GaN HEMT Based High Power and High Efficiency Doherty Amplifiers with Digital Pre-Distortion Correction for WiBro Applications

Jun-Chul Park¹ · Dongsu Kim² · Chan-Sei Yoo² · Woo Sung Lee² · Jong-Gwan Yook¹ · Sang-Hyun Chun³ · Jong-Heon Kim³ · Cheol Koo Hahn²

Abstract

This paper presents high power and high efficiency Doherty amplifiers for 2.345 GHz wireless broadband (WiBro) applications that use a Nitronex 125-W (P_{3dB}) GaN high electron mobility transistor (HEMT). Two- and three-way Doherty amplifiers and a saturated Doherty amplifier using Class-F circuitry are implemented. The measured result for a center frequency of 2.345 GHz shows that the two-way Doherty amplifier attains a high P_{3dB} of 51.5 dBm, a gain of 12.5 dB, and a power-added efficiency (PAE) improvement of about 16 % compared to a single class AB amplifier at 6-dB back-off power region from P_{3dB} . For a WiBro OFDMA signal, the Doherty amplifier provides an adjacent channel leakage ratio (ACLR) at 4.77 MHz offset that is -33 dBc at an output power of 42 dBm, which is a 9.5 dB back-off power region from P_{3dB} . By employing a digital pre-distortion (DPD) technique, the ACLR of the Doherty amplifier is improved from -33 dBc to -48 dBc. The measured result for the same frequency shows that the three-way Doherty amplifier, which has a P_{3dB} of 53.16 dBm and a gain of 10.3 dB, and the saturated Doherty amplifier, which has a P_{3dB} of 51.1 dBm and a gain of 10.3 dB, provide a PAE improvement of 11 % at the 9-dB back-off power region and 7.5 % at the 6-dB back-off region, respectively, compared to the two-way Doherty amplifier.

Key words: Class-F, Digital Pre-Distortion (DPD), Doherty Amplifier, Gallium Nitride (GaN), WiBro.

I. Introduction

Commercial wireless communication systems are increasingly required to transmit high data rate signals for numerous multimedia communications, which usually have a large signal bandwidth and high peak-to-average ratio (PAR). With this current trend, the wireless broadband (WiBro) system, the official name of the portable internet system in Korea, is heading towards commercial service. The WiBro is a homegrown variant standard of IEEE 802.16e and is designed to provide seamless mobile connectivity over the 2.3 GHz spectrum at ground speed up to 60 kilometers per hour, with an average bandwidth of 16 Mbps [1]. WiBro is based on orthogonal frequency division multiplexing access (OFDMA), which is a technology that uses discrete multi-tone signals. Compared to a single-carrier channel, it can cope with data error caused by multipath channels; hence, it results in almost errorless transmission over fading channels. Although the OFDMA technique has an advantage of errorless data transmission, it places more severe requisites on the system, especially the power amplifier.

Multi-tone signals have a non-constant envelope waveform and the PAR depends on the number of tones and relative phases among the tones. Accordingly, the signal for a WiBro system typically has peak-to-average envelope excursions of about 8~12 dB or more. For this reason, the power amplifiers for WiBro applications have to be highly linear to allow amplification of this kind of waveform with little distortion, thereby ensuring errorless demodulation and efficient operation at a large back-off power region. In addition, due to the OFDMA signal bandwidth of 8.75 MHz, a WiBro system has to deal with a broad bandwidth. Therefore, power amplifiers for WiBro applications have three technical points to consider: broadband operation, linearity, and efficient operation.

At present, several kinds of efficiency enhancement techniques are being evaluated for high PAR applications, including the Doherty amplifier, envelope tracking (ET), envelope elimination and restoration (EER), linear amplification with nonlinear components (LINC), and switch-mode amplifiers, among others [2]. Of these, the Doherty amplifier has been the most extensively inves-

Manuscript received November 30, 2011 ; revised February 15, 2011. (ID No. 20101130-036J)

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tigated due to its simple circuitry, ease of configuration, and wide bandwidth compared with other techniques [3].

An increase in the operating power and frequency band of the WiBro system also requires GaN high electron mobility transistor (HEMT) technology because of its high breakdown voltage, electron saturation velocity, frequency, and power performance. Many research groups have developed GaN-based Doherty amplifiers using load-modulation techniques or switch-mode class E/F amplifiers [4~6]. Doherty amplifiers with class E or F amplifiers have also been proposed for 2.1 GHz WCDMA applications in order to provide additional efficiency [7~8].

In this paper, high power two- and three-way Doherty amplifiers that use GaN HEMT devices for 2.345 GHz WiBro applications are designed, fabricated to satisfy the specifications of WiBro [9, 10], and tested. The two- and three-way Doherty amplifiers show a substantial improvement in the efficiency at the 6-dB and 9-dB back-off region, respectively, when compared to a single class-AB amplifier. The use of digital pre-distortion correction also provides high linearity performance for the two-way Doherty amplifier. In addition, the use of Class-F circuitry in a saturated Doherty amplifier achieves further improvement in efficiency.

II. Analysis for Operation Principles

2-1 Two-way Doherty Amplifier

A schematic of the two-way Doherty amplifier for 2.345 GHz WiBro application is shown in Fig. 1. The input signal is divided into the two amplifiers by a 90° hybrid coupler. The transistors of the main and peaking amplifiers are the same size and have a symmetric structure. In an ideal classical Doherty amplifier, both transistors operate at the bias condition of class-B [11]. However, a transistor operated at this bias condition provides very high efficiency at the expense of poor linearity. Current wireless communication systems are required to have high linearity because of high data transfer rates; thus, the general approach is to employ a class-AB for the main amplifier and a class-C bias condition for the peaking amplifier [4, 7].

The Doherty amplifier technique is based on a change in load impedance, which is referred as load modulation, according to the input power level. Because of load modulation, the Doherty amplifier operates at two different conditions: low power and high power regions. In the low power region, only the main amplifier operates; the peaking amplifier remains at an open state at the load of the main amplifier. On the other hand, in the high power region, the main amplifier begins to saturate and the peaking amplifier is turned on. This precise opera-

tion of a two-way Doherty amplifier can be readily seen in simulations using the Advanced Design System simulator and the design model of GaN transistor, as is used in our work. The output power characteristics of the two operating regions are shown in Fig. 2. The main and peaking amplifiers begin to saturate and operate, respectively, at the peaking point, which is at about a 6 dB back-off power region from P_{3dB} of Doherty amplifier. The total power of the two amplifiers is the power of the Doherty amplifier. In the low power region, the peaking amplifier remains in the cut-off state and has a very high load impedance, while the load impedance of the main amplifier is two times larger than that of the output load impedance: 50 ohm in a general system. As the peaking amplifier is turned on, the load impedance of the main amplifier varies from 100 ohm to 50 ohm, as shown in Fig. 3. With the variance in the load impedance, the current of the peaking amplifier begins to flow at the 6 dB back-off power region, which is 45 dBm in this simulation, as shown in Fig. 4.

2-2 N-way Doherty Amplifier

The two-way Doherty amplifier has a 6 dB back-off

Fig. 1. Schematic of the two-way Doherty amplifier.

Fig. 2. Simulated output power characteristics.

Fig. 3. Simulated load impedances of the main and the peaking amplifiers.

Fig. 4. Simulated current and voltage amplitudes of the main and the peaking amplifiers.

power region, but the PAR of the WiBro OFDMA signal is about 8~12 dB. Therefore, amplifiers for WiBro applications are required to have a back-off power region higher than 6 dB. The three-way Doherty amplifier has about a 9 dB back-off power region in general and is a good solution for this problem. The schematic of the common three-way Doherty amplifier is shown in Fig. 5. The structure of the three-way Doherty amplifier is similar to that of the two-way Doherty amplifier. One more peaking amplifier is added to get a higher back-off power region by controlling load impedance and two more 90° hybrid couplers are added to adjust the phases of the three transistors.

The ideal efficiency characteristics of the Doherty amplifier were obtained using the formula induced by Raab. The ideal efficiency characteristics of the N-way Doherty amplifier can be written as [12]. Ideal efficien-

Fig. 5. Schematic of the three-way Doherty amplifier.

Fig. 6. Ideal efficiencies of the N-way Doherty amplifier.

cies of the N-way Doherty amplifiers are shown in Fig. 6. In the case of the three-way Doherty amplifier, the peaking point is formed at about a 9 dB back-off power region.

2-3 Class-F Amplifier

A saturated Doherty amplifier can improve efficiency by controlling harmonic components and can be employed with the Doherty amplifier to provide further enhancement of efficiency [7]. For the ideal class-F operation with a half-sine drain current waveform and a rectangular voltage waveform, the harmonic control network should be short and open, for even and odd harmonics, respectively.

Because there is no overlap between the drain voltage and current waveforms of a class-F power amplifier, an ideal efficiency of 100 % is achieved. Although the ideal class-F power amplifier has 100 % efficiency when all of the harmonics are controlled, the proposed class-F

Fig. 7. Proposed output network of a class-F amplifier.

harmonic control circuit treats only two harmonic components, the 2nd and 3rd, which are the main factors of harmonic control; this enables the amplifier to have high efficiency [7]. As shown in Fig. 7, the harmonic control circuit consists of a 3rd harmonic control component, a 2nd harmonic control component, and a fundamental matching component. The physical length of each transmission line is expressed as the electrical length based on a fundamental frequency. The 2nd and 3rd harmonic control components include two shunt stubs for better harmonic control and a tuning line between them to adjust the quarter wavelength in the fundamental frequency, together with the 3rd harmonic control component.

III. Implementation and Measurement Results

3-1 Two-way Doherty Amplifier for WiBro Applications

The proposed Doherty amplifier was fabricated and evaluated. A photograph of the proposed Doherty amplifier is shown in Fig. 8. A GaN HEMT, the NPT25100 by Nitronex Corporation, is used as the main and peaking amplifier. The NPT25100 is a 125 W P_{3dB} peak envelope power, pre-matched, 36 mm gate periphery GaN HFET mounted into an air-cavity CPC package. Matching circuits were designed from the load-pull data-sheet of the NPT25100. The peaking bias point and compensation line length were optimized to obtain an accurate load modulation, so that the output impedance of the peaking amplifier at the combining point is almost open at the low power region. The substrate is a Taconic RF-35, which has a dielectric constant of 3.5, a substrate thickness of 0.762 mm, and a dissipation factor of 0.0018 at 2.345 GHz. The 90 deg hybrid coupler, theXC2500E-03S by Anaren, is used in front of the two amplifiers.

The measured and simulated characteristics of the

Doherty amplifier using a 2.345 GHz continuous wave (CW) are shown in Fig. 9. The measurement used the Agilent E8267D PSG Vector Signal Generator and E4440A PSA Series Spectrum Analyzer. The drive amplifier, with a gain of 51 dB, was a class-AB amplifier, the CBP02064741 from CERNEX Inc. The Doherty amplifier can carry on a P_{3dB} of 51.5 dBm and has a power gain of 12.5 dB. The measured results of the amplifier are in good agreement with the simulated results. Fig. 10 shows the power-added efficiency (PAE) of the Doherty amplifiers and for a single class-AB amplifier, according to output power back-off levels for a CW signal. The peaking bias of the Doherty amplifier is tuned from -1.5 V (Class-AB) to -4.5 V, so that the optimum bias point was reached. This made the amplifier have the highest efficiency at the 6 dB back-off power region. The Doherty amplifier displays excellent effi-

Fig. 8. Top view of the proposed two-way Doherty amplifier.

Fig. 9. Simulated and measured characteristics of the two-way Doherty amplifier for a continuous wave.

Fig. 10. Measured power added efficiency of the two-way Doherty amplifier for a continuous wave.

Fig. 11. Measured error vector magnitude of 2.345 GHz WiBro OFDMA signal at an average output power of 42 dBm.

ciency of about 41 % at the 6 dB back-off power region, which is 16 % higher than seen for a single class-AB amplifier, when the peaking bias is selected as -4 V. Fig. 11 shows the measured error vector magnitude (EVM) spectrum of a WiBro OFDMA signal at an average output power of 42 dBm. The linearity specification for the modulation signal is about 3 % of the EVM [10]. The proposed Doherty amplifier has 2.58 % of the EVM and fully satisfies this in-band-error specification.

For a WiBro OFDMA signal, the proposed Doherty amplifier has a poor ACLR of -30 dBc at the 6 dB back-off region with the ± 4.77 MHz offset frequency of WiBro standards. Accordingly, digital pre-distortion using the test bench, as shown in Fig. 12, has been applied to improve the linearity of the GaN Doherty power amplifier [13]. The test bench consists of a programmable signal generator (Agilent PSG 8267D), a device

Fig. 12. Test bench for digital pre-distortion.

under test with a drive amplifier, a 40 dB attenuator, a performance spectrum analyzer (Agilent PSA E4440A) with 40 MHz analysis bandwidth, and a personal computer with the Agilent Advanced Design System 2008, the Agilent 89601 Vector Signal Analysis, and the Mathworks Matlab 2008. The PSA for the receiver has an analysis bandwidth better than 26.25 MHz to compensate for the 3rd order distortion, because the 1FA WiBro modulated signal has an 8.75 MHz signal bandwidth. The memory polynomial based PD (of the 7th polynomial order, with 3 memory terms) was used to minimize the AM-AM and AM-PM distortion of the GaN Doherty power amplifier.

Fig. 13 shows the measured 1FA WiBro spectrum of a GaN Doherty power amplifier with non-applied and applied digital pre-distortion at 42 dBm, which is the 9.5 dB output back-off power region from P_{3dB} . At a

Fig. 13. 1FA WiBro spectrum of the two-way Doherty amplifier with non-applied and applied DPD.

Table 1. ACLR of GaN Doherty power amplifier with non-applied and applied DPD.

	ACLR (Lower)	ACLR (Upper)	EVM
Non-applied DPD	-34.6 dBc	-33.2 dBc	2.58 %
Applied DPD	-48.3 dBc	-49.9 dBc	0.93 %

± 4.77 MHz offset frequency, a linearity improvement of 13.7 dBc and 16.7 dBc, respectively, was achieved and 1.65 % of EVM was enhanced with DPD.

Table 1 shows the measured ACLR and EVM of the GaN Doherty power amplifier with non-applied and applied digital pre-distortion at ± 4.77 MHz offset frequency.

3-2 Three-Way Doherty Amplifier for Extension of the Efficiency Range

According to the basic concepts, a three-way Doherty amplifier was designed and fabricated as shown in Fig. 14. The input signal is divided into the three transistors by 90° deg hybrid couplers, which are added to adjust the phase of the three transistors, and three compensation lines with the same length are added to the output load of each transistor for the open state of the peaking amplifier in the low power region.

The gate voltage is a bias condition of the class-AB and class-C for one main and two peaking amplifiers, respectively, and the drain voltage is 28 V. In order to have an identical phase for the two peaking amplifiers, the same bias condition and compensation line used for class-C operation are also used here. The measured characteristics of the three-way Doherty amplifier using a 2.345 GHz CW signal are shown in Fig. 15. This Doherty amplifier can carry on a high P_{3dB} of 53.16 dBm and has a power gain of 10.3 dB. Fig. 16 shows the measured PAE of the three-way Doherty amplifier for 2.345 GHz CW signal. A high PAE of 40.5 % is obtained at the 9-dB back-off output power region from P_{3dB} . This is 11 % higher than that of the two-way Doherty amplifier and is a 23 % improvement over that of the single class-AB amplifier.

3-3 Saturated Doherty Amplifier for the Higher Efficiency

The saturated Doherty amplifier was constructed by first designing the output harmonic control circuit based on class-F circuitry. By adjusting each length, the shunt stubs of the 2nd and 3rd harmonic control circuit can ad-

Fig. 14. Top view of the proposed three-way Doherty amplifier.

Fig. 15. Measured characteristics of three-way Doherty amplifier for a continuous wave.

Fig. 16. Comparison of the measured power added efficiency.

just the resonance frequency, which is respectively 4.69 GHz and 7.035 GHz in this case, and the series lines, such as the tuning line in Fig. 7, can control the exact phases of the 2nd and 3rd harmonic components. Fig. 17 shows the simulated performance of the designed harmonic control circuit. The impedances at the 2nd and 3rd harmonic frequencies are placed at short and open state, respectively. With this harmonic control circuit, the saturated Doherty amplifier for 2.345 GHz WiBro applications is designed, fabricated, and measured. Fig. 18 shows the top view of the fabricated saturated Doherty amplifier. The basic construction and bias conditions of the two transistors are the same as for the two-way Doherty amplifier.

Fig. 19 shows the measured characteristics of the saturated Doherty amplifier using a 2.345 GHz CW signal. The fabricated saturated Doherty amplifier provides a high P_{3dB} of 51.1 dBm and a power gain of about 12.2 dB, which is similar to the operation of two-way Doherty amplifier. Fig. 20 shows the PAE of the fabricated Doherty amplifier for 2.345 GHz CW signal. A high PAE of 48.5 % is obtained at the 6 dB back-off output power region from P_{3dB} . This is 7.5 % and 23.5 % higher than for the two-way Doherty amplifier and the single class-AB amplifier, respectively. Although the saturated Doherty amplifier has a demerit over the three-way Doherty amplifier on the PAE around the 9 dB back-off region, if an N-way saturated Doherty amplifier is designed in the near future, we expect to obtain a better performance on PAE at higher back-off power regions. Finally, measuring the PAE of the fabricated Doherty amplifiers for the WiBro OFDMA signal of 2.345 GHz, as shown in Fig. 21, shows that the technique to improve efficiency by controlling harmonic

Fig. 17. Simulated impedance points of the output matching circuit.

Fig. 18. Top view of the fabricated saturated Doherty amplifier.

Fig. 19. Measured characteristics of the saturated Doherty amplifier for a continuous wave.

Fig. 20. Comparison of the measured power added efficiency for a continuous wave.

Fig. 21. Comparison of the measured power added efficiency for WiBro OFDMA signal.

Fig. 22. Performance comparison of reported Doherty power amplifiers.

components can be applicable to amplifiers used in WiBro applications. All of design parameters used to make Doherty amplifiers in this paper are expressed in Table 2 and, based on Fig. 22, the suggested Doherty amplifiers provide additional efficiency when compared with previous designs.

IV. Conclusions

High power two- and three-way Doherty amplifiers, and a saturated Doherty amplifier, which use a GaN HEMT device for 2.345 GHz WiBro applications, have been successfully implemented. For a 2.345 GHz CW signal, the two-way Doherty amplifier provides a high P_{3dB} of 51.5 dBm, a power gain of 12.5 dB, and a PAE of 41 % at the 6 dB back-off power region from P_{3dB} .

Table 2. Design parameters of the proposed Doherty amplifiers

Parameters	Two-way	Three-way	Saturated
DC gate voltage (Main amp)	−1.43 V	−1.45 V	−1.43 V
DC gate voltage (Peaking amp)	−4 V	−3.8 V	−3.9 V
DC drain voltage	28 V	28 V	28 V
Quiescent drain Current (Main amp)	600 mA	600 mA	600 mA
Linear power gain	12.5 dB	10.3 dB	12.2 dB
P_{3dB}	51.5 dBm	53.16 dBm	51.1 dBm
PAE @ P_{3dB}	50 %	49.8 %	60.3 %
PAE @ 6 dB back-off region	41 %	38.5 %	48.5 %
PAE @ 9.5 dB back-off region	29.5 %	40.5 %	33 %

Because of the poor linearity characteristics of the GaN device, an ACLR of the Doherty amplifier was improved using a digital pre-distortion technique for a WiBro OFDMA signal. A three-way Doherty amplifier and a saturated Doherty amplifier using Class-F circuitry are also designed and fabricated to obtain better performance from an efficiency point of view. Compared to the two-way Doherty amplifier, the three-way Doherty amplifier, which has a P_{3dB} of 53.16 dBm and a gain of 10.3 dB, and the saturated Doherty amplifier, which has a P_{3dB} of 51.1 dBm and a gain of 10.3 dB, provide a PAE improvement of 11 % at the 9-dB back-off power region and 7.5 % at 6-dB back-off region, respectively. In the near future, an N-way saturated Doherty amplifier will be developed for more than a 9 dB back-off operation with DPD correction.

This work was supported by the IT R&D program of MIC/IITA. [2009-F-044-01, Development of GaN Power Amplifier for 4G Base Station]. The authors would also like to thank C. Y. Park and J. W. Park at RFHIC Inc. for their helpful discussions.

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