The Analytic Doherty-Outphasing Power Amplifiers
Continuum Theory
(Invited Paper)

Chenyu Liang
Department of Electrical and Computer Engineering
The Ohio State University, Columbus
Columbus, OH USA
liang.521@buckeyemail.osu.edu

Patrick Roblin
Department of Electrical and Computer Engineering
The Ohio State University, Columbus
Columbus, OH USA
roblin.1@osu.edu

Abstract—This paper reviews a narrow and wide band high-efficiency dual-input power amplifiers (PA) design approach based on the previously reported Doherty-Outphasing PA continuum theory. The key derived analytic equations are summarized to explain the theory. Several GaN PA demonstrator circuits are presented and experimentally evaluated. The promising performance achieved validates the usefulness of the Doherty-Outphasing PA continuum theory.

Index Terms—Doherty power amplifier, Chireix outphasing power amplifier, load modulation technique.

I. INTRODUCTION

The 5G communication utilizes complex modulated wireless signals exhibiting large peak-to-average power ratio (PAPR). To efficiently amplify such signals, the deployed power amplifiers (PAs) shall not only exhibit high saturation power efficiency but also present high output power backoff (OBO) efficiency. Several techniques have been investigated to enhance the PA back efficiency, such as supply modulation [1], varactor load tuning [2] and load modulation techniques [3]-[8]. Among all these methods, the load modulation techniques have drawn the most attentions from PA designers. Doherty PAs have been one of the most popular PA architectures. They rely on quarter-wave transformer and a load connected between the carrier and peaking PA to perform the load modulation [3]. The bandwidth limitation is, however, one of the major concern from the conventional Doherty PA, due to the fact that Doherty combiner network is inherently narrow band. There have been numerous effort to extend the bandwidth of the load modulated PAs, among which the recently invented load modulated balanced amplifiers (LMBA) have been extensively investigated [6] to [8]. The design of LMBA typically requires two balanced amplifiers based on a branch-line hybrid coupler and one control amplifier to achieve the desired wideband load modulation.

A quasi-analytic Doherty-outphasing continuum analysis was proposed by Andersson et al. in [9]. The dual-input PA output combiner includes two transmission lines (TLINEs) with variable characteristic impedance and electrical length and a shunt resistive output load connected in between. The PA combiner design parameters were numerically swept in a systematic fashion to yield the optimum combination which delivers the highest average efficiency within a determined bandwidth. Instead of relying on a brute-force numerical simulation approach, the recent work in [10] derived the analytic equations which unravel the operating mechanism underneath the Doherty-Outphasing PA (DOPA) continuum. Several high-efficiency narrow/wide band PAs reported in [10], [12] and [14] were then subsequently designed and evaluated experimentally to validate the analytic Doherty-outphasing power amplifier continuum theory.

This paper is organized as follows: in Section II, the analytic Doherty-outphasing PA theory is reviewed and summarized. In section III, the dual-input hybrid Chireix-Doherty (HCD) PA and the hybrid Doherty-maximum (HD-max) PA designed with the continuum theory are reviewed and presented. Finally, the design methodology for the dual-input wideband hybrid DOPA is reviewed in Section IV. Conclusions are then drawn and future work proposed in Section V.

II. THE ANALYTIC DOHERTY-OUTPHASING CONTINUUM THEORY

In this section, the analytic Doherty-Outphasing continuum PA theory in [10] used for designing dual-input PAs is reviewed. The derivation of the analytic theory is based on the PA conceptual diagram shown in Figure 1, in which a lossless three-port combiner network and terminating load resistance $R_L$ are connected between the two current sources. The $Z$-parameters of the reciprocal and lossy two-port combiner network $Z$ (red dashed-line box), is obtained by using the...
optimum fundamental currents and voltages from the main and auxiliary devices operating at both the backoff and peak power levels, respectively. Four current- and voltage-ratio factors are introduced here to simplify the derivation of the equations:

\[ |V_{mp}| = K_{vm}|V_{mb}|, \quad |V_{ap}| = K_{va}|V_{ab}|, \]
\[ |I_{mp}| = K_{im}|I_{mb}|, \quad |I_{ap}| = K_{ia}|I_{ab}|. \]

The subscripts \( m \) and \( a \) refer to the main and auxiliary devices, respectively. The subscripts \( b \) and \( p \) refer to the backoff and peak power level, respectively. The lossy two-port network \( Z \) is realized with a lossless three-port combiner network terminated with a resistive load \( R_L \) also shown in Figure 1. The \( Z \)-parameters of the two-port network \( Z \) are given by:

\[
Z = \frac{1}{\Delta} \left[ V_{mp}I_{ab} - V_{mb}I_{ap} \right. \\
\left. V_{ap}I_{ab} - V_{ab}I_{mp} \right. \\
\left. V_{mb}I_{mp} - V_{mp}I_{mb} \right]
\]

with \( \Delta = I_{mp}I_{ab} - I_{mb}I_{ap}. \)

The two-port network is reciprocal: \( Z_{12} = Z_{21} \), which leads to the following two identities:

\[ \theta_p + \theta_b = \pi, \]  
\[ |V_{mb}||I_{mp}| - |V_{mp}||I_{mb}| = |V_{ab}||I_{ap}| - |V_{ap}||I_{ab}|. \]

where \( \theta_p \) and \( \theta_b \) are defined as the outphasing angles between the main and auxiliary devices at backoff and peak powers, respectively. Based on (3), the asymmetry power ratio \( n \) between the auxiliary and main devices at peak power can be derived, which is useful to determine the device cell size and output backoff range (OBO). The \( n \) and OBO are given as follows:

\[
n = \frac{P_{ap}}{P_{mp}} = 0.5|V_{ap}|/|I_{ap}| = 0.5|V_{mp}|/|I_{mp}| = 1/K_{im} - 1/K_{va}. \]

\[
OBO = \frac{P_b}{P_a} = K_{va}K_{ia} \frac{1 - K_{im} + K_{im}(1/K_{ia} - 1/K_{va})}{1 - K_{im} - K_{ia} + K_{va}}.
\]

The three-port network in Figure 1 is lossless in theory, which leads to:

\[
\text{Real}[Z_{12}]\text{Real}[Z_{21}] = \text{Real}[Z_{11}]\text{Real}[Z_{22}].
\]

Solving this identity, it yields four possible analytic solutions for the outphasing angles at both the backoff and peak power levels:

\[
\theta_p = \pi \pm \cos^{-1} \left( \pm \sqrt{\frac{(K_{ia} - 1)(K_{im} - K_{va})}{(K_{im} + 1)(K_{ia} + K_{va})}} \right),
\]

\[
\theta_p = \pi - \theta_b.
\]

It is found that if \( |K_{vm}| = |K_{va}| = 1 \), the generalized two-port network shown in Figure 1 can be synthesized by using a resistive load \( R_L = R_{mp}/(n+1) \) and two TLINEs as shown in Figure 2 with, respectively, characteristic impedances \( Z_1 = R_{mp}, \ Z_2 = R_{ap} \), and electrical lengths \( \theta_1 \) and \( \theta_2 \) which are given by:

\[
\tan \theta_1 = \frac{K_{im}(K_{ia} - 1)}{K_{ia} + K_{im}} \tan \theta_b,
\]
\[
\tan \theta_2 = \frac{K_{ia}(K_{va} - K_{im})}{K_{va}(K_{ia} + K_{im})} \tan \theta_b.
\]

By sweeping the three variables \( K_{im}, K_{ia} \), and \( K_{va} \), there exists a three dimensional (3-D) continuum that includes all possible solutions for the dual-input DOPA output combiners. Given a fixed OBO, \( K_{im} \) can be obtained in terms of \( K_{ia} \) and \( K_{va} \) as illustrated in equation (20) of [10]. The outphasing angles at backoff power level given by (6) is plotted versus \( K_{ia} \) and \( K_{va} \) as shown in Figure 3 to visualize Doherty-Outphasing continuum on a 3-D surface. In Figure 3, the outphasing angle for the Doherty PA is indicated by the green circle and the outphasing angle for the Chirex-outphasing PA with 9.54 dB OBO is indicated by the green rectangle. Besides these two well-known types of PAs, the existence of other mode of operation combining features of both the Doherty and outphasing PAs are revealed. Among this continuum of modes of operation two new canonic types of PA operation named HDC and HD-max indicated by a green triangle and a star, respectively, are discovered. These new types of PAs will be reviewed in the following sections.

III. DESIGN OF NARROW BAND HDC AND HD-MAX PAS

For a conventional Doherty PA, the peak-to-backoff voltage ratio of the auxiliary PA: \( K_{va} = \sqrt{OBO} \) (see Table I in [10]). Since OBO is typically larger than 1, the backoff fundamental voltage applied on the auxiliary PA is smaller than the peak voltage, which degrades the auxiliary PA’s efficiency and causes the double-hump behavior shown in a classical Doherty PA efficiency curve. To address this issue, mixed-mode Chirex-outphasing PA was proposed in [11]. In [11], the fundamental drain voltage sustained by both transistors are constant at both peak power and backoff, which results in a flatter PA efficiency response versus power. However, the mixed-mode Chirex-outphasing PA suffers from a nonlinear
AM/AM response due to the fact that the two transistors are always turned on and interact with each other even in the small-signal regime unlike the Doherty PA modulation for which the dual transistor operation only occurs in the high power regime. Alternatively the dual-input HCD PA reported in [10] combines both of the key features of the Doherty and Chireix operations such that the fundamental drain voltages applied on either the main or auxiliary transistors remain constant at peak power and backoff to ensure a flat efficiency response. Meanwhile, the HCD PA is turned off at lower power regime like in a Doherty PA operation to achieve a similar linear gain response. By maintaining OBO=9.54 dB constant and auxiliary PA turned off \( (K_{ia} = \infty) \) and sweeping \( K_{va} \), the load modulation trajectories from the Doherty to HCD PA at device current-source reference planes are plotted in Figure 4. The corresponding drain efficiency and gain response are also plotted in Figure 5. It is noted that when \( K_{va} \) is set to be slightly higher than 1, there exists another type of optimal hybrid PA, named as HD-max PA, which is able to achieve higher output power, drain efficiency and flatter gain response as marked by black circle in Figure 4 and 5.

The narrow-band dual-input Doherty PA, HCD PA and HD-max PA demonstrator circuits were designed and fabricated as shown in Figure 6 (a) to (c), respectively. The simulated and measured drain efficiency and gain at 2GHz for the Doherty and HCD PA are presented and compared in Figure 7. It is noted that in the higher power regime, the HCD PA achieves a higher and flatter drain efficiency response than that of the Doherty PA. The measured and simulated drain efficiency of the HD-max PA at 2.08 GHz are shown in Figure 8 to demonstrate that even higher drain efficiency and output power can be achieved without compromising the linear gain response.

IV. DESIGN OF WIDE BAND HYBRID DOHERTY-OUTPHASING PAS

The conceptual diagram of the dual-input Doherty-outphasing PA shown in Figure 2 can also be used to design wide band PA as is reported in [14]. By setting \( K_{ia} = \infty \) and \( n = 1 \), the design parameters for the two TLINEs \( Z_1, Z_2, \theta_1, \theta_2 \) and \( R_L \) are simplified and given by:

\[
Z_1 = R_{mp}, Z_2 = R_{ap}, R_L = \frac{R_{mp}}{2}.
\]
The goal is to perform the impedance matching from the GaN device are incorporated in the design. The first design branch is shown in Figure 10, where the linear parasitics of the main branch (θ_red) and the auxiliary branch (θ_blue) are designed and optimized such that the synthesized electrical phase delays across the frequency are close to the theoretical values. Figure 9 shows the comparison between the synthesized phase delays as depicted in Figure 9. The fabricated wide band hybrid Doherty-outphasing PA is shown in Figure 6(a). The simulated and measured PA performance from 1.4 to 2.5 GHz are shown in Figure 11.

V. CONCLUSION

This paper first reviewed the analytic Doherty-outphasing continuum theory. Two types of narrow-band hybrid PAs combining both features of the Doherty and Chireix-outphasing modes were discovered based on the continuum theory. These two types of PAs were implemented and evaluated to validate the theory. Furthermore, a wide band version of the dual-input hybrid PA was developed and experimentally evaluated to further exploit the capability of the continuum theory. However, all the developed PAs presented here rely on a dual-input operation which requires dynamically changing the two input power along with the outphasing angles at the two input ports of the PA. Future work will report on the conversion of the wide hybrid Doherty-outphasing PA from a dual-input to a single-input architecture to further promote the advantages of the Doherty-outphasing continuum theory.

REFERENCES


