Progress In Electromagnetics Research Letters, Vol. 32, 187–195, 2012

A 460 MHz DOHERTY AMPLIFIER FOR IMT-ADVANCED SYSTEM

R. W. Zhou*, Y. Dong, and J. F. Bao

Institute of Electronic Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China

Abstract—A 2-way symmetrical Doherty power amplifier (PA) with high efficiency is presented. This amplifier delivers 49.2 dBm (83 W) of saturated output power and 63% drain efficiency with 38.2 dB of power gain at 460 MHz. The drain efficiency at 6 dB backed-off power level shows about 62%. After digital pre-distortion (DPD) system corrected, about 48% power-added efficiency (PAE) at 42.2 dBm (16.6 W) average output power has been demonstrated, while achieving −52 dBc (−28 dBc before linearization) Adjacent Channel Leakage Ratio (ACLR) at 20 MHz offset using a LTE-Advanced input signal with 6.5 dB peak to average ratio (PAR) to meet the IMT-Advanced system requirements. We also used a π type structure network based on lumped elements to replace the traditional Doherty amplifier $1/4\lambda$ transmission line, and compared the performance.

1. INTRODUCTION

With the rapid development of modern wireless communication, the future business will turn to focus on data and multimedia transmission from voice. International Mobile Telecommunications-Advanced (IMT-Advanced) will carry the global wireless communication services as the next world standard of mobile communication. Systems such as LTE-Advanced use signals with high PAR. It becomes particularly challenging since these signals require amplifiers to operate in large back-off output power region. However, a traditional class-AB power amplifier operating at large back-off has low efficiency. Hence, RF amplifiers with high linearity and efficiency are required for the base stations.

Received 22 May 2012, Accepted 13 June 2012, Scheduled 19 June 2012

* Corresponding author: Rong Wei Zhou (harryzhourong@gmail.com).

Various PA architectures with efficiency enhancement techniques have been investigated [1–5], among others, the Doherty power amplifier technique has been in particular a front contender [6–8].

In the 2007 World Radiocommunication Conference (WRC-07), the Radiocommunication Sector of International Telecommunications Union (ITU-R) divided a new frequency band 450–470 MHz for the International Mobile Telecom System (IMT) [9]. In this paper, we demonstrate a high efficiency Doherty PA operating at 460 MHz. The Doherty PA exhibits 49.2 dBm (83 W) of saturated output power. By using DPD system, it achieves 54% drain efficiency (48% PAE), −52 dBc ACLP at the average output power of 42.2 dBm (16.6 W) for a 20 MHz LTE-Advanced signal with 6.5 dB PAR.

2. DOHERTY POWER AMPLIFIER

The Doherty technique was first invented in 1936 as a means of achieving high efficiency for tube amplifiers by William H. Doherty [10]. It does not require additional complex peripheral circuit structure [11]. Fig. 1 shows the typical symmetrical Doherty architecture.

It is consisted of a carrier amplifier and a peaking amplifier, the input power is equally distributed to the two amplifiers through an input power splitter. With the aim to achieve load modulation for the carrier PA, two $1/4\lambda$ transmission lines as an impedance inverter combine the two amplifiers. The offset line at the output of the peaking amplifier is aim to compensate phase delay and prevent power leakage, the $1/4\lambda$ transmission line before the peaking amplifier and the other offset line play a role in keeping phase balance.

A proper load modulation of the carrier amplifier is supposed to provide nearly constant efficiency for the targeted output power back-off range of usually up to 6 dB. The load impedance Z_A and Z_C in

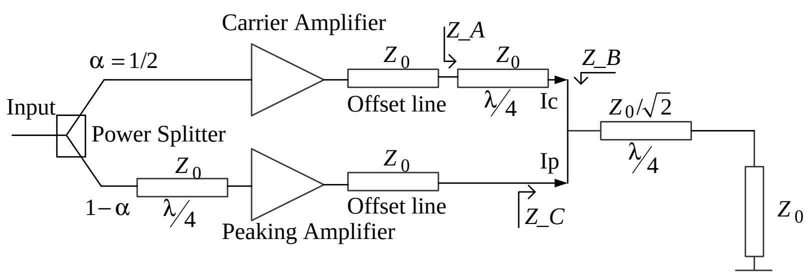

Figure 1. Structure of the symmetrical Doherty PA.

Fig. 1 are given by [12]:

$$Z\_A = \frac{2Z_0}{1 + \frac{I_p}{I_c}} \tag{1}$$

$$Z\_C = \left(1 + \frac{I_c}{I_p}\right) \cdot \frac{Z_0}{2} \tag{2}$$

where I_c and I_p denote the output currents of the carrier and peaking amplifiers, respectively. At low input power levels, the carrier PA maintains a load impedance of $2Z_0$ while the peaking PA is turned off. With the input power increasing, the peaking PA will turn on when the carrier PA reaches its first maximum efficiency point. For typical symmetrical Doherty amplifier, $\alpha = 1/2$, which means the maximum output power of the carrier PA is one-half of the maximum output power of the Doherty PA, so I_p will increase from zero to I_c. It can be deduced from (1) and (2), ideally, Z_A moves gradually from $2Z_0$ to Z_0 while Z_C drops from a very high impedance value to Z_0.

Usually, the carrier amplifier is biased at class AB or B mode while the peaking amplifier is biased at class C mode [13]. In this case, the saturated power of the carrier and peaking amplifier is equivalent. Therefore, a maximum output power of two times the carrier PA power capacity can be achieved. This ensures that the Doherty PA operates at a large back-off output power level with high efficiency [14]. It can be derived from Eq. (3):

$$Backoff = 10 \log \left(\frac{P_{Doherty\_\max}}{P_{Carrier\_first\_saturation}} \right) \tag{3}$$

where $P_{Doherty\_\max}$ is the maximum output power of the Doherty PA and $P_{carrier\_first\_saturation}$ is the maximum output power of the carrier amplifier at the first saturation point. The carrier amplifier will reach the first saturation point 3 dB in advance due to the load modulation, so the value of $Backoff$ is given by:

$$Backoff = 10 \log(4) \approx 6\,\mathrm{dB} \tag{4}$$

The second efficiency peak will occur when the carrier and the peaking amplifiers both get the maximum output power. And the maximum drain efficiency of an ideal class-B PA will be 78.5% [15]. Hence, the Doherty PA will reach the maximum drain efficiency point twice. The theoretical drain efficiency of a typical Doherty PA is shown in Fig. 2.

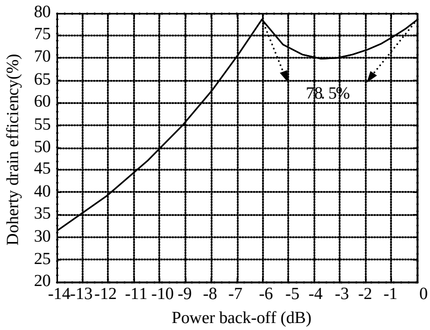

Figure 2. Theoretical drain efficiency of a typical Doherty PA.

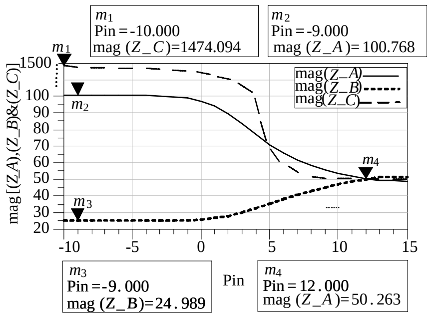

Figure 3. Simulated load modulation of Z_A, Z_B and Z_C.

3. DOHERTY AMPLIFIER DESIGN

The Doherty PA is designed and simulated to operate at 460 MHz. The carrier and peaking amplifier are both using 54 W LDMOS devices (MRFE6S9045N). The carrier PA is biased in a Class-AB condition, resulting in VDS = 28 V and VGS = 3.1 V. With all harmonics terminated to 50 Ω, the optimum output power impedance Z_{opt} of the device has been determined from a load pull simulation to be $Z_{opt} = 3.5 + j4.7\,\Omega$, the Z_{opt} is matched to $Z_0 = 50\,\Omega$ through the carrier PA output network.

The peaking PA is designed to have the same input and output network with the carrier PA for they both use the same device. But the peaking PA is biased in a class-C condition, resulting in VDS = 28 V and VGS = 2.0 V. And the Z_{opt} is matched to 50 Ω to operate in its full capacity [16]. The complete peaking PA comprises the offset line to prevent power leakage and compensate phase delay [17]. This is very important, because when the input signal is at low power levels, only the carrier amplifier is operating, and too much output power leaking to the peaking PA may destroy the transistor. The load impedance of the peaking PA is infinity in theoretical. But it could not be reached in practice, therefore, to some extent, the offset line makes up the unexpected result. Then, the carrier and the peaking PA are combined and output matched to 50 Ω using an additional $1/4\lambda$ transmission line with the characteristic impedance of 35.36 Ω (see Fig. 1).

The simulated load modulation of Z_A, Z_B and Z_C (see Fig. 1) is depicted in Fig. 3.

Bulky $1/4\lambda$ transmission line at 460 MHz is nearly 100 mm ($Er = 3.48$), a compact network can be employed for the narrow band

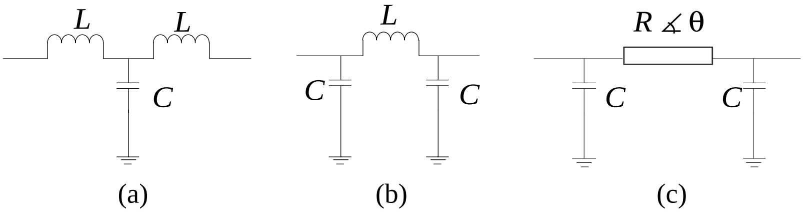

Figure 4. Three alternative configurations for the network based on lumped elements.

Table 1. Calculated components values in 450–470 MHz ($Z_0 = 50\,\Omega$).

Components / Frequency	Inductor (nH)	Capacitor (pF)
450 MHz	17.7	7.1
460 MHz	17.3	6.9
470 MHz	16.9	6.8

realization. Fig. 4 shows three alternative configurations for the network based on lumped elements. For these cases, the components values are given by [18]

$$L = Z_0/\omega_0 \tag{5}$$

$$C = 1/Z_0\omega_0 \tag{6}$$

where ω_0 is the operational frequency and Z_0 is the characteristic impedance of the $1/4\lambda$ transmission line. In this paper, we used a π type structure network with two shunt capacitors and an inductor (see Fig. 4(b)). The calculated components values in 450–470 MHz ($Z_0 = 50\,\Omega$) are shown in Table 1.

For practical components restricted, we used a 14 nH Coilcraft RF inductor and two 6.8 pF ATC RF capacitors to achieve 75° phase shift, and then connected a 15° transmission line to realize the function of $1/4\lambda$ transmission line.

4. EXPERIMENTAL RESULTS

A photograph of the symmetrical Doherty PA realized on a Rogers 4350 ($Er = 3.48$) substrate is shown in Fig. 5. The square with dotted line in Fig. 5 is replaced by the designed π-network with lumped elements and zoomed to obtain Fig. 6.

The Doherty PA is characterized using a single-tone (CW) signal in order to determine larger signal output power, gain and efficiency.

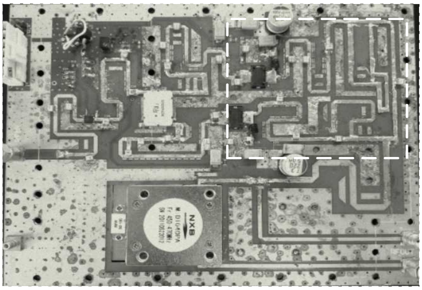

Figure 5. Top view of the designed Doherty PA.

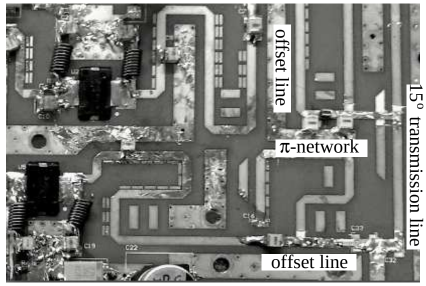

Figure 6. Designed π-network with lumped elements.

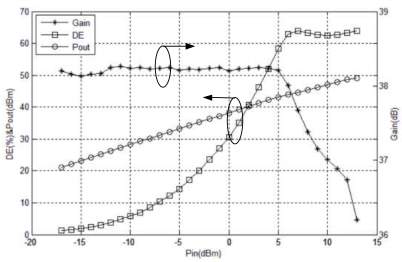

Figure 7. Gain, output power and drain efficiency.

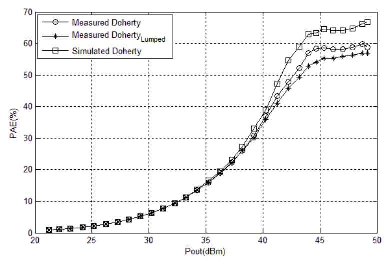

Figure 8. Simulated and measured PAE of the conventional Doherty PA and measured PAE of the Doherty PA with designed π-network.

The measured RF performances are shown in Fig. 7. 49.2 dBm (83 W) saturated output power and 38.2 dB of power gain with constant drain efficiency of 62% up to 6 dB back-off have been achieved. Fig. 8 shows the simulated, measured PAE of the conventional Doherty PA and measured PAE of the Doherty PA with designed π-network. The Doherty PA with lumped elements network exhibits the same saturated output power and reduces the size of the circuit, but has a slightly lower PAE (about 4% at a high power level) than the conventional one. Fig. 9 shows the measured bandwidth performance at the average output power of 42.5 dBm. The gain flatness is about 0.2 dB within the whole concerned frequency band.

The linearity performance of the Doherty PA under practical conditions has been tested using a LTE-Advanced signal with 6.5 dB PAR at 0.01% on the CCDF. Excellent drain efficiency of 54% (48% PAE) and -28 dBc ACLR before linearization (measured at

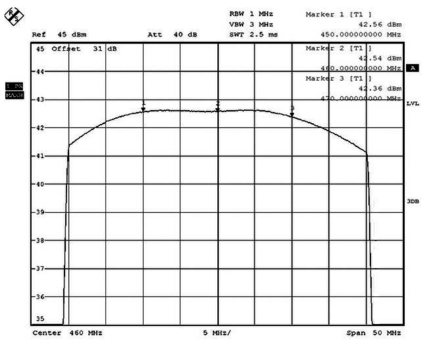

Figure 9. Measured bandwidth performance at the average output power of 42.5 dBm.

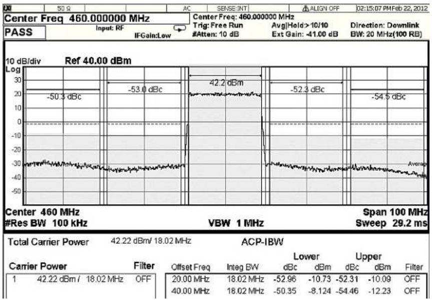

Figure 10. Measured output spectrum after DPD linearization.

20 MHz offset) at the average output power of 42.2 dBm (16.6 W) were obtained.

In order to fulfill the linearity requirements of the IMT-Advanced system (supposed to be −45 dBc), digital pre-distortion (DPD) has been applied. Fig. 10 shows the power spectrum density of the signal after linearization. Less than −52 dBc ACLR has been achieved to meet the system requirements.

5. CONCLUSION

A 460 MHz Doherty amplifier for IMT-Advanced system has been reported in this paper. The Doherty PA produced 83 W of CW saturated power at 63% drain efficiency. We obtained 48% power-added efficiency at the average output power of 42.2 dBm (16.6 W) using a LTE-Advanced input signal with 6.5 dB PAR. And the Doherty PA has been linearized using DPD to achieve −52 dBc ACLR. Furthermore, a π-network with lumped elements was designed to shrink the circuit size and just performed slightly worse than the conventional Doherty did. This work provides an alternative efficiency enhancement solution for the base stations.

ACKNOWLEDGMENT

This work was supported by the High Efficiency and Linearity, Broadband Power Amplifier Module Program (No. 2010ZX03007-003). The authors would like to thank Huawei Ltd. for providing commercial DPD system.

REFERENCES

1. Darraji, R. and F. M. Ghannouchi, "RF/DSP codesign methodology of enhanced doherty amplifiers," *IEEE Transactions on Circuits and Systems II: Express Briefs*, Vol. 59, No. 4, 219–223, Apr. 2012.
2. Tuffy, N., A. Zhu, and T. J. Brazil, "Novel realisation of a broadband high-efficiency continuous class-F power amplifier," *2011 European Microwave Integrated Circuits Conference (EuMIC)*, 120–123, Oct. 10-11, 2011
3. Tanany, A. A., D. Gruner, and G. Boeck, "Harmonically tuned 100 W broadband GaN HEMT power amplifier with more than 60% PAE," *2011 41st European Microwave Conference (EuMC)*, 159–162, Oct. 10–13, 2011.
4. Jimenez-Martin, J. L., V. Gonzalez-Posadas, J. E. Gonzalez-Garcia, F. J. Arques-Orobon, L. E. Garcia-Munoz, and D. Segovia-Vargas, "Dual band high efficiency class ce power amplifier based on CRLH diplexer" *Progress In Electromagnetics Research,* Vol. 97, 217–240, 2009.
5. Kim, J., B. B. S. Fehri, and J. Wood, "Power efficiency and linearity enhancement using optimized asymmetrical doherty power amplifiers," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 59, No. 2, 425–434, Feb. 2011.
6. Deguchi, H., N. Ui, K. Ebihara, K. Inoue, N. Yoshimura, and H. Takahashi, "A 33 W GaN HEMT Doherty amplifier with 55% drain efficiency for 2.6 GHz base stations," *IEEE MTT-S International Microwave Symposium Digest, MTT'09*, 1273–1276, Jun. 7–12, 2009.
7. Landon, T., C. Steinbeiser, P. Page, R. Hajji, G. Burgin, R. Branson, O. Krutko, J. Delaney, and L. Witkowski, "Design of a 600 W Doherty using generation 2 HVHBT with 55% WCDMA efficiency linearized to −55 dBc for 2c11 6.5 dB PAR," *2012 IEEE Topical Conference on Power Amplifiers for Wireless and Radio Applications (PAWR)*, 73–76, Jan. 15–18, 2012.
8. Lee, J. Y., J. Y. Kim, J. H. Kim, K. J. Cho, and S. P. Stapleton,, "A High power asymmetric doherty amplifier with improved linear dynamic range," *2006 IEEE MTT-S International Microwave Symposium Digest*, 1348–1351, Jun. 11–16, 2006
9. De La Torre, M., "Impact of WRC-07 and the US implementation of the digital dividend," Telecommunications Management Group, Inc., Apr. 2008.
10. Doherty, W. H., "A new high efficiency power amplifier

for modulated waves," *Proceedings of the Institute of Radio Engineers*, Vol. 24, No. 9, 1163–1182, Sept. 1936.

11. Lee, M.-W., S.-H. Kam, Y.-S. Lee, and Y.-H. Jeong, "A highly efficient three-stage Doherty power amplifier with flat gain for WCDMA applications," *Journal of Electromagnetic Waves and Applications*, Vol. 24, Nos. 17–18, 2537–2545, 2010.
12. Cripps, S. C., *RF Power Amplifiers for Wireless Communications,* Artech House, Nor-wood, MA, 1999.
13. Colantonio, P., F. Giannini, R. Giofre, and L. Piazzon, "The AB-C Doherty power amplifier. Part I: Theory," *IJRFMCAE*, Vol. 19, No. 3, 293–306, May 2009.
14. Bousnina, S., "Maximizing efficiency and linearity," *IEEE Mic. Magazine*, Vol. 10, No. 5, 99–107, Aug. 2009.
15. Raab, F., "Efficiency of outphasing RF power-amplifier systems," *IEEE Transactions on Communications*, Vol. 33, No. 10, 1094–1099, Oct. 1985
16. Steinbeiser, C., T. Landon, and C. Suckling, "250 W HVHBT Doherty with 57% WCDMA efficiency linearized to −55 dBc for 2c11 6.5 dB PAR," *CSIC 2007 IEEE Compound Semiconductor Integrated Circuit Symposium,* 1–4, Oct. 14–17, 2007.
17. Kim, B., J. Kim, I. Kim, J. Cha, and S. Hong, "Microwave Doherty power amplifier for high efficiency and linearity," *2006 International Workshop on Integrated Nonlinear Microwave and Millimeter-Wave Circuits*, 22–25, Jan. 30–31, 2006.
18. Park, H. C., J. Van, S. C. Jung, M. S. Kim, H. Cho, S. W. Kwon, J. H. Jeong, K. H. Li, C. S. Park, and Y. Yang, "A new compact load network for Doherty amplifiers using an imperfect quarter-wave line," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 55, No. 11, 2313–2319, Nov. 2007.