Intrinsically Mode-Reconfigurable Load-Modulation Power Amplifier Leveraging Transistor's Analog-Digital Duality

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***Abstract*— This paper presents a new way of designing multi-mode switchable power amplifier without relying on any extra tuning elements. By operating the RF GaN transistor as a switch (digital) or amplifier (analog), it enables three different modes within a quadrature-balanced load-modulation architecture, including series/parallel Doherty and hybrid load modulated balanced amplifier (H-LMBA), which can be optimally configured according to different load conditions. Based on this new method, an intrinsically mode-switchable load-modulation PA is designed with GaN transistors and branch-line quadrature coupler at 1.7 GHz. Together with the unique harmonic-tuned method, the nominal mode of H-LMBA (for matched condition) achieves a high-order load modulation with $>62\%$ measured efficiency across a 10-dB output back-off (OBO) range. Efficient performance is also demonstrated at series/parallel Doherty modes, which are configured with exchangeable main/auxiliary roles and dedicated switch settings offering mismatch resilience.**

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

I. Introduction

The insatiable demands for wireless data speed have triggered complex spectrally efficient modulation schemes, leading to substantially increased peak-to-average power ratio (PAPR) of signals. To efficiently amplify such high-PAPR signals, advanced PA architectures, e.g., Doherty and envelope tracking, have been widely adopted. Meanwhile, the 5G system features array-based massive MIMO that introduces antenna mismatch issues during beam steering known as scan impedance [1]. As a result, PAs in the array can be subject to significant performance degradation. To solve the antenna mismatch issue, discrete antenna tuners and PA-antenna isolation have been implemented for mobile handsets and cellular base stations, respectively. However, these solutions are either limited by tuning speed to track the variation of scan-impedance due to beam steering or prohibited by the cost and bulkiness for massive-scale integration.

Recently, the counteraction against variable load has been moved to the PA stage through mismatch-aware reconfiguration, e.g., switching between series/parallel modes [2], [3], switching between Doherty and balanced modes [4], digital-assisted dual-input DPA with load-dependent supply voltage [5], etc. It is important to note that most of the existing solutions rely on extra tuning elements, while the high-order load modulation (e.g., 3-way DPA) has not been considered in the mismatched condition despite its suitability for amplifying high-PAPR signals.

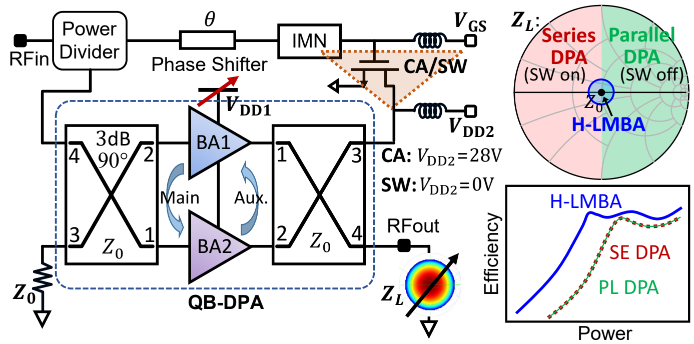

Fig. 1. Illustration of intrinsically mode-switchable PA based on quadrature-balanced load-modulation platform, in which the analog-digital duality of transistor is leveraged for reconfiguration.

This paper presents, for the first time, an intrinsically mode-switchable load-modulation (LM) PA based on quadrature balanced topology, as illustrated in Fig. 1. For matched load, the PA operates in the nominal mode of hybrid load-modulated balanced amplifier (H-LMBA) that contains a quasi-balanced Doherty PA (QB-DPA) and a control amplifier (CA), forming a 3-way modulation with extended OBO range. For mismatched load, the CA can be configured to a switch, thus enabling series/parallel reconfiguration of QB-DPA for different mismatch conditions. Such a reconfiguring scheme ensures not only a highest possible efficiency at nominal condition but also strong resilience to mismatch. The proposed concept is well validated using a developed hardware prototype, achieving desired LM behavior and efficient performance for all three modes.

II. Quadrature-Balanced Load-Modulation Platform with Intrinsic Reconfigurability

The schematic of intrinsically reconfigurable quadrature balanced load-modulation PA is illustrated in Fig. 1. In this architecture, BA1 and BA2 form a quasi-balanced DPA (QB-DPA) in either series or parallel mode depending on the main/auxiliary setting and short-/open-circuit loading of isolation port. This two-state switchable loading can be implemented by operating the CA digitally as a switch. For the H-LMBA mode, the CA turns on at the saturation of QB-DPA behaving as an analog amplifier to continue the load modulation like a LMBA [6], [7], [8], achieving $\geq$ 10-dB dynamic range at nominal load condition. Meanwhile,

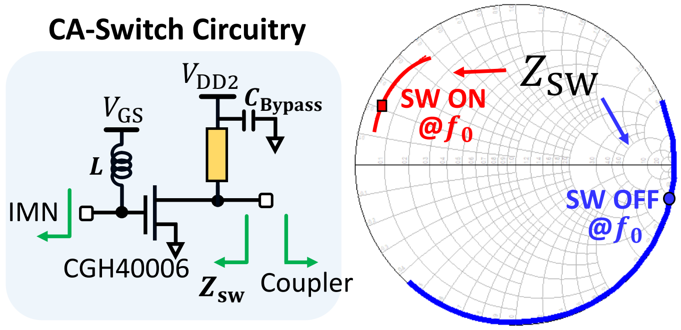

Fig. 2. Design of control amplifier and switch in a unified circuitry.

integrated harmonic-tuned design is also necessary to optimize the efficiency across the entire power back-off range.

A. *Design of Control-Amplifier/Switch in A Unified Circuitry*

The key aspect for realizing the proposed analog-digital duality is to make the CA operable as both an amplifier and a switch in a unified circuitry. To achieve this, the OMN of CA is simplified as a shunt inductance (offered by the bias line) connecting to the isolation port impedance (Z_0). These two parameters are utilized to offer an optimal loadline to the transistor for power amplification. For a typical 28-V, $6-10$-W GaN transistor, Z_0 is close to 50Ω. Meanwhile, from the switch perspective, this simplified OMN of a shunt inductance also functions as a parasitic compensator that well supports the switching behavior. As shown in Fig. 2, the CA presents favorable on/off state with the corresponding impedance close to the ideal short-/open-circuit, by setting the V_{DD2} on CA to 0 and using V_{GS} as the control.

B. *Harmonic-Tuned Design with* 90°*-Coupler-Transformer*

The overall performance of either H-LMBA or QB-DPA relies heavily on the efficiency of the main amplifier, since it forms the first efficiency peak that can strongly influence the efficiency over the entire power back-off. Thus, harmonic-tuned design of main amplifier is necessary. Given the proposed architecture with main amplifier being BA1 or BA2 in different modes, they are designed with identical harmonic-tuned matching to suit the role exchange in series/parallel reconfiguration. However, the harmonic-tuned matching normally involves complex networks with large phase dispersion that can compromise the Doherty performance. Therefore, we choose to design a simplified harmonic-tuning network with associated with fundamental matching provided by the quadrature coupler as a transformer, as shown in Fig. 3. In this design, the second harmonic loading is properly set by an open-ended quarter-wave line (@$2f_0$)in conjunction with a tuning line. The fundamental matching is then realized using the coupler-transformer in parallel with the bias line as a shunt inductor. Overall, the harmonic-tuned design in coordination with the coupler-transformer minimizes the phase dispersion between the main/auxiliary devices and the Doherty combiner resulting in the proper load-modulation behavior. This is valid for both series and parallel operations.

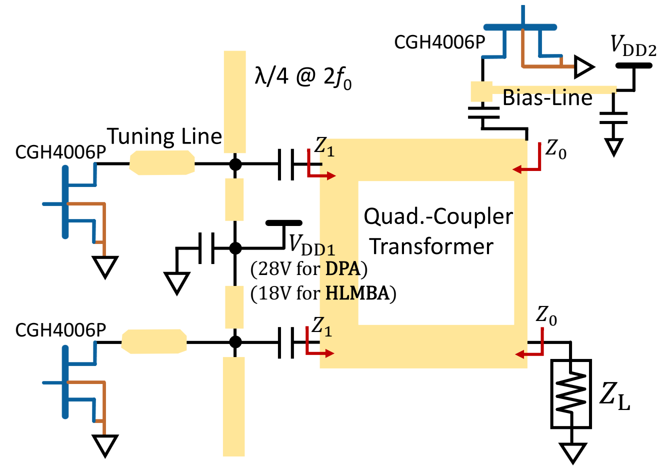

Fig. 3. Schematic of the harmonic-tuned design with coupler transformer.

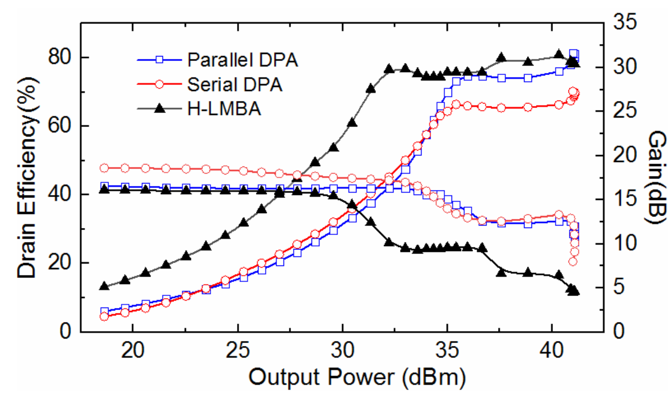

Fig. 4. Simulated efficiency and gain profiles of all three modes of the proposed architecture.

III. Prototype Design of RF-Input Mode-Switchable Load-Modulation PA

The prototype of mode-switchable load-modulation PA is designed at 1.7 GHz using GaN devices (CGH40006P) for all amplifier stages. The input quadrature coupler of QB-DPA is implemented using a standard 3-dB branch-line hybrid, and its the output stage is designed using the harmonic-tuned schematic shown in Fig. 3. The H-LMBA mode aims to offer a high efficiency over >10-dB of OBO range, which is also desired to deliver the same maximum power as the QB-DPA of about 40 dBm. Thus, the V_{DD1} for BA is reduced to 18 V in H-LMBA mode to cover the dynamic range from 10 dB to 4 dB of OBO range, which is further modulated to maximum power by the CA with proper amplitude and phase controls [6]. In simulation, the HLMBA is able to promise close to 80% of efficiency over the entire 10-dB OBO range, as depicted in Fig. 4. Highly efficient QB-DPA performance is also achieved for both parallel and series modes as shown in Fig. 4, while the efficiency of series mode is slightly lower due to the non-ideal 'on' impedance of switch. The inputs of QB-DPA and CA are merged through a $2:1$ uneven Wilkinson divider to equally supply input power into three amplifiers, obtaining an RF-input HLMBA. The relative phase offset between QB-DPA and CA

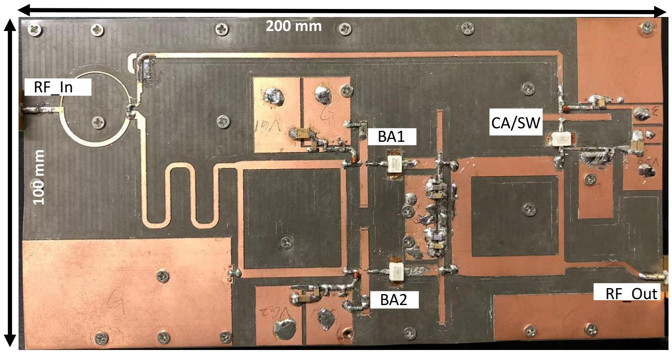

Fig. 5. Fabricated hardware prototype at 1.7 GHz using GaN transistors.

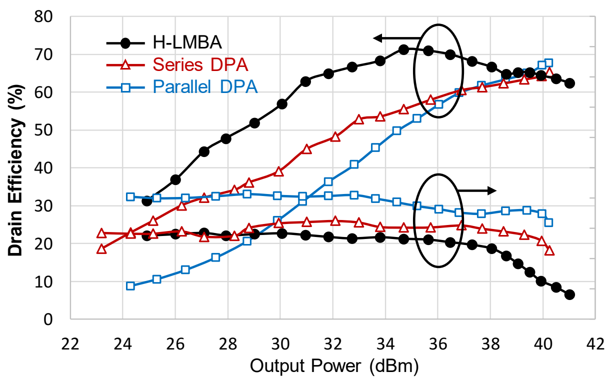

Fig. 6. Continuous-wave measurement results of efficiency and gain for all three modes at 1.7 GHz.

branches are optimized and realized using transmission lines with proper electrical lengths.

IV. Implementation and Experimental Results

The prototype of the multi-mode switchable PA is fabricated on a 20-mil thick Rogers Duroid-5880 PCB board with dielectric constant of 2.2 as shown in the Fig. 5. It is implemented at 1.7 GHz with the GaN CGH40006 packaged transistors. In the nominal load condition, the H-LMBA mode is activated with CA as an analog amplifier targeting for transmitting a high-PAPR signals. The gate voltages are at -4.8-V and -2.9-V for BA1 and BA2 forming a parallel QB-DPA at lower OBO range, while a gate bias of -6.7-V is applied for the CA as a deep Class-C operation mode to further enlarge the overall OBO range. The drain supply voltages are set to 18 V and 28 V for BAs and CA to ensure an efficient Doherty performance at relatively lower power range, while maintaining the high efficiency when the CA turns on. The series/parallel QB-DPA modes are measured as well through digitally operating CA as a RF switch to properly configure the transformer isolation port loading. Specifically, for the series mode, the V_{DD} of CA is set to 0-V with a above-threshold voltage 0-V for the gate bias to generate a quasi-short switch impedance. On the other hand, a deep negative gate voltage -15-V is applied to form the parallel DPA together with swapping the bias settings of main/auxiliary PAs.

The continuous-wave measurement in Fig. 6 well proves the concept. A $>62\%$ efficiency is observed over 10-dB

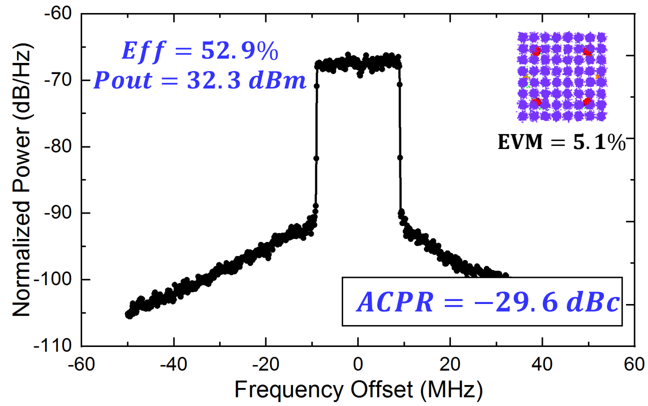

Fig. 7. Modulation measurement using a 20-MHz 10.5-dB-PAPR signal at H-LMBA mode for 1.7 GHz.

OBO range for H-LMBA mode. For series/parallel QB-DPA modes, the V_{DD} is identically set to 28-V for BAs to achieve a comparable output power with H-LMBA. A desired Doherty profile are obtained for both series and parallel modes, respectively. Further, a 20-MHz-bandwidth LTE signal with a PAPR of 10.5 dB is used to perform modulated signals test at H-LMBA mode. The Keysight PXIe vector transceiver (VXT M9421) is functioned as the signal generator and analyzer. The measured output spectrum at 1.7 GHz are shown in Fig. 7, with 52.9% average efficiency, while the ACPR of the measured frequency is up to -29.6 dBc and maintaining a decent EVM without any digital predistortion.

V. Conclusion

This paper presents the design and implementation of a multi-mode switchable load-modulated PA that can be reconfigured between series DPA, parallel DPA, and HLMBA modes. It is, for the first time, proved that the GaN transistor can be designed to operate as an amplifier or a switch for offering intrinsic reconfigurability. As a proof-of-concept demonstration, a physical prototype based on quadrature-balanced load-modulation platform is designed using GaN transistors and branch-line couplers. The proposed concept is validated by the functioning prototype with a state-of-the-art efficiency performance and a decent linearity response. The promising performance together with mismatch-resilient reconfigurability offers an ideal solution for emerging 5G massive MIMO communication systems. This work also opens a new vision of designing tunable RF circuits leveraging the transistor's intrinsic features without having to use any external tuning components, leading to minimized loss, cost, and complexity.

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