A highly Efficient Asymmetric Doherty Power Amplifier with a New Output Combining Circuit

Junghwan Son[1], Ildu Kim[2], Junghwan Moon[1], Juyeon Lee[1], and Bumman Kim[1]

[1]*Department of Electrical Engineering, Pohang University of Science and Technology (POSTECH),*
San 31, Hyoja-dong, Nam-gu, Pohang, Gyeongbuk, 790-784, Republic of Korea
Tel : +82-54-279-5584, Fax : +82-54-279-8115
[2]*Telecommunication System Division, Samsung Electronics Company Ltd.,*
Suwon, Gyeonggi, 442-742, Republic of Korea
`jhson@postech.ac.kr, bmkim@postech.ac.kr`

***Abstract*—An asymmetric Doherty Power Amplifier (ADPA) is introduced using a new output combining circuit for easy of implementation with a large matching tolerance. The proposed APDA has been implemented using GaN HEMT devices at 2.6 GHz for WiMAX signal with 5MHz bandwidth and 8.3 dB peak to average power ratio. This ADPA delivers a saturated output power of 51.7 dBm and a drain efficiency of 60.4% at an average output power of 43.6 dBm. After linearization using digital feedback predistortion technique, the ADPA satisfies the linearity specification with -51.98 dBc of adjacent channel leakage ratio at 10MHz offset. To the best of our knowledge, the drain efficiency of 60.4% is the highest efficiency at 2.6GHz frequency for a WiMAX signal with 8.3dB PAPR.**

I. INTRODUCTION

Wireless communications are becoming increasingly important for everyday life. To handle the large data rate within the limited bandwidth, modulation scheme is evolved to the spectrum efficient method, making the signal to have a large peak to average power ratio (PAPR). Thus, power amplifiers (PA) for the systems should be operated at a large back off power (BOP) to maintain the linearity, in which the PA's efficiency is poor.

To improve efficiency around the average output power level, several efficiency enhancement techniques have been introduced such as Envelop Elimination and Restoration (EER), Envelope Tracking (ET), and Doherty PA technique [1]–[8]. Among these techniques, Doherty Power Amplifier (DPA), which employs a load impedance modulation technique, has been widely used in base station due to its simple structure and high efficiency at an average output power region. The conventional 2-way Doherty PA is optimized for a modulation signal with 6 dB PAPR, which is not an optimum structure for the modulated signal with PAPR a lot larger than 6 dB. To enhance the average efficiency for amplification of the signal, Asymmetric Doherty Power Amplifiers (ADPAs), which can control the BOP region using an asymmetric cells of carrier and peaking PAs, have been also proposed [9]–[11].

In this paper, we present a 3-way ADPA using two asymmetric devices with a new output combining circuit. This ADPA has an advantage for easy of implementation with large matching tolerance, compared to the conventional output combining circuits in [9]–[11].

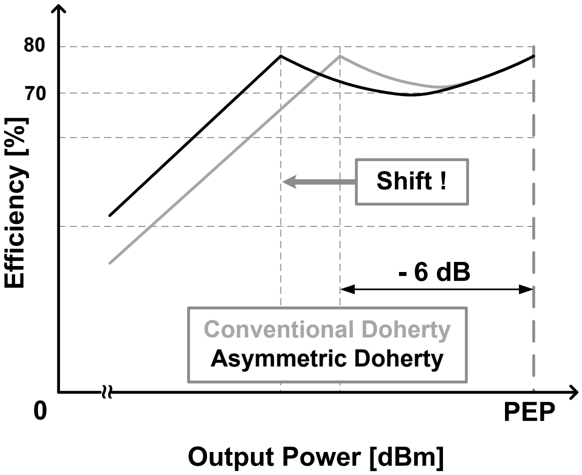

Fig. 1. Efficiencies of conventional Doherty PA and asymmetric Doherty PA.

II. ANALYSIS OF ADPA WITH A NEW OUTPUT COMBINING CIRCUIT

The conventional 2-way Doherty PA delivers the maximum efficiency at the 6-dB BOP due to the carrier and peaking PAs with the same size. To lower BOP for the maximum efficiency as shown Fig. 1, the size of the peaking device should be larger than that of the carrier PA, and the back-off level can be expressed as

$$P_{Back-off} = -10 \cdot log((1+\delta)^2) \tag{1}$$

where δ is the size ratio of the peaking PA over the carrier PA. Thus, by controlling the peaking cell size, we can achieve higher efficiency from the DPA for amplification of the modulation signal with a high PAPR.

The conventional output combining circuit is shown in Fig. 2 (a). The output impedance of the peaking PA is R_0/δ at the peak power region, which means that we should design

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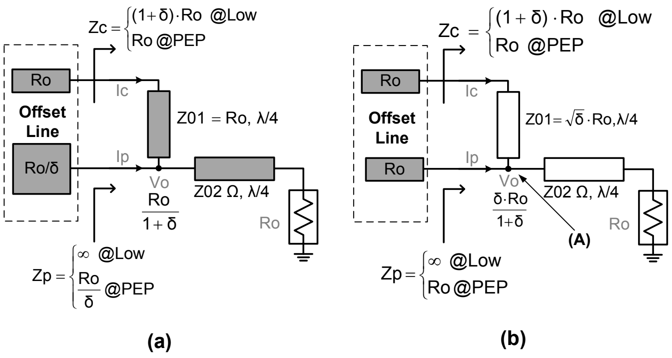

Fig. 2. (a) Conventional output combining circuit and (b) Proposed output combining circuit.

the peaking PA at the R_0/δ impedance system. On the other hand, the proposed ADPA shown in Fig. 2 (b), the output impedance of the peaking PAs becomes R_0. Since most of the PAs are designed at the R_0 impedance system, we can easily implement the ADPA using the new combiner. Moreover, the impedance transformation ratio in the output combining circuit of the conventional structure is larger than the proposed one, which requires a matching circuit with higher Q-factor. The impedance at the combining point (A) of the proposed output combining circuit is δ times larger than that of the conventional one. Using the $\lambda/4$ quarter wave transformer with Z01 impedance, this higher impedance in the proposed output combining circuit allows to use lower Q-matching, loosing the matching tolerance.

To analyse variation of the load impedances of the carrier PA and the peaking PA, we calculate the characteristic impedance of Z_{01} and Z_{02}. The characteristic impedance of Z_{01} which satisfies load impedances of the carrier PA at back-off (2) and peak power region (3) can be expressed as

$$Z_{01}^2 = (1+\delta)\cdot R_0 \cdot \frac{R_0}{N} = \frac{1+\delta}{N}\cdot R_0^2 \quad @ \quad BOP \tag{2}$$

$$\frac{Z_{01}^2}{R_0} \parallel R_0 = \frac{R_0}{N} \quad @ \quad PEP \tag{3}$$

where the R_0 / N is combining load impedance. In the equation (3), the characteristic impedance of Z_{01} at the peak power level can be written as

$$Z_{01}^2 = \frac{R_0^2}{N-1} \tag{4}$$

and by two equations of (2) and (4), the combining load impedance(R_0/N), the characteristic impedance of Z_{01} and Z_{02} are calculated as

$$N = \frac{1+\delta}{\delta}, \quad Z_{01} = \sqrt{\delta}\cdot R_0, \quad Z_{02} = \sqrt{\frac{\delta}{1+\delta}}\cdot R_0 \tag{5}$$

This new output combining circuit can be applied for the ADPA with any size of peaking PA. Using this output combining circuit, the load impedance of the carrier and the peaking PA, according to the α, are expressed as

$$Rc = \frac{Z_{01}^2}{Rc'} = \frac{\delta\cdot R_0^2}{1+\alpha}\cdot\frac{1+\delta}{R_0\cdot\delta} = \frac{1+\delta}{1+\alpha}\cdot R_0 \tag{6}$$

$$Rp = (1+\frac{1}{\alpha})\cdot\frac{R_0}{N} = \frac{1+\alpha}{\alpha}\cdot\frac{\delta}{1+\delta}\cdot R_0 \tag{7}$$

$$where,\ \alpha = \frac{Ip}{Ic},\quad Rc' = \frac{R_0}{N}\cdot(1+\alpha) \tag{8}$$

For the asymmetric size with the ranges of $\alpha = 0 \sim \delta$, equations of (6) and (7) become

$$Rc = (1+\delta)\cdot\ R_0 \rightarrow R_0 \tag{9}$$

$$Rp = \infty \rightarrow R_0 \tag{10}$$

The proposed output combining circuit shows the proper load modulation for ADPAs.

III. IMPLEMENTATION AND EXPERIMENT RESULTS

The ADPA has been implemented to operate at 2.6GHz for WiMAX signal with 8.3 dB PAPR. For asymmetric devices, 50W (CGH27060) and 100W (CGH40120) GaN HEMT devices from Cree Inc. have been used for the carrier PA and the peaking PA, respectively. This ADPA has a peak efficiency at 9.5 dB back off, which is suitable for the WiMAX signal with 8.3 dB PAPR. The gate voltages of the carrier PA and the peaking PA are set to -3.05 V (class AB-bias), and -6.5 V (class C-bias), respectively. Fig. 3 shows a photograph of the proposed ADPA with a size of 100 X 100 mm. For the ADPA input power dividing, an unequal power divider [12] is used to drive more power to the peaking PA to compensate low power gain of peaking PA. Fig. 4 shows the performance of the APDA for the 2.6GHz continuous wave (CW) test. In this figure, we measured the peak output power of near 50 dBm due to gate leakage current problem in the CW test. To know the maximum power level under modulation signal, we use the agilent distortion suite software. Under this test, we confirm maximum power of 51.7 dBm (148W) and this implemented ADPA has the first peak efficiency at output power of 42.2dBm which is the 9.5 dB back off level.

Fig. 5 shows the performance at the 2.6GHz WiMAX modulated signal test. For the WiMAX signal with 5MHz signal bandwidth, this ADPA shows the high efficiency of 60.54% and ACPR of -35.5dBc before linearization at an average output power of 43.6 dBm, 8.1 dB back off from the peak power. To compensate the nonlinear characteristics, the proposed APDA is linearized using Digital Feedback Predistortion (DFBPD) technique. After the linearization, the ADPA delivers a maximum drain efficiency of 60.40% at an average output power of 43.63 dBm while satisfying linearity. The linearity is improved to -51.98 dBc by linearization using digital feedback predistortion and the performance of proposed ADPA before and after the linearization is summarized in Table I.

The measured output spectra at the ADPA before and after the linearization are shown in Fig. 6. After DFBPD technique,

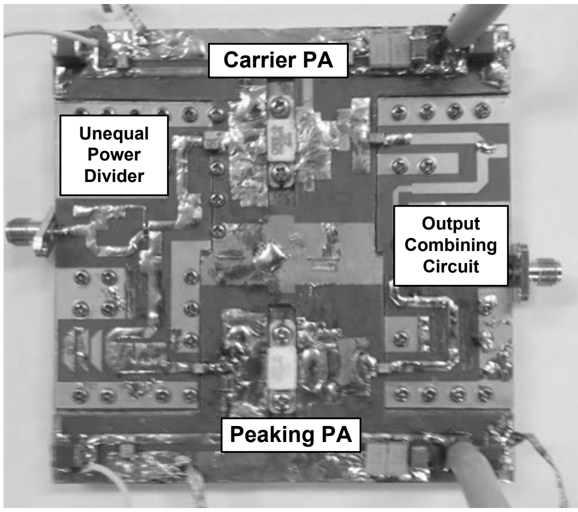

Fig. 3. The photograph of proposed the ADPA.

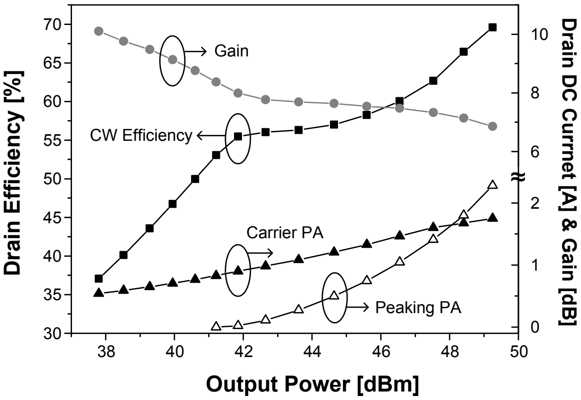

Fig. 4. The performance at the 2.6GHz continunous wave (CW) test.

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TABLE I
SUMMARIZES THE PERFORMANCE OF PROPOSED ADPA BEFORE AND AFTER LINEARIZATION

	P_{out} [dBm]	Gain [dB]	DE [%]	PAE[%]	ACPR [dBc]
Befor PD	43.62	7.46	60.54	49.68	-35.50
After PD	43.63	7.43	60.40	49.48	-51.98

the ACLR at an offset of 10MHz is -51.98 dBc, which is an improvement of approximately 16.48 dB. This spectrum satisfies the spectrum mask of the mobile WiMAX system. Fig. 7 and Fig. 8 show the AM/AM characteristics before and after the DFBPD and AM/PM characteristics before and after the DFBPD. Table II shows the comparison of the performance of WCDMA and WiMAX transmitter. This proposed ADPA delivers high efficiency for high PAPR modulation signal compared to the reported DPAs and ADPAs

IV. CONCLUSION

We have proposed an ADPA using a new output combining circuit. The proposed output combining circuit can be easily

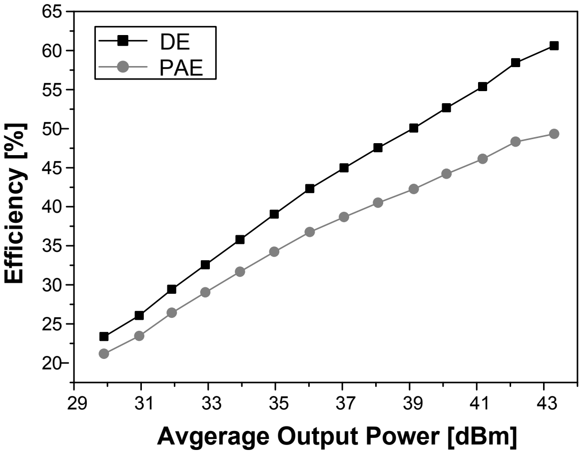

Fig. 5. The performance at the 2.6GHz WiMAX modulated signal test.

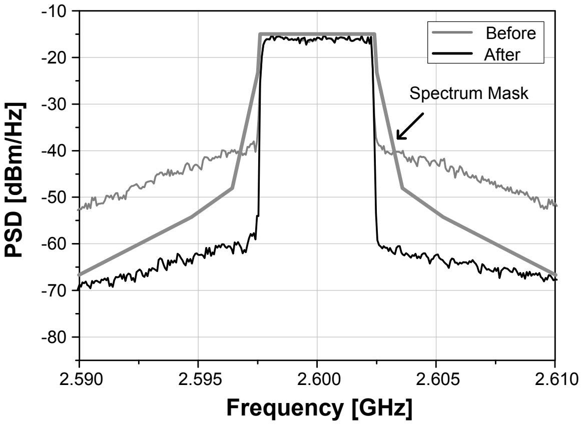

Fig. 6. The Measured output spectra at the ADPA before and after the linearization.

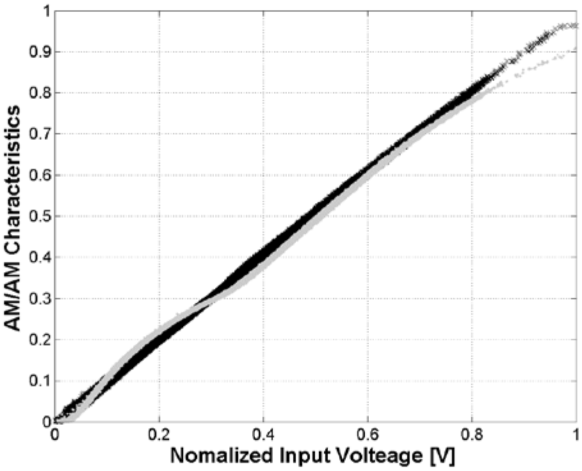

Fig. 7. The AM/AM characteristics before and after the DFBPD.

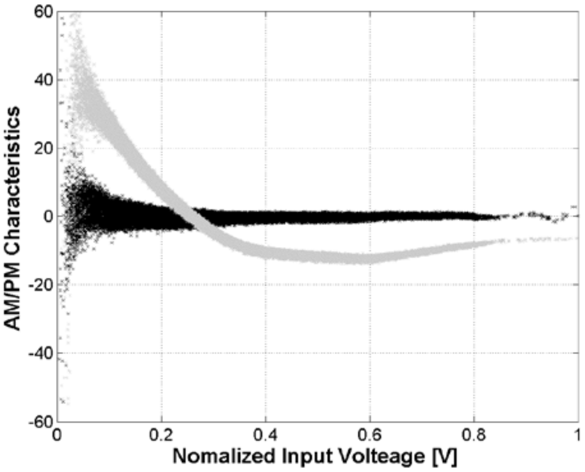

Fig. 8. The AM/PM characteristics before and after the DFBPD.

TABLE II
COMPARISON OF THE PERFORMANCE OF WCDMA AND WIMAX TRANSMITTER

Ref.	Deguchi et. al. [13]	Pelk et. al. [14]	I.Kim et. al. [15]	J. Moon et. al. [16]	This Work
Freq. [GHz]	2.6	2.14	2.655	2.655	2.6
PAPR [dB]	6.9	11.5	7.8	7.8	8.3
Back-off [dB]	7.3	11.5	8	7.5	8.2
P_{out} [dBm]	45.2	38.5	42.5	42.0	43.6
DE [%]	55	55	55.4	49.3	60.4

implemented and has a advantage of lower Q-matching. The APDA has been implemented using the Cree Inc. CGH27060 and CGH40120 GaN HEMT devices and tested using WiAMX signal with 8.3 dB PAPR at 2.6GHz. The proposed ADPA delivers a maximum drain efficiency of 60.4% at an average output power of 43.6 dBm, which is 8.1 dB back-off from the peak power, and satisfies the linearity specification with -51.98 dBc ACLR at 10MHz offset after linearization. These results show that the proposed ADPA delivers high efficiency and good linearity for the modulated signal with a high PAPR.

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