Highly Efficient Three-Stage Doherty Power Amplifier with Adaptive Driving Amplifier for 3.5 GHz WiMAX Applications

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Abstract — **This paper describes a new three-stage Doherty power amplifier (DPA) with an adaptive driving amplifier inserted at the input of the carrier cell. This driving amplifier controls the input power of the carrier cell to eliminate the gate leakage current at high input power levels. Using an envelope tracking technique, the gate bias voltage of the driving amplifier is adjusted according to the input power levels. For verification, the driving amplifier, carrier, and peaking cells are fabricated using 10-W, 15-W, and 35-W GaN HEMTs, respectively, at 3.5 GHz. For a continuous wave signal, total drain efficiencies (DEs) of 37.3% and 45.6% are achieved at approximately 9.5- and 4.3-dB back-off powers (BOPs), respectively. For a worldwide interoperability for microwave access (WiMAX) signal, the proposed DPA has a total DE of 39.5 % at an 8-dB BOP.**

Index Terms — **Doherty power amplifier, efficiency, envelope tracking, driving amplifier, GaN HEMT, WiMAX.**

I. INTRODUCTION

Various techniques that enhance the efficiency of power amplifiers (PAs) have been investigated and developed, with the goal of reducing the thermal problem and operating costs [1]-[10]. The Doherty PAs (DPAs), which use simple circuitry consisting of the carrier and peaking cells, are regarded as a beneficial solution because they are highly efficient at a 6-dB back-off power (BOP). Moreover, advanced DPAs such as N-way, N-stage, and asymmetrical DPAs have been suggested for achieving high efficiency at a large BOP since a modulated signal with a high peak-to-average power ratio (PAPR) is widely used in modern communication systems [4]-[8]. Several DPAs using the envelope tracking (ET) or power tracking techniques have been also proposed to enhance these systems' performances [9], [10].

The silicon laterally diffused metal oxide semiconductors (Si LDMOS) have been widely used in DPAs due to their low cost and stability, although they have several disadvantages including a large output capacitance when the operating frequency increases. In contrast, the gallium nitride high electron mobility transistors (GaN HEMT) operate at a high frequency, over 3 GHz, due to a high saturation velocity [11], and the high-efficiency PAs using GaN HEMTs have been reported. But it is difficult to design N-stage DPAs due to a gate leakage current of the carrier amplifier at high input power levels.
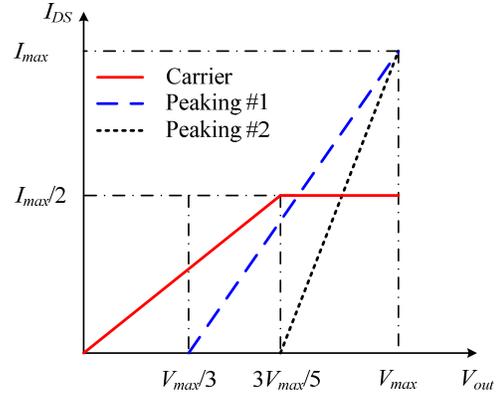

Fig. 1. Drain currents of the three-stage DPA. The device size ratio of the carrier cell, peaking cell #1, and peaking cell #2 is 1 : 2 : 2.

In this paper, a three-stage DPA with an adaptive driving amplifier is implemented. It uses GaN HEMTs and is tested with a continuous wave (CW) and a worldwide interoperability for microwave access (WiMAX) signals with a PAPR of 8 dB at 3.5 GHz. The driving amplifier is employed at the input of the carrier cell, and controls the input power levels by adjusting its gate bias voltage in accordance with the power levels using the ET method. The measured results show high efficiency at a large BOP for both a CW and a WiMAX signal at 3.5 GHz.

II. DESIGN OF THE THREE-STAGE DPA WITH ADAPTIVE DRIVING AMPLIFIER USING ENVELOPE TRACKING METHOD

The ideal drain currents of a three-stage DPA are shown in Fig. 1, where the device size ratio of the carrier, peaking cell #1, and peaking cell #2 cell is 1 : 2 : 2. While the peaking #2 cell is operating, the drain current of the carrier cell is saturated and maintains half of the maximum current (I_{max}), until the peaking cells #1 and #2 reach I_{max}. The three-stage DPA has three peak efficiency points, which depend on the device size between the carrier and peaking cells. When the device size ratio of the carrier cell, peaking cell #1, and
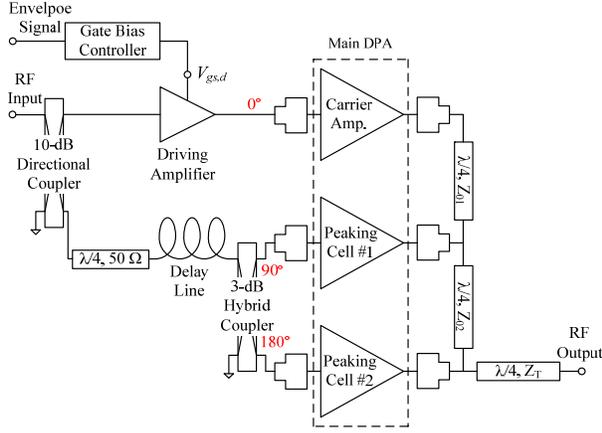
Fig. 2.   Schematic diagram of the proposed three-stage DPA with an adaptive driving amplifier using an envelope tracking technique.

peaking cell #2 is $1 : m_1 : m_2$, the high-efficiency back-off points, k_1 and k_2, are obtained by [6]

$$k_1 = \frac{1 + m_1}{1 + m_1 + m_2} \qquad (1)$$

$$k_2 = \frac{1}{1 + m_1} \qquad (2)$$

When GaN HEMT devices are used in three-stage DPAs, the drain current of the carrier cell cannot maintain $I_{max}/2$ until the full power condition of the peaking cells occurs, because the gate leakage current of the carrier cell increases with the source signal. For the ideal operation of a three-stage DPA even with an increased source signal, it is necessary to provide constant input power with the carrier cell.

Fig. 2 shows the proposed three-stage DPA with an adaptive driving amplifier. The output structure of the main DPA is the same as with a conventional DPA. However, with the proposed DPA, the driving amplifier at the input port of the carrier cell provides constant input power to the carrier cell by decreasing the gate bias voltage ($V_{gs,d}$) at high RF input power levels. As the gate bias of the driving amplifier decreases, the gain of the driving amplifier is reduced. Therefore, the output power of the driving amplifier remains constant despite increased RF input power. The delay line is inserted at the peaking cells to compensate for a delay mismatch among the driving amplifier, the carrier, and the peaking cells. The delayed signal is divided equally by a 3-dB hybrid coupler with a 90° phase difference between the peaking cells #1 and #2. The 10-dB directional coupler is used to balance the input power of the carrier and peaking cells. The 50-Ω quarter wavelength transmission line at the
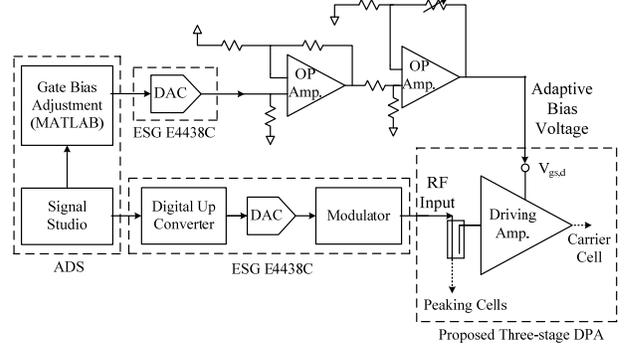

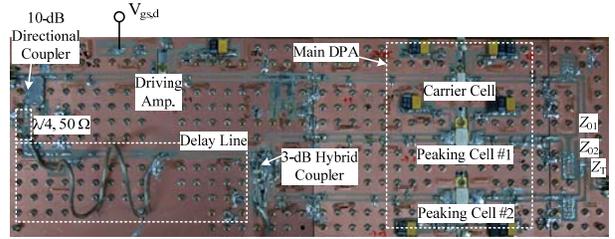Fig. 3.   Experimental setup for the envelope tracking technique using an adaptive driving amplifier.

Fig. 4.   Photograph of the fabricated three-stage DPA with the gain controller.

delay line creates a 90° phase difference between the carrier cell and peaking cell #1.

Fig. 3 dipicts the experimental setup for the ET technique controlling the $V_{gs,d}$. The Agilent ESG E4438C modulates the WiMAX signal generated by the Agilent signal studio. The MATLAB is used to generate the adaptive gate bias voltages according to the magnitudes of the RF input signal. A two-stage operational (OP) amplifier is used as the gate bias controller to provide sufficient voltage for the $V_{gs,d}$ of the driving amplifier, because the output power voltage of the digital-to-analog converter (DAC) is insufficient for this purpose.

III. IMPLEMENTATION AND EXPERIMENTAL RESULTS

Fig. 4 shows a photograph of the fabricated GaN HEMT three-stage DPA with the driving amplifier. The driving amplifier was implemented using a Cree CGH40010 10-W GaN HEMT device with a drain bias of 25 V. The carrier and peaking cells were implemented using Cree CGH35015 15-W and CGH40035 35-W GaN HEMT devices, respectively. The gate bias voltage of the carrier cell was set to a class-AB bias of –2.5 V (quiescent current, I_{DQ}=100 mA) with a drain bias voltage of 28 V. The gate bias voltages of the peaking and peaking cells #2 were set to a class-C bias of –5.9 V and –6.2 V, respectively, with drain bias voltages of 28 V. Assuming
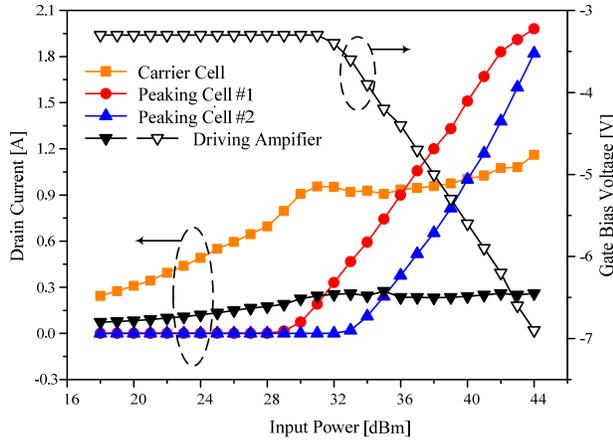
Fig. 5. Measured drain currents of the proposed DPA and the gate bias voltage of the driving amplifier according to input power levels for a CW at 3.5 GHz
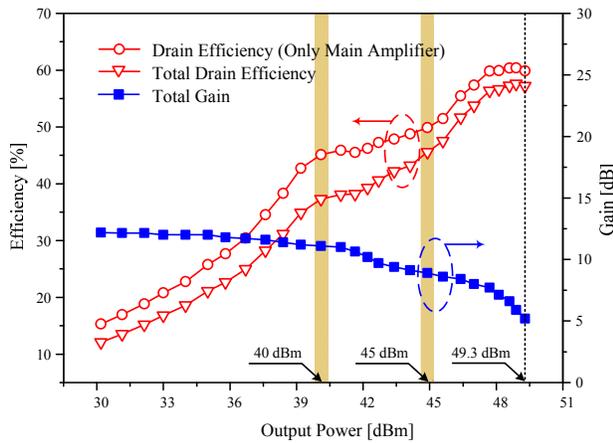

Fig. 6. Measured drain efficiency and gain of the proposed DPA for a CW at 3.5 GHz

TABLE I
MEASURED DE AND GAIN CHARACTERISTICS AT OUTPUT
POWER LEVELS OF 40 DBM AND 45 DBM FOR A 3.5-GHZ CW

Output Power [dBm]	Drain Efficiency [%]		Gain [dB]
	Only Main DPA	Total DE	
40	45.1	37.3	11.1
45	49.9	45.6	8.9

that the load impedances of the carrier and peaking cells were 50 Ω at the full power loading condition, then the impedances of Z_{01}, Z_{02}, and Z_T were 31.6 Ω, 33.3 Ω, and 70.7 Ω, respectively [6]. From (1) and (2), the proposed three-stage DPA has two peak efficiency points at 9.5- and 4.3-dB BOPs
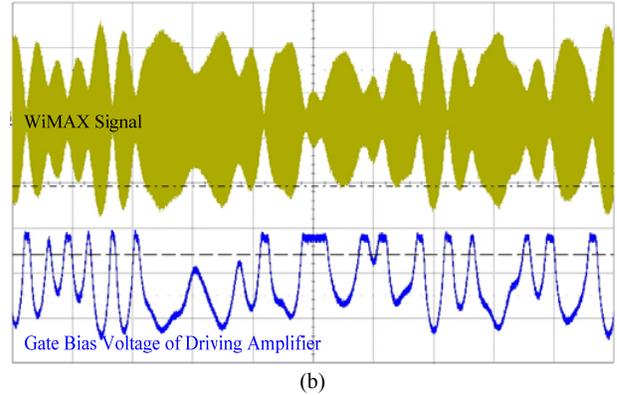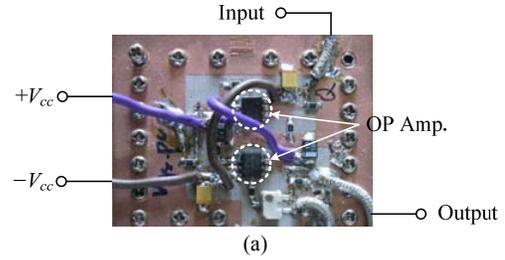

(a)

(b)

Fig. 7. (a) Implemented gate bias controller and (b) measured gate bias voltage of the driving amplifier according to the magnitude of the WiMAX signal.

from the saturation output power, since the device size ratio $1 : m_1 : m_2$ is approximately $1 : 2 : 2$. The implemented DPA has been tested using the CW and the WiMAX signal with a PAPR of 8 dB at 3.5 GHz.

Fig. 5 shows the measured drain currents for the driving amplifier, carrier, and peaking cells, as well as the $V_{gs,d}$ of the driving amplifier, as they vary with the input power levels for a CW at 3.5 GHz. The $V_{gs,d}$ of the driving amplifier is set to the class-AB bias of –3.3 V (quiescent current, I_{DQ}=50 mA) at low input power levels. The drain current of the carrier cell increases until the peaking cell #2 turns on. Since the gate leakage current increases with the gate bias of the carrier cell, the $V_{gs,d}$ of the driving amplifier decreases, and the output power of the driving amplifier is reduced. Therefore, the input power levels of the carrier cell are constant, and the drain current of the carrier cell maintains about 1A. This occurs even though the drain currents of the peaking cells #1 and #2 reach their maximum and the output power of the proposed three-stage DPA is saturated.

Fig. 6 represents the measured drain efficiency (DE) and gain characteristics of the proposed three-stage DPA according to output power levels for a CW at 3.5 GHz. The saturation output power is 49.3 dBm. Thus, the proposed three-stage DPA has its peak efficiency points at 40 dBm and 45 dBm, and the measured results are summarized in Table I. The total DEs with the driving amplifier are 37.7 % and
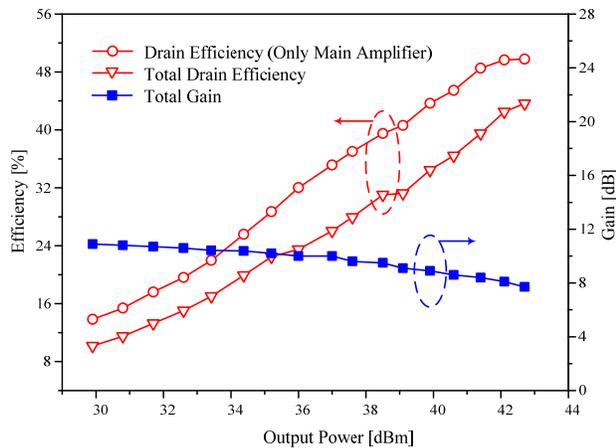
Fig. 8. Measured efficiency and gain characteristics according to output power levels for a WiMAX signal at 3.5 GHz

45.6 % at output power levels of 40 dBm and 45 dBm, respectively.

The fabricated gate bias controller is shown in Fig. 7(a). The TI THS3001 OP amplifiers are used to supply the adaptive bias voltage of the driving amplifier. Fig. 7(b) shows the WiMAX signal and the output of the gate bias controller. As the magnitude of the WiMAX signal increases, the $V_{gs,d}$ voltage decreases and reduces the gain of the driving amplifier. Thus, the input power levels of the carrier cell remain constant at high input power levels.

Fig. 8 represents the measured DE and gain characteristics according to output power levels for the WiMAX signal at 3.5 GHz. The DE of the main DPA and total DPA is 48.6 % and 39.5 %, respectively, with a gain of 8.4 dB at the output power of 41.4 dBm.

IV. CONCLUSION

We propose a three-stage DPA with an adaptive driving amplifier. By use of the ET technique, the adaptive driving amplifier is used at the input port of the carrier cell to reduce the carrier cell's leakage current that accurs at large input power levels. To verify this method, the carrier and peaking cells in the proposed DPA are implemented using GaN HEMT devices. For a CW at 3.5 GHz, the total DE is 37.3 % and 45.6 % at about 9.5- and 4.3-dB BOPs, respectively. For the WiMAX signal with a PAPR of 8 dB, the proposed DPA has a total DE of 39.5 % at an output power of 41.4 dBm. Therefore, the proposed three-stage DPA can be a promising solution to for achieving high efficiency over a wide output power range for 3.5-GHz WiMAX applications.

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