2024 IEEE Wireless and Microwave Technology Conference (WAMICON)

Hybrid Load-Modulated Double-Balanced Amplifier (H-LMDBA) with Four-Way Load Modulation and >15-dB Power Back-off Range

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2024 IEEE Wireless and Microwave Technology Conference (WAMICON) | 979-8-3503-4494-3/24/$31.00 ©2024 IEEE | DOI: 10.1109/WAMICON60123.2024.10522799

***Abstract*—In this work, we present a new architecture of Hybrid Load-Modulated Double-Balanced Amplifier (H-LMDBA) featuring four-way load modulation and large dynamic power range. By appropriately biasing the four sub-amplifiers in balanced control amplifier (CA1, CA2 as carrier, primary peaking) and balanced peaking amplifier (BA1, BA2 as secondary, third peaking), a hybrid load modulation mode with four-way modulation can be realized. To demonstrate the concept, a H-LMDBA prototype is designed with GaN devices and branch-line hybrid quadrature couplers operating at 2.1 GHz. Measurement results show that the H-LMDBA prototype achieves an efficiency of 65.2% at peak power and 51.5% at 15.4-dB output back-off (OBO) under the matched load. In modulated evaluation using a 1024QAM OFDM signal with 20-MHz modulation bandwidth and >13-dB PAPR. Under matched condition, an average efficiency of ACPR of 50.2% is measured at an average power of 29.1 dBm. In contrast to multi-way Doherty power amplifiers (PAs), this novel PA topology provides an extended power back-off range and enhanced efficiency without significantly increasing the system complexity.**

***Index Terms*—Balanced amplifier, high efficiency, four-way, load modulation, power amplifier, PAPR.**

I. INTRODUCTION

Indeed, data rates and user capacity requirements are continuously rising in response to the ever-expanding wireless ecosystem and the proliferation of new applications. As the demand for high-speed and reliable wireless communication grows, communications systems must evolve to meet these increasing demands. This progression includes a notable increase in the peak-to-average power ratio (PAPR) of the signal. It is necessary to improve power amplifiers' (PAs') efficiency over a wide OBO range in addition to at peak power to transmit high PAPR modulated signals efficiently. Numerous novel designs and methodologies have emerged alongside the existing technologies like as envelope tracking power amplifier (ETPA) and Doherty Power Amplifier (DPA). Recently, load-modulated balanced amplifiers have become more popular, offering wide OBO range and efficiency [1], [2], [3] than conventional DPA. With CA acting as the carrier and BA acting as the peaking, or vice versa, LMBA can be further developed using a Doherty-type biasing scheme. A new mode, known as pseudo-Doherty LMBA or sequential LMBA, has been able to achieve a Doherty-like efficiency enhancement with an enlarged dynamic range [4], [5]. However, it is important to note that many LMBA variations, such as PD-LMBA, involve only two-way modulations. As the dynamic range of active load modulation expands, an unavoidable decline in efficiency occurs in the center of the back-off levels [6], [7]. In order to tackle this problem, this research proposes a new high-order load modulation platform named H-LMDBA, which integrates aspects of traditional DPA and HALMBA [8].

This work was supported in part by the National Science Foundation (NSF) CAREER program under award no. 2239207.

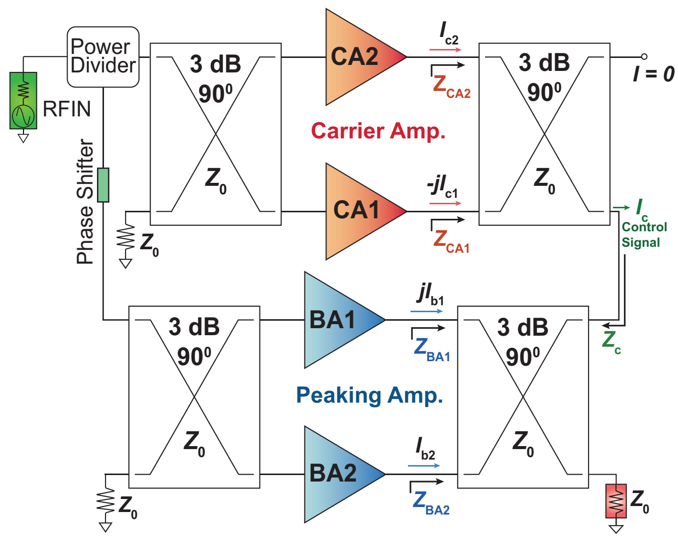

Fig. 1. Overview of the hybrid load-modulated double-balanced amplifier (H-LMDBA) for application in array-based systems.

This work introduces a novel architecture of a power amplifier that introduces a new hybrid load modulation mode similar to a four-way DPA with an extended power back-off range. The fundamental design overview of this new hybrid load-modulated double-balanced amplifier is illustrated in Fig. 1, revealing its composition of two asymmetrical balanced amplifiers: a balanced control amplifier (CA) serving as the carrier and another balanced amplifier (BA) serving as the peaking

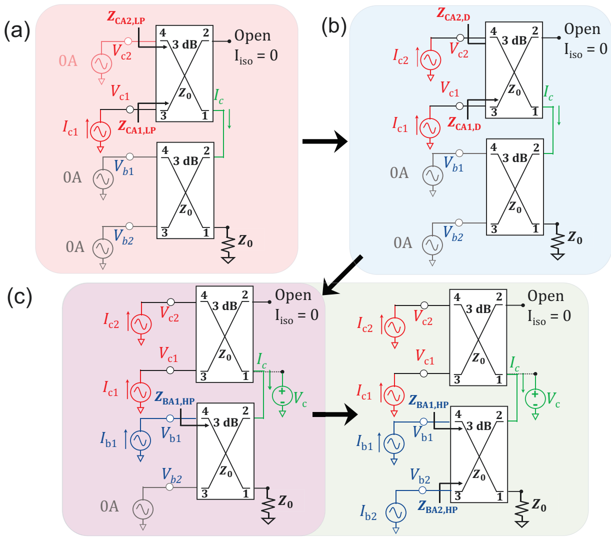

Fig. 2. Ideal generalized schematic for analyzing four-way load modulation of H-LMDBA architecture: (a) low power region (CA1 only); (b) Doherty region (CA1+CA2); (c) H-ALMBA region (CAs+BAs).

component. But in this configuration, the threshold voltages of the two transistors in each balanced amplifier are different. Consequently, the sequential activation of CA1, CA2, and BA1, BA2 can thus produce four efficiency peaks over the longer OBO. As a result, this innovative architecture may retain gain and good efficiency while maintaining four-way load modulation behavior. The proposed H-LMDBA has been designed and prototyped for further experimental validation of its operation.

II. Theoretical Analysis of Hybrid Load-Modulated Dual-Balanced Amplifier (H-LMDBA)

LMBA is an evolution from the traditional BA architecture, achieved by substituting a nominal $50\text{-}\Omega$ load at the isolation port of the output coupler with a control amplifier. To achieve high efficiency and linearity across broad output power levels, the pseudo-Doherty LMBA was invented, which mimics the concepts of Doherty architecture and applies load modulation to a balanced amplifier [1], [3], [8], [9]. The concept of H-LMDBA which comprises four PAs, is developed from the previously published reported LMBA [5], [6], [10]. The control signal is generated by an asymmetrical balanced amplifier, and the operation of H-LMDBA is segmented into four distinct regions based on which PA is activated. By selectively activating different PAs of an LMDBA at varying OBO levels, the performance of the H-LMDBA can be further improved through load modulation [11]. The load modulation behaviors in terms of current with 3-dB quadrature hybrid coupler are also plotted in Fig. 2 under the ideal case.

A. Low Power Region ($P_{\mathrm{OUT}} < P_{\mathrm{Max}}/\mathrm{LBO}$)

In the low-power region with only CA1 operating, the CA can be considered as a carrier amplifier of a Doherty PA. In this scenario, the quadrature coupler with an open-ended isolation

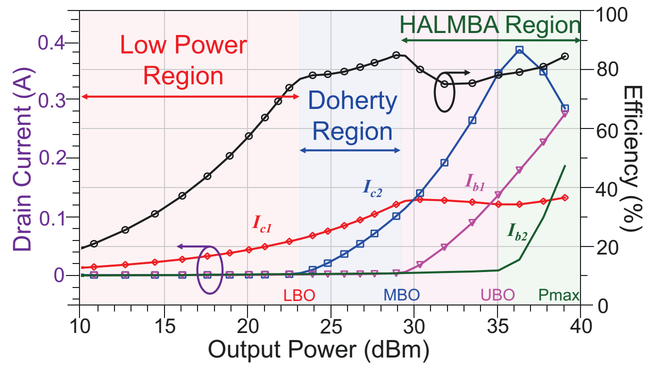

Fig. 3. Fundamental current and efficiency profile versus P_{OUT} of ideal H-LMDBA for different mode operating in corresponding power regions.

port functions as an impedance inverter. The impedance seen by the CA1 is fixed and no load modulation is involved at this region. The impedances of CA1 and CA2 in the low-power (LP) region can be expressed as:

$$Z_{\mathrm{CA1,LP}} = 2Z_0\,; \qquad Z_{\mathrm{CA2,LP}} = \infty. \tag{1}$$

B. Doherty Region ($P_{\mathrm{Max}}/\mathrm{LBO} < P_{\mathrm{OUT}} < P_{\mathrm{Max}}/\mathrm{MBO}$)

In the Doherty region, CA2 is turned on while CA1 continues conducting. The isolation port of the quadrature hybrid coupler is open-circuited, and the entire CA is equivalent to a typical parallel DPA. The impedances of CA1 and CA2 are modulated to lower values and at the peak power of the Doherty region, these impedances are given by:

$$Z_{\mathrm{CA1,D}} = Z_{\mathrm{CA2,D}} = Z_0. \tag{2}$$

At the low back-off (LBO) level, CA1 is designed to be voltage-saturated which corresponds to the first efficiency peak. As the output power increases to the mid-back-off level (MBO), the CA becomes saturated, which corresponds to the second efficiency peak. After the second efficiency peak, the CA is considered as a constant control signal for the subsequent portion of the operation of H-LMDBA.

C. HALMBA Region ($P_{\mathrm{Max}}/\mathrm{MBO} < P_{\mathrm{OUT}} < P_{\mathrm{Max}}$)

In this region, BA1 and BA2 are turned on sequentially. As it can be seen in Fig. 3, BA1 turns on at MBO level where I_{b1} starts conducting while BA2 remains off. Thus, the entire CA and BA1 form another DPA-like PA. Notably, the whole CA maintains voltage saturation and provides maximum efficiency across the Doherty and HALMBA areas. At the upper back-off level (UBO), the BA2 is turned on, and the two balanced amplifiers (CA and BA) function like as an ALMBA with different transistor biases. The impedances seen by BA1 and BA2 can be expressed as:

$$Z_{\mathrm{BA1,HP}} = Z_0\left(2 - \frac{I_{\mathrm{b2}} - 2I_{\mathrm{c1}}}{I_{\mathrm{b1}}}\right). \tag{3}$$

$$Z_{\mathrm{BA2,HP}} = Z_0\left(\frac{I_{\mathrm{b1}} + 2I_{\mathrm{c1}}}{I_{\mathrm{b2}}}\right). \tag{4}$$

In summary, the four amplifiers (CA1, CA2, BA1, and BA2) are turned on sequentially at various OBO levels and have

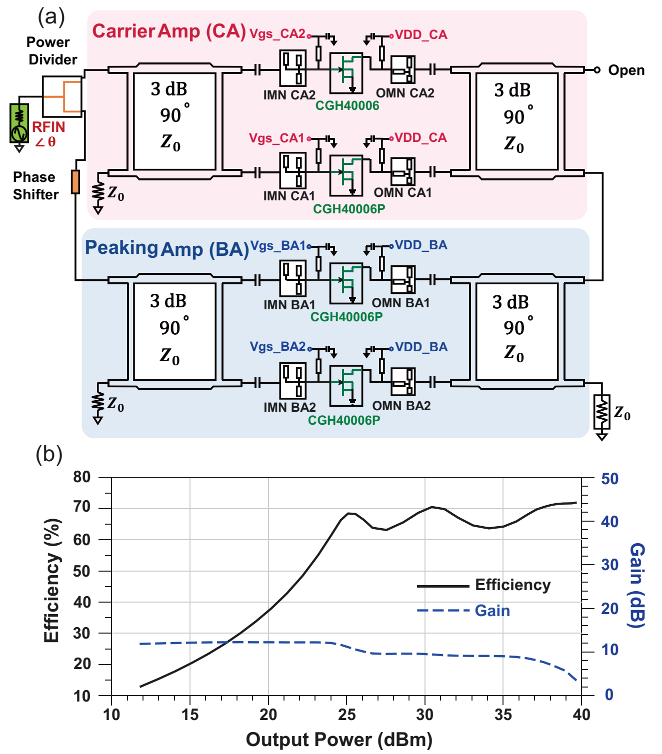

Fig. 4. Practical design of H-LMDBA with branch-line coupler and GaN devices: (a) circuit schematic; (b) simulated results.

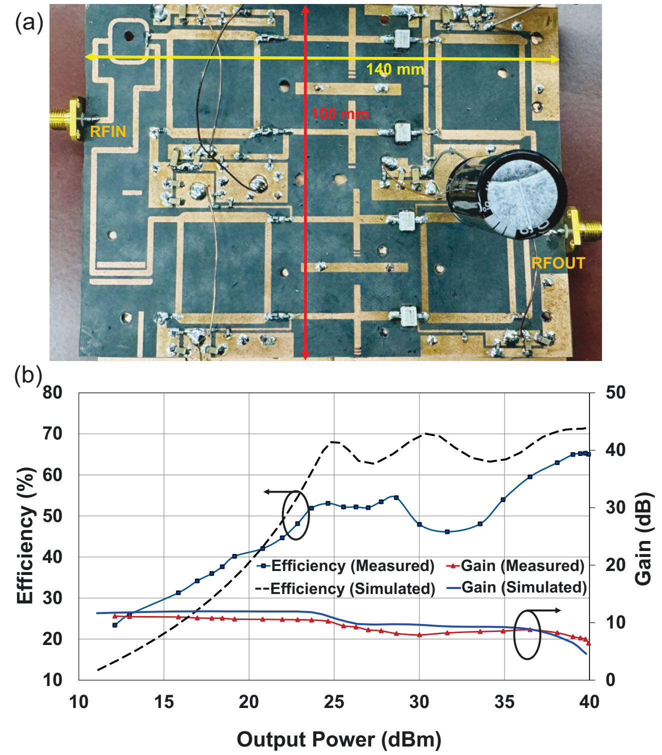

Fig. 5. (a) Fabricated H-LMDBA prototype; (b) CW measurement results at 2.1 GHz.

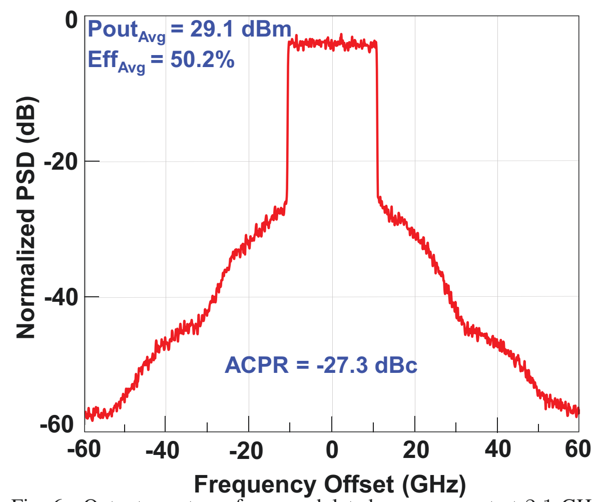

Fig. 6. Output spectrum from modulated measurement at 2.1 GHz.

separate load modulation behaviors. The proposed H-LMDBA is equivalent to a four-way DPA.

III. Design and Implementation of H-LMDBA Prototype

The proposed architecture is designed and implemented utilizing 6W GaN devices (CGH40006P) operating at 2.1 GHz. Fig. 4(a) illustrates the realized circuit schematic featuring four 50-Ω single-section branch-line quadrature hybrid couplers are inserted at the input and output ends to establish the balanced structure of CA and BA.

Two transistors in CA are biased with gate voltages of -3.1 V and -3.8 V, whereas BA1 and BA2 have biased gate voltages of -4.7 V and -7 V respectively. In order to guarantee a saturation of $>$ 15-dB OBO, $V_{\mathrm{DD,CA}}$ is set at 11 V accommodating the high PAPR of newly emerging 5G signals. $V_{\mathrm{DD,BA}}$ is set to 28 V to achieve the maximum output power of approximately 40 dBm.

A transmission-line-based low-pass matching network has been employed to implement the input matching networks (IMNs) of both CA and BA. However, the output matching network (OMN) is primarily established by using a bias line (which functions as a shunt inductor) and the coupler as a transformer. This approach reduces the complexity associated with phase dispersion and load-modulation control. By using a 50-Ω transmission line with optimum electrical lengths at the input end of BA, the relative phase discrepancy induced by the additional delay in the CA path can be rectified [6], [10].

Fig. 4(b) shows the simulated efficiency and gain versus output power of the designed H-LMDBA prototype at 2.1 GHz. Under the matched load condition, the first efficiency peak is found at around 15-dB OBO (LBO), and the second peak is at around 9.5-dB OBO (MBO) which is the backoff due to HALMBA mode. A consistent high efficiency ($>$ 65%) is maintained towards the peak power, while the gain response is sustained around 10-dB as depicted in the same graph. It is proven that high efficiency for a long back-off and gain can be secured by this proposed PA architecture.

TABLE I
PERFORMANCES OF THE STATE-OF-ART PAS WITH EXTENDED OBO.

Reference	Architecture	Total OBO (dB)	η_{max} (%)	$\eta_{15dB\ OBO}$ (%)	$P_{out,max}$ (dBm)
[1] 2022	Symmetrical LMBA	10	61	35	48.7
[2] 2022	DLMBA	13	62	46	45.7
[3] 2020	PD-LMBA	10	72	33	43
[7] 2018	RF input LMBA	6	67	20	45.6
[11] 2023	LMDBA	10	76	40	40.5
This Work	**H-LMDBA**	**15.4**	**65.2**	**54**	**40**

IV. FABRICATION AND MEASUREMENT RESULTS

In order to validate the proposed theory, the prototype circuit is then implemented on a Rogers Duroid-5880 PCB board with a dielectric constant of 2.2. The fabricated H-LMDBA is illustrated in Fig. 5(a). It is first measured with a single-tone continuous-wave (CW) stimulus signal at 2.1 GHz under matched conditions. The measured results along with the simulated results are illustrated in Fig. 5(b). A maximum drain efficiency (DE) of 65.2% and 15.4-dB OBO DE of 51.5% is achieved with an optimal CA-BA phase offset and biasing setting.

The developed H-LMDBA prototype is further evaluated using a 1024QAM OFDM signal with 20 MHz modulation bandwidth and $>$ 13-dB PAPR under matched condition. Fig. 6 shows the PA output spectrum, where an ACPR of -27.3 dBc is measured at an average power of 29.1 dBm together with 50.2% of average efficiency.

V. CONCLUSION

A novel load-modulated, hybrid double-balanced amplifier architecture has been introduced for the first time that offers four-way large power back-off efficiency. In this new topology, the asymmetry of the amplifiers has been realized by properly adjusting the thresholds for each balanced amplifier, resulting in a hybrid load modulation that combines a HALMBA region with a Doherty-like region. Consequently, a four-way Doherty PA-style load modulation has been accomplished and it achieves the simulated peak efficiency of 71.89% and efficiency of 68.45% at 15-dB OBO. To validate the theory, a prototype of the H-LMDBA is built and measured at 2.1 GHz, utilizing GaN transistors and branch-line quadrature hybrid couplers. The prototype achieves a peak efficiency of 65.2% and an efficiency of 51.5% at a 15.4 dB OBO. By expanding upon the original LMBA's design area, this design presents a promising option for the development of next-generation, energy-efficient wireless transmitters.

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