Wideband Quasi-Balanced Doherty Power Amplifier with Reciprocal Main/Auxiliary Setting and Mismatch-Resilient Parallel/Series Reconfiguration

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***Abstract*— This paper presents a novel reconfigurable quasi-balanced Doherty power amplifier (QB-DPA) with wide bandwidth and strong resilience to load mismatch. By leveraging the complementarity of reciprocal main/auxiliary setting and parallel/series modes, we demonstrate the first-ever broadband mismatch-resilient QB-DPA. To validate the proposed theory, a broadband $1.55{-}2.7$-GHz QB-DPA is developed using GaN technology and 3-section branch-line coupler. With matched load, the experimental results exhibit an efficiency of $57{-}80\%$ at peak output power and $49{-}71\%$ at 6-dB output back-off (OBO), respectively. Modulated measurement using a 20-MHz LTE signal with 10.5-dB peak to average ratio (PAPR) shows a $44{-}51\%$ average efficiency across the operation bandwidth and up to -36 dB ACPR. More importantly, a consistent output power and improved efficiency at $\mathrm{OP}_{1\mathrm{dB}}$ are experimentally maintained through the parallel/series modes reconfiguration at $2:1$ voltage standing wave ratio (VSWR).**

***Keywords*— Load modulation, balanced amplifier, Doherty, power amplifier, high efficiency, wideband.**

I. Introduction

The ever-increasing demand for higher data rate and spectral efficiency has triggered the development of complex modulation schemes, leading to a dramatic increase of signal's peak-to-average power ratio (PAPR). As a result, advanced PA architectures, e.g., Doherty and envelope tracking, are needed to efficiently amplify such high-PAPR signals. Moreover, to support the on-going 4G/5G band proliferation, the RF bandwidth of a single PA is desired to be as wide as possible. On the other hand, the use of massive MIMO technique brings about strong mutual couplings between co-located antennas, which can cause instantaneous variation of antenna impedance at very fast time scales [1], [2], [3]. Consequently, the PA can suffer from significant performance degradation due to the load mismatch. Conventional solutions, e.g., discrete antenna tuners on mobile platforms and PA-antenna isolator/circulators in the base stations, are either bottle-necked by the tuning speed that is insufficient to track the fast antenna impedance variation, or prohibited by the bulkiness for array integration.

Recently, attempts targeted for recovering the mismatch at the PA stage have demonstrated promising potential. In [4], [5], a parallel/series switchable DPA is reported with reconfigurable weighting of main/aux.PAs currents and phase offset without investigation of mismatch recovery across operation bandwidth. Doherty-to-balanced reconfiguration presented in [6], [7] improves the linearity with the expenses of compromising the linear efficiency. Until now, to maintain both the efficiency and linearity over a large impedance variation range and broad bandwidth remains a major challenge.

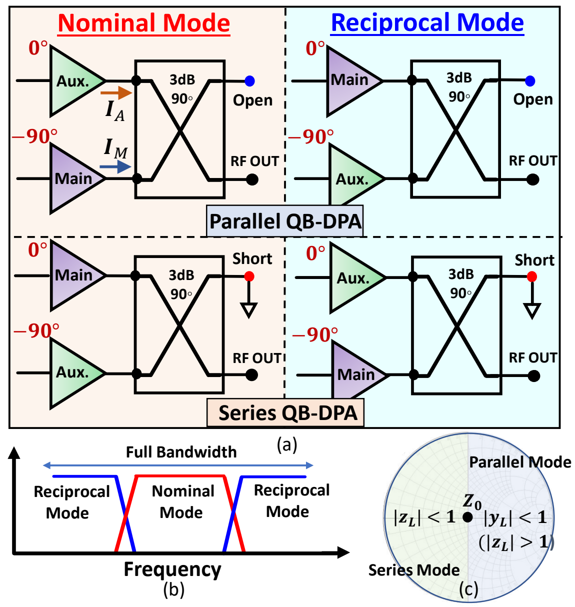

Fig. 1. Illustration of the proposed QB-DPA: (a) reconfiguration between parallel/series modes and nominal/reciprocal biasing, (b) wideband coverage with complementary reciprocal biasing, (c) mismatch resilience through parallel/series mode switching.

This paper proposes the first-ever reciprocal biased qausi-balanced Doherty power amplifier (QB-DPA), which not only significantly extends the operational bandwidth but also provides wideband mismatch resilience. The conceptual schematic shown in Fig. 1(a) illustrates the scheme of wideband QB-DPA design through reciprocally exchanging the main and auxiliary amplifiers, which is presented in Fig. 1(b) and is applicable for both series and parallel QB-DPA. The proposed concept is experimentally validated by the developed wideband QB-DPA prototype demonstrating the desired Doherty behavior over $1.55-2.7$ GHz and good mismatch tolerance.

II. Parallel/Series QB-DPA and Wideband Design

The load modulation (LM) of main and auxiliary amplifiers in parallel/series QB-DPA can be theoretically represented using the four-port Z-matrix of quadrature coupler [6], [7].

A. Parallel/Series QB-DPA Theory

For the parallel QB-DPA as shown in Fig. 1 (a), the LM behaviors for main/aux. PAs are derived as

$$Z_{\mathrm{M}} = Z_0(2 + \frac{I_{\mathrm{A}}}{I_{\mathrm{M}}}) \quad \& \quad Z_{\mathrm{A}} = Z_0\frac{I_{\mathrm{M}}}{I_{\mathrm{A}}}, \qquad (1)$$

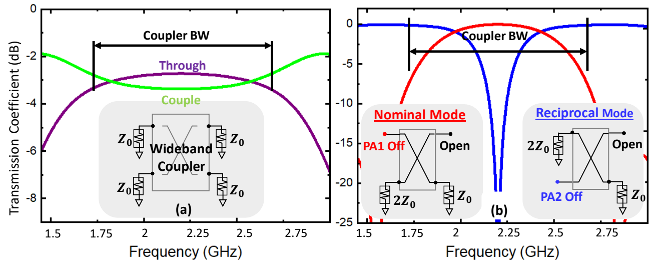

Fig. 2. Wideband QB-DPA design using reciprocal biasing: (a) wideband branch-line coupler, (b) low-power equivalent circuit of parallel QB-DPA.

where I_{M} and I_{A} represent the main and auxiliary currents. The same LM behavior can be derived for the series QB-DPA with exchanged roles of main/aux. PAs and isolation port short circuited, shown in Fig. 1(a).

The ideal loadlines seen by the main and auxiliary PAs in Eq. (1) are subject to significant change under load mismatch. Given an arbitrary load admittance of Y_{L}, the main and auxiliary loadlines of parallel QB-DPA at back-off and saturation can be obtained as

$$\begin{aligned} Z_{\mathrm{M_{PL}},\mathrm{bo}}(y_{\mathrm{L}}) &= 2y_{\mathrm{L}}Z_0 \quad \& \quad Z_{\mathrm{A_{PL}},\mathrm{bo}} = \infty, \\ Z_{\mathrm{M_{PL}},\mathrm{sat}}(y_{\mathrm{L}}) &= (2y_{\mathrm{L}}-1)Z_0 \quad \& \quad Z_{\mathrm{A_{PL}},\mathrm{sat}} = Z_0, \end{aligned} \tag{2}$$

in which y_{L} represents the normalized value of Y_{L}. For $|y_{\mathrm{L}}| > 1$, the main amplifier suffers from voltage clipping, which can largely degrade the linearity, $\mathrm{OP_{1dB}}$, and efficiency.

Similarly, the main and auxiliary loadline profiles of series QB-DPA under load mismatch are derived as

$$\begin{aligned} Z_{\mathrm{M_{SE}},\mathrm{bo}}(z_{\mathrm{L}}) &= 2z_{\mathrm{L}}Z_0 \quad \& \quad Z_{\mathrm{A_{SE}},\mathrm{bo}} = \infty, \\ Z_{\mathrm{M_{SE}},\mathrm{sat}}(z_{\mathrm{L}}) &= (2z_{\mathrm{L}}-1)Z_0 \quad \& \quad Z_{\mathrm{A_{SE}},\mathrm{sat}} = Z_0, \end{aligned} \tag{3}$$

where z_{L} denotes the normalized load impedance. The voltage clipping and performance degradation happen for $|z_{\mathrm{L}}| > 1$.

The elegant complementarity of two QB-DPA modes reveals the fact that a parallel/series reconfigurable QB-DPA can be perfectly clipping-free (mismatch-resilient) if operating in parallel mode for $|y_{\mathrm{L}}| < 1$ (i.e., $|z_{\mathrm{L}}| > 1$) and in series mode for $|z_{\mathrm{L}}| < 1$, as illustratively described in Fig. 1(c).

B. Reciprocal Main/Auxiliary Setting for Wideband Design

The above theoretical analysis is based on the ideal coupler. However, the frequency-dependent imperfections of the realistic wideband coupler can cause invalidation of the DPA operation at certain in-band frequencies. For example, a wideband three-section branch-line hybrid is designed to cover a bandwidth from 1.7-2.7 GHz. The transmission and coupling coefficients are extracted with all four ports terminated with Z_0, as shown in Fig. 2(a). To mimic the ideal parallel QB-DPA at low-power region, the auxiliary port is open circuited as well as the isolation port, and the main port is set to $2Z_0$ representing the Doherty loadline, as depicted by the left inset schematic of Fig. 2(b). The corresponding transmission response (red curve in Fig. 2(b)) shows that the bandwidth is greatly compromised as compared to the original coupler. By exchanging the main/aux. setting, a complementary frequency

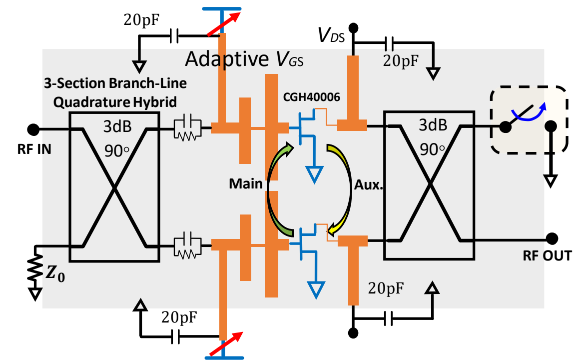

Fig. 3. Schematic of the designed wideband QB-DPA at parallel mode.

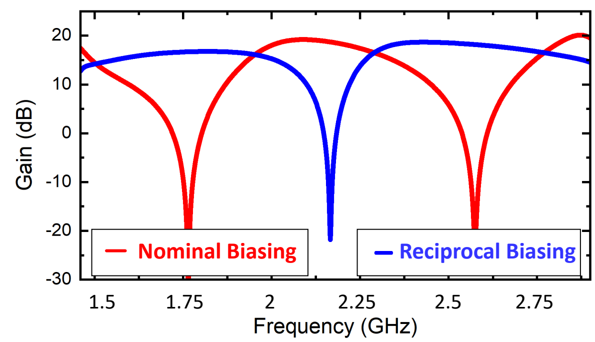

Fig. 4. Simulated S_{21} of the proposed QB-DPA showing complementary frequency responses of two biasing settings to cover the target bandwidth.

response can be achieved (blue curve in Fig. 2(b)). Overall, a hybrid combination of two modes can greatly extend the bandwidth of parallel QB-DPA. The same operation is also valid for series QB-DPA due to the symmetry.

III. Design of Wideband QB-DPA

To verify the theory, a physical prototype is designed and implemented using GaN devices (CGH40006P) targeting for a frequency range from 1.7 to 2.7 GHz. The realized circuit schematic is shown in Fig. 3. Two 3-section branch-line quadrature hybrid with characteristic impedance of Z_0 are employed at the input and output ends to offer the required bandwidth. The input matching is realized with a 2-stage low-pass matching network building on previous research of [8], which is designed identically at main and auxiliary paths to maintain the phase balance of nominal and reciprocal modes. The output matching is mainly set by the coupler and the bias line (equivalent to a shunt inductor). The circuit primarily operates in parallel mode for the matched load. In this proof-of-concept demonstration, the switching to series mode is realized by manually placing a bypass capacitor for mismatch recovery. The determination of optimal wide-band operation mode is described in Fig. 4. Through reciprocal main/aux. setting, the gain response of QB-DPA can fully cover the coupler bandwidth, which well verifies the analysis presented in Fig. 2.

IV. Implementation and Experimental Results

The fabricated PA is shown in the inset of Fig. 5, which is implemented on a 20-mil thick Rogers Duroid-5880 PCB

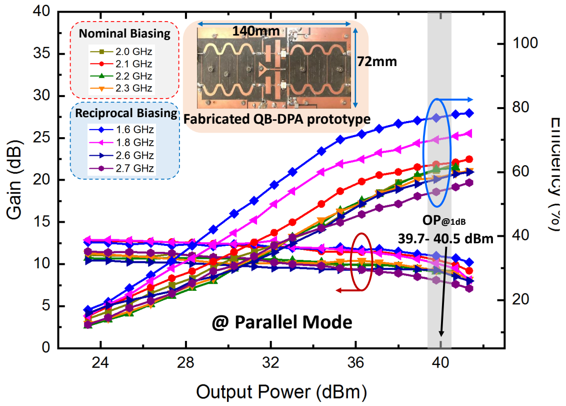

Fig. 5. Fabricated wideband QB-DPA prototype and power-swept measurement of efficiency and gain at nominal and reciprocal settings.

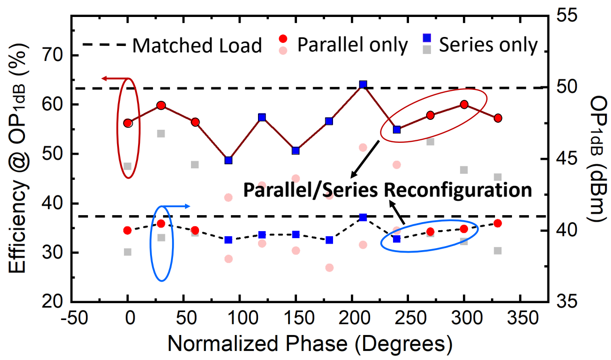

Fig. 6. Measured CW efficiency and OP_{1dB} over 2:1 VSWR at 2.1 GHz.

board. In nominal biasing, the voltage of main PA is biased in Class-AB, while the aux.PA is set as Class-C with 28-V drain bias. The gate biases are swapped in the reciprocal setting.

In the continuous-wave measurement, a single-tone signal is used to measure the QB-DPA performance at different power levels. Fig. 5 shows the frequency response of the QB-DPA. A peak efficiency of $60-64\%$ is measured in the nominal setting, together with $49-52\%$ efficiency at 6-dB OBO. The measured peak efficiency exhibited a $57-81\%$ at different frequencies with the corresponding 6-dB OBO efficiency ranging from $45-65\%$ when the setting is reciprocal. A flat gain profile is observed in both biasing settings with the operation bandwidth extended from $1.55-2.7$ GHz compared with simulation.

In order to verify the mismatch recovery capability, the designed QB-DPA is further evaluated with a CW stimulus over the 2:1 VSWR circle at the centered frequency 2.1 GHz. The testing points are conducted with a 30° step of the phase sweep as shown in Fig. 6. Both parallel and series modes are test under the mismatch. To enable the series mode, a bypass 20 pF RF bypass capacitor is used to connect the isolation-port ground together with the gate biases swapped. The efficiency at OP_{1dB} can be significantly improved over the entire 2:1-VSWR circle through reconfiguration between parallel and series modes. Meanwhile, a consistent OP_{1dB} of $39.1-40.5$ dBm is maintained.

To validate the effectiveness of the QB-DPA in realistic communications, a 20-MHz-bandwidth LTE signal with a

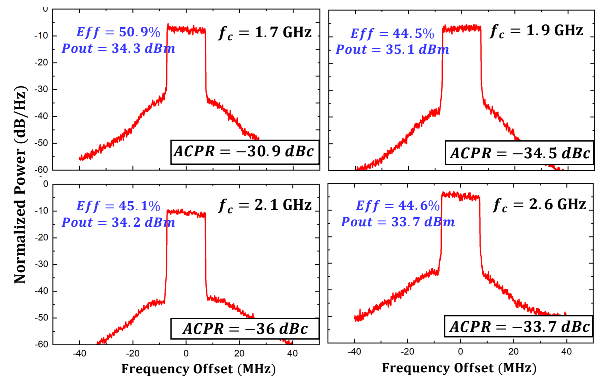

Fig. 7. Modulation measurements using a 20-MHz 10.5-dB-PAPR LTE signal at parallel mode from $1.7-2.6$ GHz.

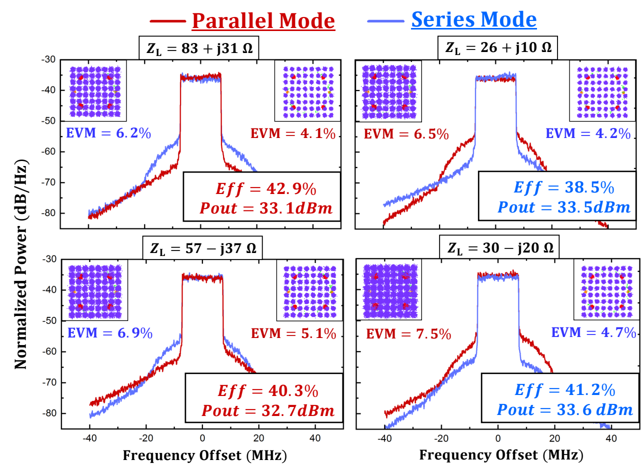

Fig. 8. Measured modulation results across 2:1 VSWR at 2.1 GHz.

PAPR of 10.5 dB is used to perform modulated testing. The modulated signals are generated and analyzed with Keysight PXIe vector transceiver (VXT M9421). The measured output spectrum ranging from $1.7-2.6$ GHz are shown in Fig. 7, with $44-51\%$ average efficiency. The best ACPR of the measured frequency is up to -36 dBc without any digital predistortion. The PA is further tested under 2:1 VSWR at 2.1 GHz shown in Fig. 8. With parallel/series reconfiguration and gate-bias tuning, the linear efficiency and average P_{out} can be largely restored while maintaining a decent linearity (EVM/ACPR).

V. Conclusion

This paper introduces the design and implementation of wideband QB-DPA through reciprocal main/auxiliary PA setting with meanwhile a strong mismatch tolerance. As a proof-of-concept demonstration, a physical prototype of the reconfigurable QB-DPA is developed. Experimental results validate its capability of efficiently amplifying signals over the $1.55-2.7$-GHz bandwidth together with decent linearity from modulated measurement. Moreover, the designed QB-DPA is demonstrated, for the first time, to be both broadband and VSWR-resilient. The theory and practices of the proposed technology clearly exhibit its promising potential for application in 5G massive-MIMO systems.

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