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Load-Modulated Double-Balanced Amplifier with Quasi-Isolation to Load

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***Abstract*—This paper presents a novel Double-Balanced power amplifiers (PAs) architecture with an intrinsic isolation to load. Derived from the generic load modulated Balanced Amplifier (LMBA), by designing the single-ended control amplifier (CA) as another balanced PA, the load-modulated double-balanced amplifier (LMDBA) can inherit the intrinsic load-mismatch tolerance of balanced amplifier without any reconfiguration and load-impedance sensing. A proof-of-concept is demonstrated using two balanced GaN power amplifiers and branch-line quadrature hybrid couplers at 2.1 GHz. The implemented PA achieves an efficiency of 76.2% at peak power and 69.5% at 10-dB output back-off (OBO) under the matched condition of load. An efficiency up to 72.5% at peak power and up to 64.1% at 10-dB OBO are measured under $2:1$ VSWR of load. In modulated evaluation with a 20-MHz OFDM signal, an EVM of 1.9%, ACPR of -41 dB is measured under matched condition after Digital Pre-Distortion (DPD). The PA's linearity profiles are well sustained experimentally against $2:1$ VSWR of load mismatch, e.g., 2.1% of EVM and up to -39.5 dB of ACPR.**

***Index Terms*—Balanced amplifier, high efficiency, linear, load modulation, mismatch, power amplifier, PAPR, wideband.**

I. Introduction

Emerging communications standards have widely embraced spectrally efficient high-data-rate modulations. However, this adoption leads to a significant increase of the signals' peak-to-average power ratio (PAPR). To efficiently transmit such high-PAPR modulated signals, the efficiency of power amplifiers (PAs) must be enhanced not only at the peak power but also over a large output back-off (OBO) range. While envelope tracking (ET) and Doherty PA are legacy technologies that can achieve this, new architectures and techniques such as load-modulated balanced amplifiers (LMBAs) have been proposed [1]–[6]. LMBAs offer unprecedented efficiency, OBO range, and bandwidth. It is important to note that most reported LMBAs suffer from poor linearity, which strongly limits their application to systems without digital pre-distortion.

On the other hand, massive MIMO has been widely deployed in 5G communications to significantly enhance the user capacity and spectrum efficiency. However, this antenna-array-based system is susceptible to strong mutual couplings between antenna elements, causing antenna mismatch known as scan impedance. As the PAs in the array are directly followed by the antennas, they are subject to constant load variations and performance fluctuations, e.g., main-beam distortion [7]. There are several ways to solve this issue. The direct solution is based on the detection of actual antenna impedance and correction using a tunable matching network between PA and antenna. An alternative solution is to transform the load-mismatch-aware reconfiguration to the PA stage. There have been many reported load-insensitive PAs, based on reconfigurable Doherty PA [8]–[10] and LMBA [11], [12]. While both solutions have been proven effective at the circuit level, a complex closed-loop control is generally required involving load detection, processing, and execution, which all add to extra complexity, latency, and power-consumption of the system.

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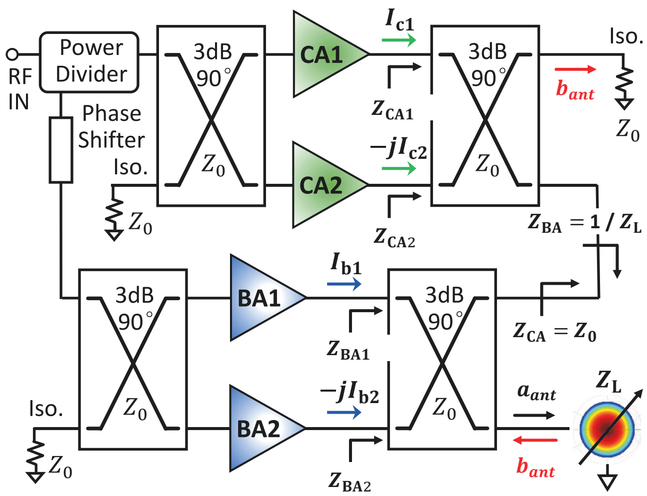

Fig. 1. Overview of load-modulated double-balanced amplifier (LMDBA) with intrinsic load insensitivity for application in array-based systems.

In this work we for the first time introduce a novel load-modulated double-balanced amplifier (LMDBA) architecture which is endowed with an intrinsic immunity to load mismatch without any reconfiguration. As shown in Fig. 1, the basic conceptual schematic of Dual-Balanced PA, LMDBA consists of two classic balanced amplifiers, including a balanced control amplifier (CA) as the carrier and another balanced amplifier (BA) as the peaking. Hence, this new topology not only has a load-modulation behavior like a LMBA, but it can also maintain its performance in terms of efficiency and

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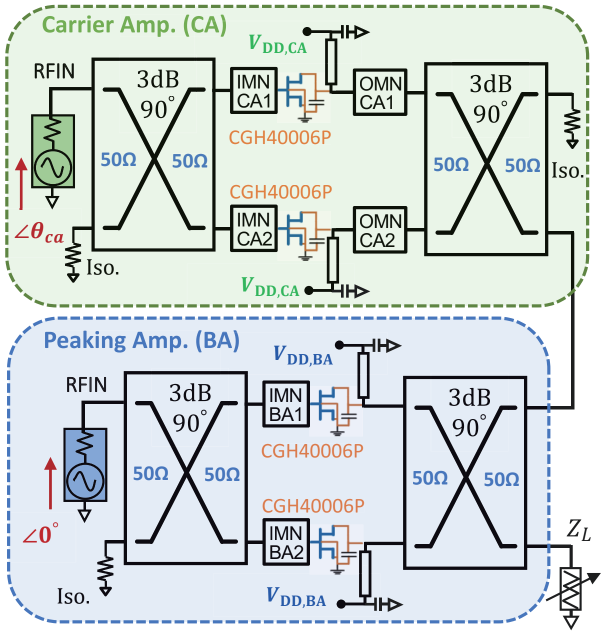

Fig. 2. Circuit schematic of designed LMDBA based on GaN transistors and branch-line hybrid couplers.

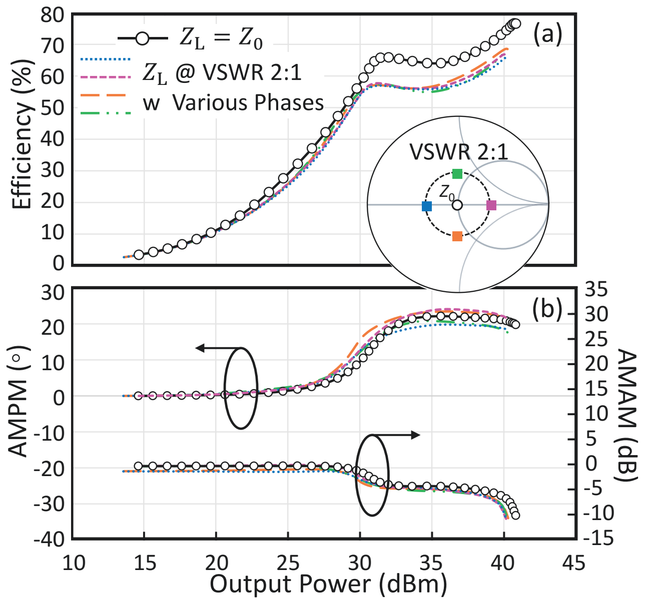

Fig. 3. Simulated LMDBA performance under various mismatch conditions: (a) efficiency, (b) linearity.

linearity against various load condition like a standard balanced amplifier. The proposed LMDBA has been designed and prototyped for further experimental validation of its operation and linearizability at realistic mismatched loads.

II. Theoretical Analysis of Load-Modulated Dual-Balanced Amplifier

Generically, LMBA is derived from the conventional BA architecture by replacing the nominal 50-Ω load at the isolated port of the output coupler with a control modulating current or control amplifier. By designating Doherty type of biasing to CA and BA, a pseudo-Doherty LMBA (PD-LMBA, also called sequential LMBA) is formed with unprecedented performance in terms of OBO range, back-off efficiency, and bandwidth [1]–[6]. In the LMDBA, the control signal is generated by a balanced CA, and the operation of LMDBA is divided into two regions for theoretical analysis.

A. Intrinsic Mismatch Resilience of Balanced CA in Low-Power Region ($P_{\mathrm{OUT}} < P_{\mathrm{Max}}/\mathrm{OBO}$)

In the low-power region with CA solely operating, this analysis can be considered as a single balanced amplifier circuit under the load-mismatch condition, where the quadrature coupler with BA1 and BA2 ports open-circuited acts as a inverter ideally. The impedances of CA1 and CA2 can be obtained by utilizing the quadrature hybrid coupler impedance matrix [13], and the relationship between the normalized CA load impedances in a balanced topology is given by:

$$z_{\mathrm{CA1}} + z_{\mathrm{CA2}} = 2. \tag{1}$$

Eq. (1) indicates that when load mismatch occurs, the relevant impedances of two PAs tend to compensate for each other, thus maintaining a constant PA performance, in terms of output power generation and efficiency. As a result, the overall output performance of PA can be nearly insensitive to the load mismatch.

B. Load-Mismatch-Resilient Load-Modulation in High-Power Region ($P_{\mathrm{OUT}} > P_{\mathrm{Max}}/\mathrm{OBO}$)

As CA reaches saturation at the predetermined OBO, the BA turns on and is load-modulated by the CA output signal. Note that the CA branch works as a regular balanced amplifier over the entire power region. Meanwhile, the CA output presents a constant Z_0 loading to BA due to the CA's balanced nature, which enforces the balanced operation of BA during its load modulation. Hence, the mismatch tolerance of the entire PA can be realized.

From the perspective of signal path, the reflected signal due to mismatch at the BA output port travels sequentially through two output couplers of BA and CA, and it is eventually absorbed by the isolation port termination of CA.

III. Practical Design and Implementation of LMDBA Prototype

A physical prototype is designed and implemented using GaN devices (CGH40006P) at 2.1 GHz to verify the proposed architecture. The realized circuit schematic is shown in Fig. 2. Four 50-Ω single section branch-line quadrature hybrid couplers are inserted at the input and output ends to create the CA and BA in balanced structure. The gate voltages of two transistors of BA are biased at -4.5V while CA are biased at -2.8V. In order to accommodate the high PAPR of newly emerging 5G signals, $V_{\mathrm{DD,CA}}$ is set at 11 V to ensure a saturation at 10-dB OBO. $V_{\mathrm{DD,BA}}$ is set to 28 V to achieve the maximum output power around 40 dBm.

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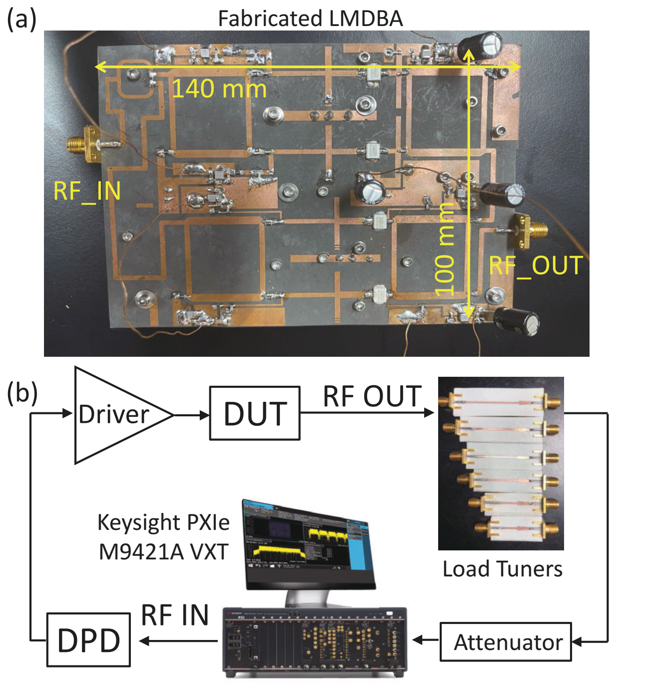

Fig. 4. (a) Fabricated LMDBA prototype. (b) Modulated measurement set up (DPD setting is unchanged for matched and mismatched load conditions).

Both the input matching networks (IMNs) of CA and BA have been implemented using a transmission-line-based low-pass matching network, while the output matching network (OMN) is primarily established through the utilization of the coupler as a transformer and a bias line (which works as a shunt inductor) which reduce the complexity of the load-modulation control and phase dispersion. The relative phase difference caused by extra delay in CA path can be simply resolved using a 50-Ω transmission line with optimized electrical lengths at the input end of BA [11], [14].

Fig. 3 shows the simulated efficiency and linearity profiles versus output power of the designed LMDBA prototype at 2.1 GHz. With the matched load, the first efficiency peak is achieved around 10-dB OBO, and the high efficiency is kept towards the peak power, as shown in Fig. 3(a), while the AMAM and AMPM responses are sustained as well without any reconfiguration as plotted in Fig. 3(b). It is demonstrated that the PA performance of proposed LMDBA is nearly independent of the load variation across 2 : 1 VSWR, which is equivalent to the cascade connection of PA and isolator.

IV. Fabrication and Measurement Results

The measurement setup and fabricated LMDBA is illustrated in Fig. 4. The circuit is implemented on a Rogers Duroid-5880 PCB board with dielectric constant of 2.2. It is first measured with a single-tone continuous-wave (CW) stimulus signal at 2.1 GHz under matched condition, the proposed circuit with an optimal CA-BA phase offset and biasing setting achieves an maximum drain efficiency (DE) of 76.2% and 10-dB OBO DE of 69.5%. The mismatch measurement is realized by connecting the PA output to a set of variable loads that cover the 2 : 1 VSWR circle on Smith chart with the phase swept at a 30° step. A DE up to 72.5% at peak power and up to 64.1% at 10-dB OBO are measured over 2 : 1 VSWR of load mismatch. The corresponding performance under both condition is shown in Fig. 5.

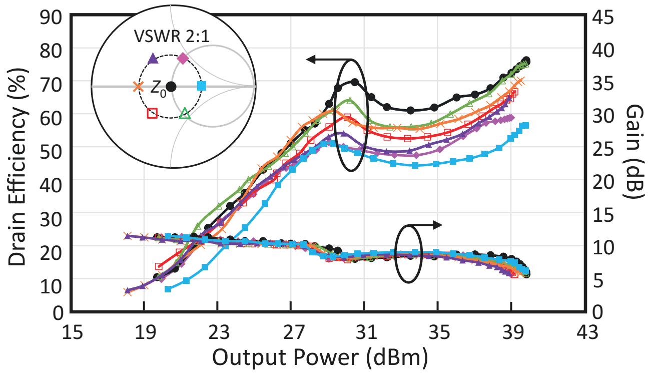

Fig. 5. Continuous-wave measurement of LMDBA at matched load and over 2 : 1 VSWR.

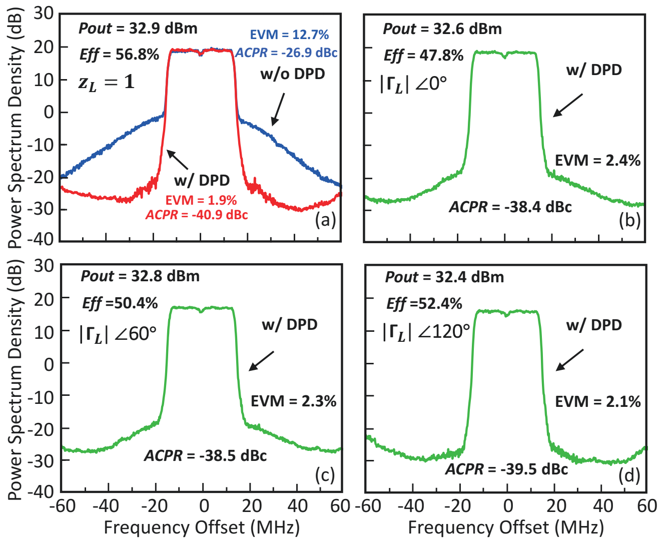

Fig. 6. Modulation signal measurement result at 2.1 GHz under different load condition: (a) matched, (b) $|\Gamma_{\rm L}|\angle 0°$, (c) $|\Gamma_{\rm L}|\angle 60°$, (d) $|\Gamma_{\rm L}|\angle 120°$.

The proposed PA is further evaluated using a 64QAM OFDM signal with 20-MHz modulation bandwidth and 11.5 PAPR. Under matched condition, the proposed PA can be successfully linearized by applying DPD based on volterra-series model to pre-distort the input signal. Fig. 6(a) shows the PA output spectrum at matched load, where an ACPR of −26 dBc is measured originally, and a −41 dBc is achieved after applying DPD. To further validate the load isolation of the LMDBA architecture, we only changed the load condition to 2 : 1 VSWR ($|\Gamma_{\rm L}| = 1/3$ with different phases) without updating the DPD model. It is found that the linearity performance of down to −39.5 of ACPR can be well maintained against various load conditions, as shown in Fig. 6(b),(c),(d), together with up to 52.4% of average efficiency that is also very close to the matched condition.

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V. Conclusion

A novel load-modulated double-balanced amplifier architecture has been reported offering quasi-isolation to load. Through qualitative analysis, this topology not only well maintains the load modulation behavior of conventional LMBA, but it is also equipped with the intrinsic mismatch tolerance of classic balanced amplifier. Moreover, LMDBA prototype is designed and implemented using branch-line quadrature couplers and GaN transistors at 2.1 GHz to verify the theory. In the matched condition, the designed circuit presents a highly efficient performance with a peak efficiency of 76.2% and DE of 69.5% at 10-dB OBO. When transmitting a OFDM signal with 11.5 dB PAPR, a high average efficiency of 56.8% and -42-dB ACPR with DPD are achieved. More importantly, the developed LMDBA also well maintains the efficiency and linearity (with the same DPD code as matched condition) under $2:1$ VSWR of load mismatch. The proposed technology is promising for solving the scan-impedance issue and main-beam distortion of array-based massive MIMO system towards energy- and spectrum-efficient wireless communications.

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