

# Wideband Harmonically-Tuned GaN Doherty Power Amplifier

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**Abstract** — This paper presents the design of a wideband harmonically-tuned Doherty amplifier. The frequency-dependent back-off efficiency degradation was minimized by compensating the effect of the frequency-sensitive impedance inverters over the design band. Suitable choice of device size ratio as well as harmonic load tuning at back-off and maximum power operations were also considered, resulting in superior performance over the targeted design band. The maximum output power ranged from 48.2 dBm to 49.6 dBm. 6 dB back-off efficiencies of  $\eta_{6dB} \geq 53\%$  (power-added efficiency  $PAE \geq 50\%$ ) were measured over 1.7–2.25 GHz (28 % bandwidth). When linearized using digital pre-distortion (DPD), the Doherty amplifier had adjacent-channel leakage ratio (ACLR) of  $-43$  dBc for a long-term evolution (LTE) signal at 1.85 GHz ( $\eta=50\%$ ) and  $-44$  dBc for a wideband code-division multiple access (W-CDMA) signal at 2.11 GHz ( $\eta=41\%$ ), at average output power of 41.0 dBm and 40.5 dBm, respectively.

**Index Terms** — Broadband amplifiers, Doherty amplifier, harmonic tuning, HEMTs, high power amplifiers.

## I. INTRODUCTION

Modern wireless communications systems utilize high data rate signals with high peak-to-average-power ratios (PAPR) up to 12 dB. Due to the high PAPR and the varying envelope of such signals, power amplifiers (PAs) that provide high efficiency as well as sufficient linearity at back-off operation are essential for these communications systems. The Doherty amplifier, first proposed in [1], and analyzed in [2], [3], is a simple efficiency-enhancement PA architecture that provides high efficiency and inherent linearity at back-off operation.

There has been a lot of work on Doherty amplifiers in the recent years. Most of the published amplifiers are narrowband and do not fulfill the wideband/multi-band requirements of modern base stations. Recently, there have been some efforts to increase the bandwidth of the Doherty amplifier. A 57 % average efficiency Doherty PA was designed for the 2.5–2.7 GHz band in [4]. In [5], A Si LDMOS Doherty PA was designed over the frequency range 1.7–2.3 GHz. In [6], the frequency response of the Doherty amplifier was analyzed taking into account the effect of the impedance inverters at the output of the amplifier architecture. Based on the analysis, two 20 W Doherty PAs covering the bands 1.7–2.25 GHz and 1.7–2.6 GHz were designed, resulting in 6 back-off efficiencies of higher than 40 % over the design band of each PA. In this paper, the analytical results of [6] were utilized to further enhance the performance of the wideband Doherty amplifier at significantly higher output power.

Section II discusses the design of the wideband

harmonically-tuned Doherty PA. The experimental results of the designed PA are then discussed in Section III. Final results and conclusions are summarized in Section IV.

## II. WIDEBAND HARMONICALLY-TUNED DOHERTY PA DESIGN

A wideband highly-efficient Doherty PA was targeted in this design. The targeted design band is 1.7–2.25 GHz, which includes a number of communications standards like the LTE downlink bands of 1.805–1.880 GHz and 1.930–1.990 GHz as defined in the 3GPP [7]. The UMTS downlink band of 2.11–2.17 GHz is also within the targeted design band.

A 35 W GaN HEMT (CGH40035F) from Cree Inc. was used as the main device, while a 45 W device (CGH40045F) was used as the peaking device for the Doherty PA design. The main/peaking device size ratio was so chosen to ensure a proper load modulation behavior without significant waste of the peaking device power capability if extreme device size ratio (e.g. 1:2) was chosen [2].

The main PA was first designed to operate in class AB mode at an operating point of  $V_{DS,m}=28$  V,  $I_{DS,m}=125$  mA. Design of the output matching network of the main PA is one of the key factors to achieve wideband Doherty behavior. First, harmonic load-pull simulations were performed using the large-signal model of the main device. Optimum fundamental and second harmonic load impedances for high efficiency at 3 dB back-off power as well as at maximum power were then obtained.

In [6], the frequency-dependent back-off efficiency degradation of the Doherty amplifier was analyzed. This degradation is caused by the lower impedance ( $Re\{Z_1\}$ ) introduced to the main device due to the quarter-wave ( $\lambda/4$ ) lines of the output combining network. To mitigate this problem, the impedance  $Z_1$  as given in [6] was used as the target load impedance for the output matching network of the main amplifier. Doing this will minimize the effect of the  $\lambda/4$ -lines over the design band.

Fig. 1 shows the impedances seen at the input and output of the main PA output matching network in the low-power region (peaking PA is still OFF). As can be noticed from the Figure, the matching network transforms the impedance  $Z_1$  into the impedance  $Z_{L,match}$  that is well matched to the optimum load impedance  $Z_{L,opt}$  (obtained from load-pull simulations). It can be also noticed that the impedance degradation of  $Z_1$  has been compensated by the matching network. This results in the non-

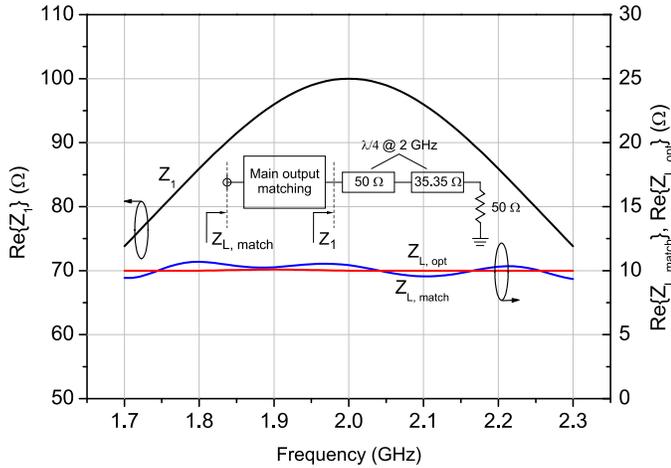


Fig. 1. Load configuration seen by the main device in the low-power region, with the impedances seen at the input and output of the matching network highlighting the compensation of the impedance inverters effect over 1.7–2.3 GHz.

degraded impedance  $Z_{L,match}$  which represents the load seen by the main device over the design band (in the low-power region). This will maintain high back-off efficiency over the design band.

The peaking PA was then designed to operate in class C mode ( $V_{DS,p}=28$  V,  $V_{GS,p}=-5.43$  V) over the design band. Again, load-pull was used to obtain the optimum fundamental and second harmonic impedances for high efficiency and sufficient maximum output power over the design band. The peaking device was matched to  $50 \Omega$  over the design band according to the load modulation behavior derived in [6].

The input and output matching networks of the main and peaking PAs had similar topologies, in order to make it easier to compensate the phase differences over the design band. The design was completed with even input power divider and conventional output combining network.

### III. EXPERIMENTAL RESULTS

The Doherty PA structure was realized on a dielectric substrate ( $\epsilon_r=3.55$ ,  $h=0.51$  mm) as shown in Fig. 2.

Single-tone large-signal measurements were performed over the design band. Fig. 3 shows an example measurement at 1.8 GHz. As can be noticed, the Doherty PA delivered a maximum output power of 49.5 dBm, where an efficiency of  $\eta_{sat}=71\%$  (PAE=63%) can be observed. At 6.2 dB output back-off, an excellent efficiency of  $\eta_{6dB}=65\%$  (PAE=62%) was measured. The efficiency performance of the Doherty PA over the design band can be observed in Fig. 4.

The maximum output power ranged from 48.2 dBm (at 2.25 GHz) to 49.6 dBm (at 1.7 GHz), with an efficiency  $\eta_{sat}$  ranging from 65% to 77%. At 6 dB back-off power (42.2–43.6 dBm), the efficiency was maintained at high levels of at

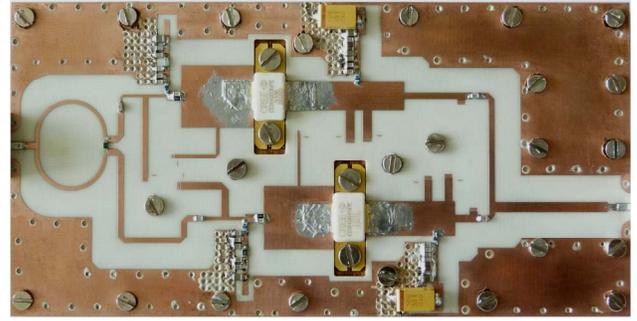


Fig. 2. Photo of the designed wideband Doherty PA architecture.

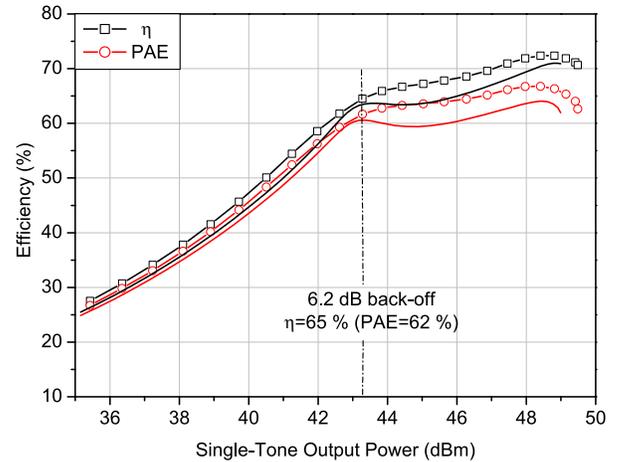


Fig. 3. Efficiency versus single-tone output power of the Doherty PA, simulated (solid lines) and measured (lines with symbols) at 1.8 GHz.

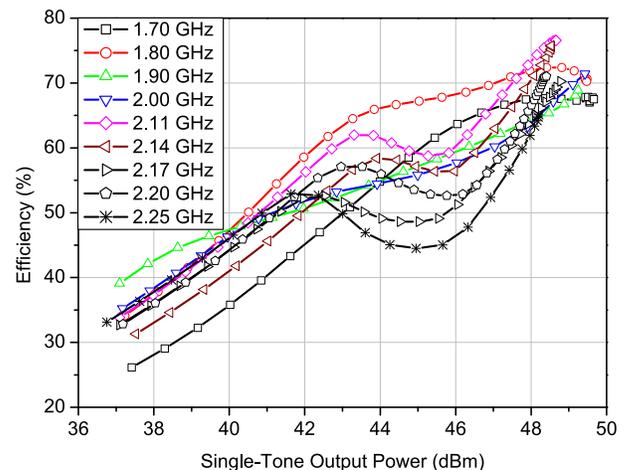


Fig. 4. Measured efficiency versus single-tone output power of the Doherty PA over 1.7–2.25 GHz.

least  $\eta_{6dB}=53\%$  (PAE=50%) over 1.7–2.25 GHz, which represents 28% bandwidth, as illustrated in Fig. 5.

The linearity of the Doherty PA was characterized using two

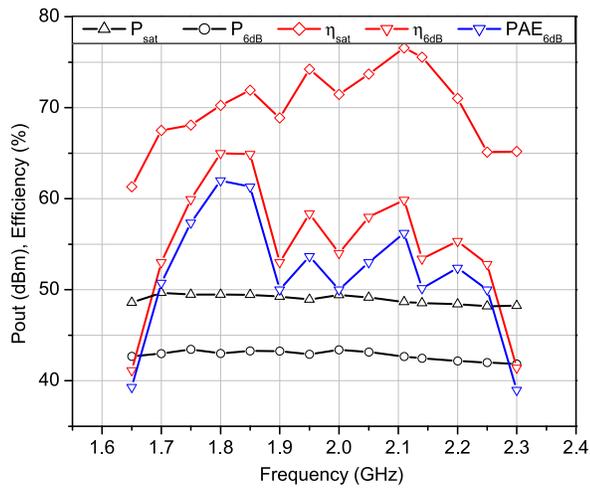


Fig. 5. Measured output power and efficiency of the wideband harmonically-tuned Doherty PA at power saturation as well as at 6 dB back-off operations, over 1.65–2.3 GHz.

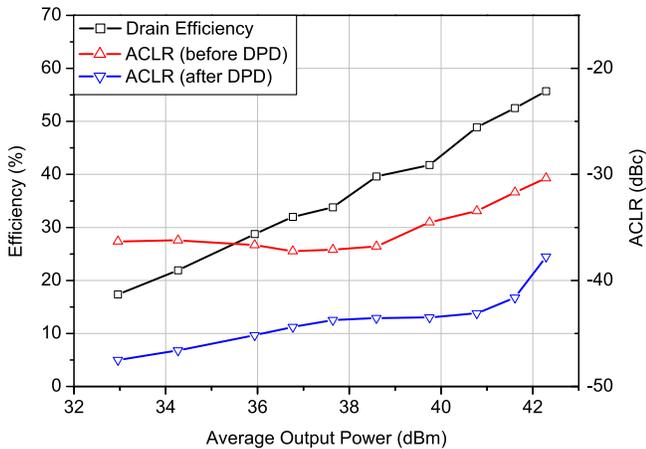


Fig. 6. Measured drain efficiency and ACLR levels (+5 MHz offset) before and after DPD linearization, using a single-carrier LTE downlink signal with PAPR=7.3 dB at 1.85 GHz.

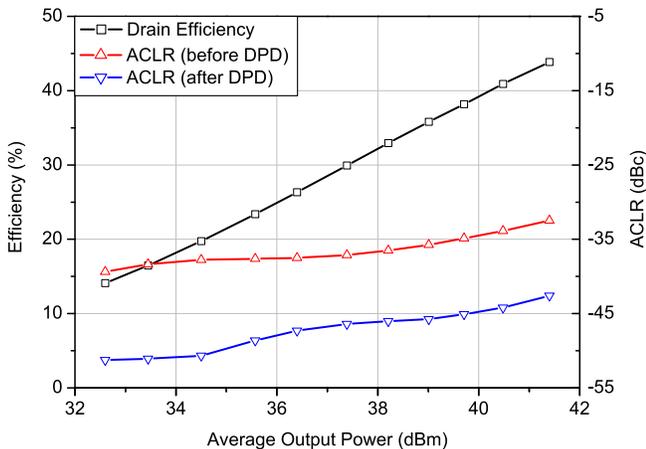


Fig. 7. Measured drain efficiency and ACLR levels (+5 MHz offset) before and after DPD linearization, using a single-carrier W-CDMA downlink signal with PAPR=8.0 dB at 2.11 GHz.

different standard signals. A single-carrier LTE FDD downlink signal (PAPR=7.3 dB) was applied at 1.85 GHz, while a single-carrier W-CDMA signal (PAPR=8.0 dB) was used at the UMTS downlink frequency of 2.11 GHz.

Fig. 6 shows the linearity performance at 1.85 GHz. At average output power of 41 dBm, efficiency of  $\eta=50\%$  together with ACLR=-33 dBc were achieved. Using memory polynomial DPD linearization, the linearity was enhanced to ACLR=-43 dBc. The W-CDMA signal was applied at 2.11 GHz, where efficiency of  $\eta=41\%$  and linearity of ACLR=-34 dBc were measured at average output power of 40.5 dBm (Fig. 7). Using the same DPD linearization procedure, the linearity was enhanced to ACLR=-44 dBc.

#### IV. CONCLUSION

A wideband GaN Doherty amplifier has been presented. The frequency-dependent back-off efficiency degradation was minimized over the design band. Suitable choice of device size ratio together with harmonic tuning of the individual PAs led to excellent performance in terms of output power and efficiency. Over 28% bandwidth (1.7–2.25 GHz), 6 dB back-off efficiencies of higher than  $\eta_{6dB}=53\%$  (PAE=50%) were measured. With additional use of DPD linearization, very good linearity for the UMTS and LTE wireless standards has been demonstrated as well. To the best of authors' knowledge, the proposed Doherty PA has the highest output power and back-off efficiency reported so far over such bandwidth.

#### ACKNOWLEDGEMENT

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