A Highly Efficient Doherty Power Amplifier Employing Optimized Carrier Cell

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***Abstract*— We have proposed a novel design of the Doherty power amplifier (PA) to improve the efficiency at a back-off output power level. It is shown that the carrier PA having 100 Ω load impedance is not an optimum for maximizing the efficiency at the back-off level due to the knee voltage effect. Thus, we introduce a Doherty PA having a load impedance larger than 100 Ω when the peaking PA is turned off. For experimental demonstration, we have implemented and tested the Doherty PA using Cree GaN HEMT CGH40045 devices at 2.655 GHz. The measured results clearly show that the proposed Doherty PA delivers better efficiency at the back-off output power level than the conventional PA due to the better load condition for improving efficiency.**

I. Introduction

As the wireless communication systems evolve into high data rates, the signals of the systems have large peak-to-average power ratios (PAPRs) due to the frequency-efficient modulation scheme, such as a wideband code division multiple access, orthogonal frequency division multiple access, and worldwide interoperability for microwave access (WiMAX). Since the output signals amplified by the power amplifier (PA) should be linear to satisfy the stringent linearity requirements, it is necessary that the PAs operate in a back-off power level. However, it degrades efficiency of the transmitter chain. There are a few candidates which can provide an excellent efficiency for the amplification, such as envelope elimination and restoration, envelope tracking, and Doherty PA [1]–[7]. Although the former two systems provide a good efficiency, they have some problems to be solved, such as the difficulty of delay adjustment for the RF and envelope paths and the complexity of linkage between the PA and bias modulator. However, the Doherty PA can accomplish the high efficiency without adding any extra circuitry.

There have been many reports on the Doherty PA, analyzing the PA under a zero knee voltage condition [1]–[7]. The purpose of this work is to further improve the efficiency of the Doherty PA in the real design environment with the non-zero knee voltage condition. We have investigated the knee voltage effects on the operation of the Doherty PA. Based on the examination, we have adopted a larger load impedance than the conventional one when the peaking PA does not operate. We have built and tested the amplifier using Cree GaN HEMT CGH40045 devices at 2.655 GHz. The experimental results clearly show that the proposed Doherty PA delivers better efficiency than the conventional one.

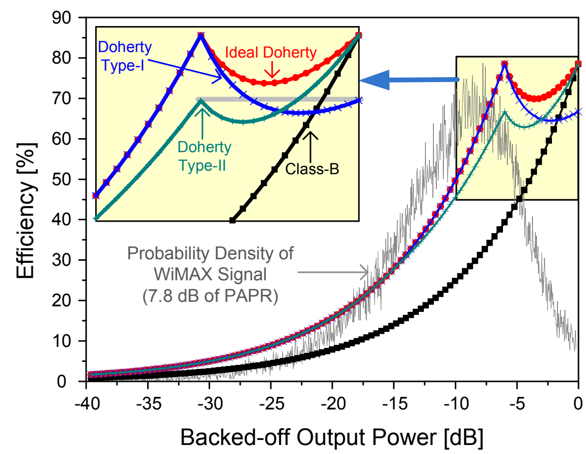


Fig. 1. Ideal efficiencies of the class-B and two-way Doherty power amplifiers and the probability density of a WiMAX signal with a 7.8 dB PAPR.

II. Analysis for Operation Characteristics of the Proposed Doherty Power Amplifier

A. Dominant Region of Doherty PA with the modulated signal for the Excellent Efficiency

For the efficiency analysis, the Doherty PA can be categorized into three types as shown in Fig. 1, i.e., Ideal Doherty, Doherty Type-I, and Doherty Type-II, where the Type-I and -II are optimized at the average and peak power, respectively. Even though PA designers want to get the ideal Doherty characteristic, the latter two cases are easily realizable. Particularly, the Doherty Type-I has efficiency degraded at the peak power level, which is caused by the imperfect load modulation at the maximum power level, i.e., the non-R_{opt} for the carrier and peaking PAs. The Doherty Type-II has efficiency decreased at the back-off power level by several reasons: a soft turn-on effect of the peaking PA, output power leakage from the carrier to peaking PA due to the finite output impedance of the peaking PA when the peaking is turned off, and the knee voltage which will be described in this paper.

TABLE I
ESTIMATED EFFICIENCY OF TWO-WAY DOHERTY AMPLIFIERS FOR THE SIGNAL WITH PAPR OF 7.8 dB.

	Ideal Doherty	**Doherty Type I**	**Doherty Type II**
η_{avg} [%]	61.5	59.4	56.3

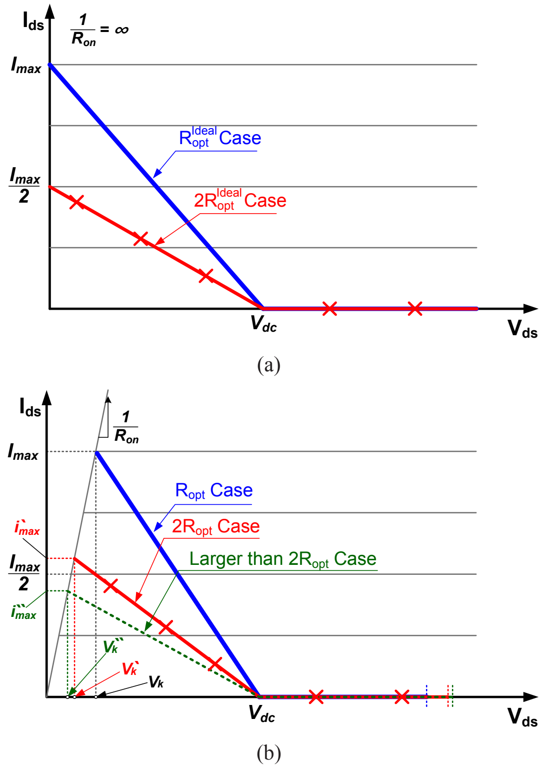


Fig. 2. Load line of the carrier amplifier. (a) Ideal case with zero knee voltage. (b) Practical case with non-zero knee voltage.

To find the optimal efficiency characteristic of the Doherty PA to maximize the efficiency for the modulated signal having a PAPR, we have calculated the average efficiencies for above three cases, performed by MATLAB using a WiMAX signal with a 7.8 dB PAPR and summarized in Table I [6]. The estimated efficiencies show that the Type-I provides an excellent efficiency, comparable to the ideal case, and give us guideline of optimum design of the Doherty PA for good efficiency.

B. Doherty PA Operation with Knee Voltage

Theoretically, the Doherty PA attains its maximum efficiency at the 6 dB back-off as well as at the peak power level. It can be achieved under the perfect load-modulated-operation of the carrier and peaking PAs and an infinite output impedance of the peaking PA with turn-off condition. The perfect load modulation of the carrier PA, depicted in Fig. 2(a), means that the output powers for both $R_{\rm opt}$ and $2R_{\rm opt}$ are P_1 and $P_1/2$, respectively. The efficiencies (ηs) are also the same at P_1 and $P_1/2$, respectively; the carrier PA is in equally saturated state for the both cases. In this case, P_1 and η are

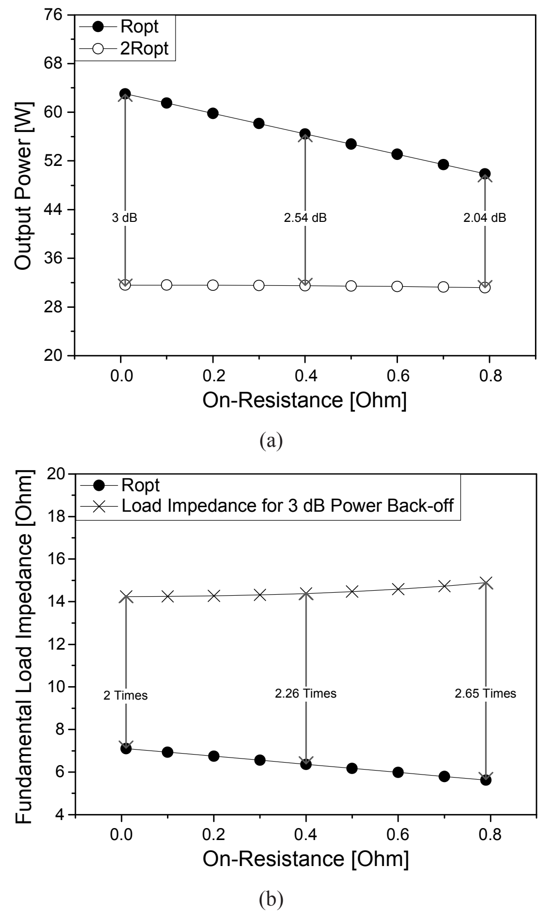


Fig. 3. (a) Maximum output powers employing $R_{\rm opt}$ and $2R^{\rm opt}$with varying $R_{\rm on}$ from 0 to 0.8 Ω. (b) $R_{\rm opt}$ and load impedance for 3 dB power back-off with varying $R_{\rm on}$ from 0 to 0.8 Ω.

$(1/4)\,V_{\rm dc}I_{\rm max}$ and $\pi/4$, respectively. However, these results can be obtained with the zero knee voltage.

In the real device, we can not neglect the knee voltage. Fig. 2(b) shows the load line having the knee voltage $V_{\rm k}$. For the $R_{\rm opt}$ and $2R_{\rm opt}$ cases, the output powers can be written by $(1/4)\,(V_{\rm dc}-V_{\rm k})\,I_{\rm max}$ and $(1/4)\,(V_{\rm dc}-V'_{\rm k})\,i'_{\rm max}$, where $V_{\rm k}$ and $V'_{\rm k}$ are $R_{\rm on}I_{\rm max}$ and $R_{\rm on}i'_{\rm max}$, respectively. Since $i'_{\rm max}$ can be expressed as a function of $V'_{\rm k}$, the output powers for both cases can be calculated according to $R_{\rm on}$ as shown in Fig. 3(a). For calculation, we assumed a $V_{\rm dc}$ supply of 30 V and $I_{\rm max}$ of 8 A with an uniform trans-conductance. This result represents that the carrier PA having $2R_{\rm opt}$ delivers more power than the expected value, $(1/2)\,(1/4)\,(V_{\rm dc}-V_{\rm k})\,I_{\rm max}$, because of the enlarged voltage swing caused by the reduced knee voltage. It deteriorates the efficiency at the 6 dB back-off region of the Doherty PA because the carrier PA does not reach to the fully saturated state until the peaking PA starts to operate. Thus, the efficiency at back-off region can not be maximized.

To solve the problem, the load impedance of the carrier PA should be increased, larger than $2R_{\rm opt}$. Fig. 3(b) shows the required load impedances for the 3 dB and 0 dB power back-off for the carrier amplifier with varying $R_{\rm on}$. As $R_{\rm on}$ increases, the load impedance of the carrier PA at a low power

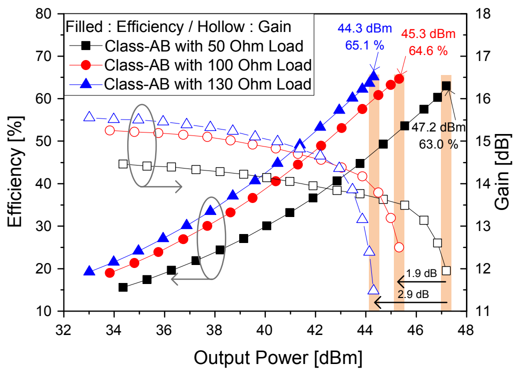


Fig. 4. Load modulation results for carrier amplifier employing the load impedances of 50 Ω, 100 Ω, and 130 Ω.

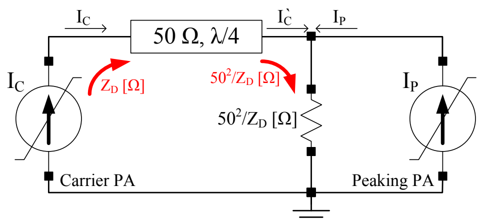


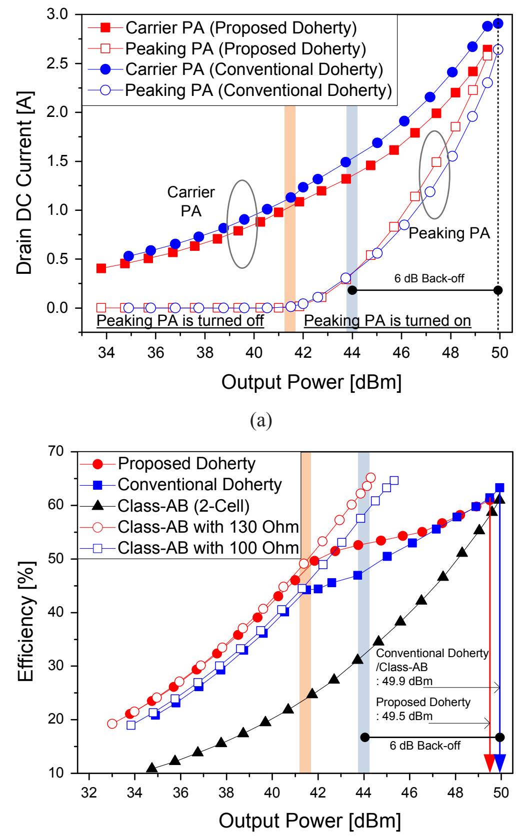
Fig. 5. Operational diagram of the proposed Doherty amplifier.

region should be larger than two times of R_{opt}. It enables the Doherty PA to maximize efficiency at the 6 dB back-off level from the peak power because the carrier PA could reach to its fully saturated state. In addition, the larger load impedance also enhances efficiency above the 6 dB back-off level.

Fig. 4 shows the load modulation results for the carrier PA employing the load impedances of 50 Ω, 100 Ω, and 130 Ω. As expected, the PA with 100 Ω delivers its maximum efficiency at less than 3 dB back-off power level due to the knee voltage effect. On the other hand, the PA with 130 Ω has its maximum efficiency at the 2.9 dB back-off point.

III. Implementations and Measurement Results

In Section II-B, we have shown that the Doherty PA should have the load impedance of the carrier PA larger than 100 Ω to improve the efficiency at the back-off region before the peaking PA is turned on. To experimentally validate the proposed scheme, we have implemented the Doherty PA using Cree GaN HEMT CGH40045 devices with a 45-W PEP at 2.655 GHz. Fig. 5 shows the operational schematic diagram of the proposed Doherty PA. To realize the load impedance larger than 100 Ω for the carrier PA, we have attached $50^2/Z_{\mathrm{D}}$ Ω at the combining point, where Z_{D} denotes the desired impedance for the carrier PA. Typically, since Z_{D} is larger than 100 Ω, $50^2/Z_{\mathrm{D}}$ is smaller than 25 Ω. In the experiments, the offset lines of the carrier PAs are optimized for delivering the maximum performances with 100 Ω and 130 Ω. Those of the peaking PAs are also adjusted to block the output power leakage from the carrier to peaking PA, and the transformed output impedance is 1200 Ω.

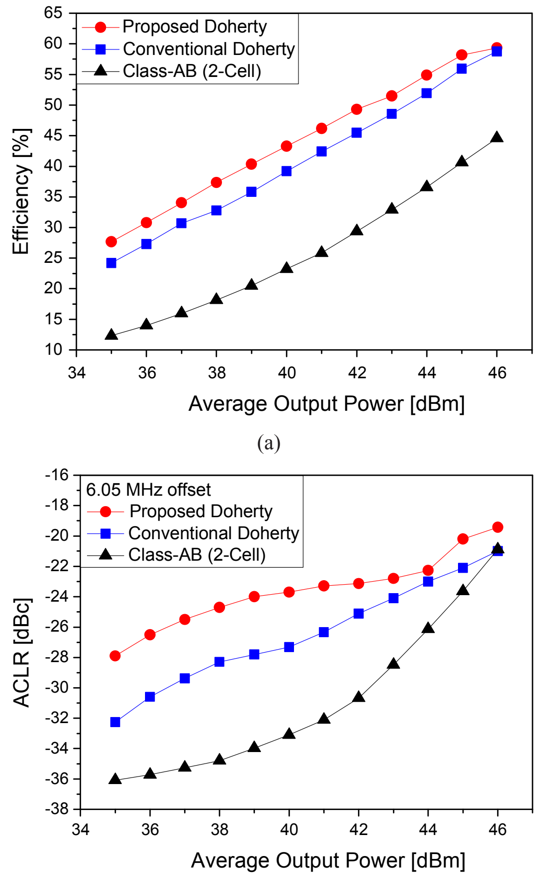


(a)

(b)

Fig. 6. Measured performances of the conventional and proposed Doherty amplifier for CW signal: (a) Drain dc supply current. (b) Drain efficiency.

Fig. 6 shows the measured drain dc currents and drain efficiencies of the conventional and proposed Doherty PAs for a CW signal, respectively. In the experiments, the turn-on power level of the peaking PA is adjusted only by the gate-source voltage V_{gs}. However, since the V_{gs} can not be lowered sufficiently due to the gate-source breakdown property of the HEMT device, the peaking PAs start to turn on earlier than the 6 dB back-off level. It decreases the efficiency at the back-off power level because the load impedance of the carrier PA can not maintain the load-modulated-impedances such as 100 Ω and 130 Ω until the 6 dB back-off output power level. When the peaking PA is turned off, the load impedance of the proposed carrier PA is higher than that of the conventional one. So the dc current level of the proposed one is lower than that of the conventional one, leading to the higher efficiency at the low power region. However, the non-25 Ω load impedance at the combining point causes the impedance mismatch for R_{opt} at the peak power region, so the peak power of the Doherty PA is degraded. Although the peak power of the proposed Doherty PA is slightly degraded, the efficiency is increased over a broad output power range. If the peaking PA could stay turn-off state below 6 dB back-off region, the efficiency can be further improved.



(a)

(b)

Fig. 7. Measured performances of the conventional and proposed Doherty amplifier for WiMAX signal: (a) Drain efficiency. (b) ACLR.

Fig. 7(a) shows the measured efficiency performances for mobile WiMAX signal having a 10 MHz signal bandwidth and a 7.8 dB PAPR. In comparison with the conventional Doherty PA, the efficiency of the proposed one is improved over a broad average output power level. Fig. 7(b) represents the measured ACLR of the implemented PAs. Since the proposed Doherty PA has the load impedance larger than conventional one, the ACLR is slightly degraded. The Doherty PAs also have ACLR worse than the class-AB PA because the peaking PAs are biased at deep class-C to turn off the PAs until the carrier PA is fully saturated, and are optimized to improve the efficiency rather than linearity. In Table II, we have summarized the measured efficiency and ACLR performances at the 8 dB back-off output power for conventional Doherty PA and the 8 dB and 7.5 dB back-off output powers for proposed Doherty PA. These results allow us to conclude that the proposed Doherty PA has an excellent efficiency with acceptable linearity.

IV. Conclusions

For a good efficiency at the average output power level, we have validated that the efficiency at the back-off level is more important than at the peak-power level using MATLAB calculation. To further improve the efficiency at the back-off power region, we have investigated the knee voltage effect on the operation of the Doherty PA. From the examination, we have found that the efficiency of the Doherty PA at the back-off region is limited by the knee voltage effect in the conventional topology. To overcome this problem, we have proposed the Doherty PA employing the load impedance larger than 100 Ω when the peaking PA is turned off. The proposed Doherty PA delivers higher efficiency because the PA is saturated enough while the conventional one is not. To experimentally validate, we have implemented and tested the Doherty PAs using Cree GaN HEMT CGH40045 devices at 2.655 GHz. The measurement results clearly show the the proposed Doherty PA can provide the excellent efficiency with acceptable linearity.

TABLE II

Measured Performances for Conventional and Proposed Doherty PAs for WiMAX 1-FA Signal

	Conventional Doherty	Proposed Doherty	
P_{avg} [dBm]	42	41.5	42
Back-off level [dB]	8	8	7.5
η_{avg} [%]	45.5	48.0	49.3
ACLR [dBc]	–25.1	–23.2	–23.1

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