelope signal applied to the PA is shaped by the shaping function #2, as shown in Fig. 5. Fig. 6(b) shows the measured ACLRs of the implemented PAs. These results clearly show that the polar transmitter with the saturated Doherty amplifier is the most promising architecture for the highly efficient PA

TABLE I
PERFORMANCE SUMMARY AT MAXIMUM AVERAGE OUTPUT POWER BACKOFF LEVEL

	Sat. PA	Sat. PA + ET	Doherty	Doherty + ET
PAE [%]	35.0	42.3	49.7	50.9
ACLR [dBc]	–37.2	–27.0	–24.5	–26.5

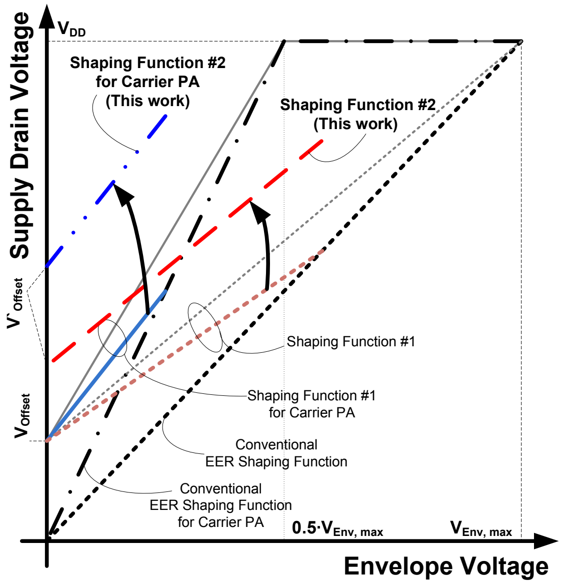


Fig. 5. Transfer function of the novel envelope shaping method for the carrier PA and the standalone saturated PA.

with acceptable linearity.

IV. CONCLUSIONS

An optimized ET operation of the Doherty amplifier consisting of the saturated PA is demonstrated using a 8 dB crest factor WCDMA 1FA signal. Compared to the general Doherty PA, the saturated Doherty PA delivers better PAE over a broad output power level. By only modulating the supply voltage of the carrier cell, the crest factor of the envelope signal applied to the cell is reduced by 6 dB compared to the conventional EER transmitter because of the load modulation behavior of the carrier PA. It results in better efficiencies of the supply modulator and transmitter. The novel envelope shaping method reduces the gain degradation caused by the low supply voltage, and provides the good PAE. The saturated PA and Doherty amplifier are implemented using Cree GaN HEMT CGH40010s. The experimental results clearly shows that the Doherty amplifier with the supply modulation technique delivers better PAE over the whole average output power back-off level with acceptable linearity. Especially, at the maximum average output power back-off level, the Doherty ET transmitter has the PAE of 50.9%, while those of the standalone saturated PA, saturated Doherty PA, and saturated PA ET transmitter are 35%, 49.7%, and 42.3%, respectively, at the same average output power back-off.

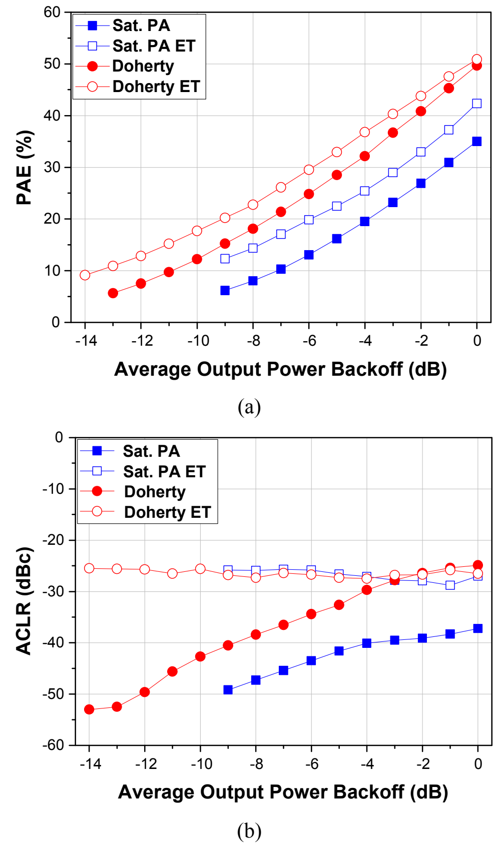


Fig. 6. Measured performance of the standalone Doherty and saturated PAs, ET Doherty PA, and saturated ET PA for WCDMA 1FA signal. (a) PAE. (b) ACLR at an offset frequency of 5 MHz.

ACKNOWLEDGEMENT

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 MKE(The Ministry of Knowledge Economy), Korea, under the ITRC(Information Technology Research Center) support program supervised by the NIPA(National IT Industry Promotion Agency)(NIPA-2010-(C1090-1011-0011)) and WCU(World Class University) program through the Korea Science and Engineering Foundation funded by the Ministry of Education, Science and Technology(Project No. R31-2008-000-10100-0).

REFERENCES

[1] S.C. Cripps, *RF Power Amplifiers for Wireless Communications*. 2nd ed. Norwood, MA: Artech House, 2006.

[2] J. Choi, et al., "Power amplifiers and transmitters for next generation mobile handset," *J. Semicond. Technol. Sci.*, vol. 9, no. 4, pp. 249–256, Dec. 2009.

[3] F. H. Raab, "Efficiency of Doherty RF power-amplifier systems," *IEEE Trans. Broadcast.*, vol. BC-33, no. 3, pp. 77–83, Sep. 1987.

[4] J. Choi, et al., "Optimized envelope tracking operation of Doherty power amplifier for high efficiency over an extended dynamic range," *IEEE Trans. Microw. Theory Tech.*, vol. 57, no. 6, pp. 1508–1515, Jun. 2009.

[5] I. Kim, et al., "High-efficiency hybrid EER transmitter using optimized power amplifier," *IEEE Trans. Microw. Theory Tech.*, vol. 56, no. 11, pp. 2582–2593, Nov. 2008.

[6] J. Moon, et al., "Investigation of class-J power amplifier with nonlinear C_{out} for an optimized operation," unpublished.