Load-Modulated Balanced Amplifiers for Next-G Wireless Communications

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***Abstract*—This article presents an overview of the recent advances in load-modulated balanced amplifier (LMBA), which has been a highly popular topic in RF research. The theory and design equations are revisited for different types of couplers, which were typically not distinguished in existing literature. Moreover, the design methodology is re-developed based on signal-flow analysis of individual balanced amplifier (BA) and control amplifier (CA) paths, indicating the intrinsic wideband nature of LMBA. Furthermore, LMBA design space are expanded with various modes showing highly desirable features for emerging wireless applications, including power back-off (PBO) range, linearity and insensitivity to load (antenna) impedance variations. A few realistic design examples are experimentally demonstrated to showcase the advantages of LMBA over state-of-the-art and the promising potential for next-G communications.**

Keywords—Efficiency, load modulation, balanced amplifier, power amplifier, communications.

I. INTRODUCTION

RF power amplifier (PA), located at the wireless transmitter front-end, is primarily responsible for boosting the radio wave to a sufficient level for establishing a stable high-speed wireless link. With the rapid wireless evolution, the research on high-efficiency PAs has been increasingly emphasized given the fact that PA is the most energy-consuming unit in any wireless systems. Also, PA stands as the last stage driving the antenna radiation, so that it must maintain a high linearity to not distort the radiated signal. Moreover, PA needs to sustain its performance when antenna condition is fluctuated, which can happen very frequently in mobile handsets due to the hand-gripping effect and in large antenna arrays due to the mutual coupling and beam scanning.

The ever-increasing data rate and communication bandwidth call for advanced modulation schemes, such as 1024/4096QAM and OFDM. However, this also leads to a surging peak to average power ratio (PAPR) of modulated signals and require efficiency enhancement technologies of PAs, which could otherwise operate at very low average efficiency, e.g., 10%. Load modulation is a widely adopted technology, but its typical circuit architecture, Doherty PA, is now facing major challenges in terms of RF bandwidth, PBO range, load insensitivity, etc. Recently, a new load-modulation platform, namely load-modulated balanced amplifier (LMBA) [1], has gained a lot of popularity with numerous successful demonstrations being reported. Moreover, LMBA can also offer decent linearity with dedicated circuit setting, and it is endowed with powerful reconfigurability for optimization at different bands and different modulations [2]-[7]. More importantly, LMBA inherits the balanced nature, which can be leveraged to operate linearly and efficiently against load mismatch [8,9].

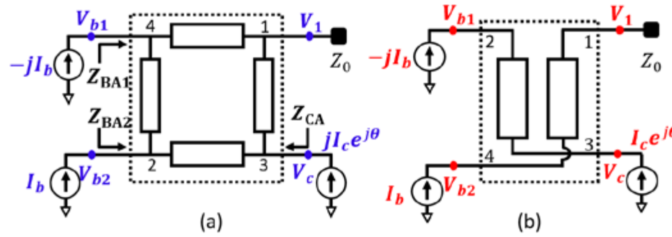

Fig. 1. Analytical LMBA models based on different quadrature couplers: a) branch-line hybrid, b) coupled-line coupler.

Overall, LMBA promises an excellent candidate for next-generation wireless communications systems. This paper provides a comprehensive overview of LMBA from theory to practice. Specifically, the LMBA theoretical model is revisited with different types of quadrature couplers, indicating a difference in design conditions that has been ignored in existing theory. The design methodology is also redeveloped based on signal flow together with multiple realistic design examples for validation and experimental demonstration.

II. REDERIVATION OF LMBA THEORY

LMBA, initially introduced in [1], consists of a balanced amplifier (BA) and a control amplifier (CA). The derivation of LMBA theory has been based on Z-matrix of quadrature coupler with ideal current generators representing the associated sub-amplifiers, i.e., BA1, BA2, and CA.

A. LMBA Theory Revisited with Different 90° Couplers

LMBA comprises two quadrature (90°) couplers as its core building block. Quadrature coupler can be implemented using either branch-line [2] or coupled-line [1]. Notably, branch-line coupler can be realized with only one metal layer, whereas a coupled-line coupler requires multiple metal layers, making it more challenging for LMBA manufacturing. However, coupled-line couplers offer the advantage of achieving a broader bandwidth without requiring the cascading of multiple sections, as is necessary with branch-line couplers. As a result, coupled-line couplers can be designed to be more broadband and compact in size compared to branch-line couplers. These coupler topologies are discussed in detail in [10].

Regularly, the derivation of LMBA theory is based on Z-matrix of the quadrature coupler. It is important to note that a branch-line coupler and a coupled-line coupler have different Z-matrices, which can be derived based on different S-matrices. However, many published papers [3]-[5] have not distinguished this discrepancy. For instance, in certain papers, the LMBA was implemented using branch-line couplers, yet the Z-matrix for coupled-line couplers was employed for theoretical analysis. This paper aims to address this gap by reviewing the theoretical derivation of LMBA using both types of couplers.

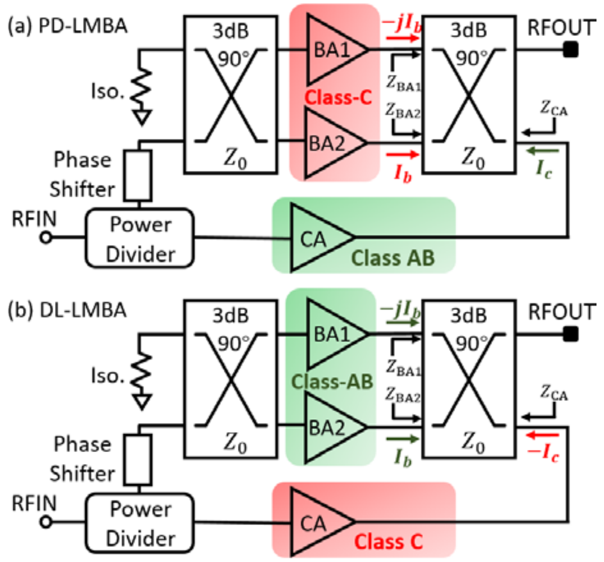

Fig. 2. LMBA with Doherty type of biasing scheme: 1) Pseudo-Doherty LMBA (PD-LMBA), b) Doherty-like LMBA.

The branch-line coupler based LMBA is depicted in Fig. 1(a), and its Z-matrix can be written as

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = Z_0 \begin{bmatrix} 0 & 0 & +j & -j\sqrt{2} \\ 0 & 0 & -j\sqrt{2} & +j \\ +j & -j\sqrt{2} & 0 & 0 \\ -j\sqrt{2} & +j & 0 & 0 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} \quad (1)$$

where $V_1 = -I_1 Z_0, I_2 = I_b$ and $I_4 = -jI_b$, representing the RF currents from BA1 and BA2. $I_3 = jI_c e^{j\theta}$ represents the RF current from CA. Note that "+j" indicates the phase of current is "+90°", while "-j" indicates the phase of current is "-90°". Utilizing the Z-matrix and the boundary conditions at each port, the impedance seen by BA1, BA2 and CA are given by

$$Z_{BA1} = Z_{BA2} = Z_0\left(1 + \sqrt{2}\frac{I_c e^{j\theta}}{I_b}\right) \quad (2)$$

$$Z_{CA} = Z_0. \quad (3)$$

The coupled-line-based LMBA is depicted in Fig. 1(b), and its Z-matrix can be written similarly as

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = Z_0 \begin{bmatrix} 0 & 0 & -j & -j\sqrt{2} \\ 0 & 0 & -j\sqrt{2} & -j \\ -j & -j\sqrt{2} & 0 & 0 \\ -j\sqrt{2} & -j & 0 & 0 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} \quad (4)$$

where $V_1 = -I_1 Z_0$, $I_2 = -jI_b$ and $I_4 = I_b$. Interestingly, the same Eqs. (2) and (3) can be obtained, but the CA current must satisfy a different phase setting as compared to branch-line coupler, i.e., $I_3 = I_c e^{j\theta}$. It is important to note that for the coupled-line-based LMBA, the relative phase offset between BA and CA is different due to the difference in couplers' responses, which will be eventually reflected in realistic design.

B. LMBA with Doherty-Type Biasing Scheme

A Doherty PA (DPA) consists of two PAs: one PA biased in Class AB mode as its carrier amplifier, and the other PA biased in Class C mode as its peaking amplifier. By applying the same biasing technic to LMBAs, the efficiency of LMBAs are enhanced by load modulation. Eqs. (2) and (3) describe the load modulation behavior of LMBAs. Depending on the LMBA mode, θ takes on different values. For example, $\theta = 180°$ corresponds to Doherty-like LMBA (DL-LMBA) [6], and $\theta = 0°$ corresponds to pseudo-Doherty LMBA (PD-LMBA) [2]. The schematics of these two LMBA modes are depicted in Fig.2, assuming coupled-line couplers are employed. In a DL-LMBA, the BA is biased in Class AB mode, and the CA is biased in Class C mode. While in a PD-LMBA, the CA is biased in Class AB mode, and the BA is biased in Class C mode. The reason behind such biasing techniques is to ensure the impedances seen by the BA decrease as input power increases in LMBAs, similar to DPAs. Unlike DPAs, LMBAs can achieve efficiency enhancement across a much broader bandwidth due to the broadband nature of the circuit.

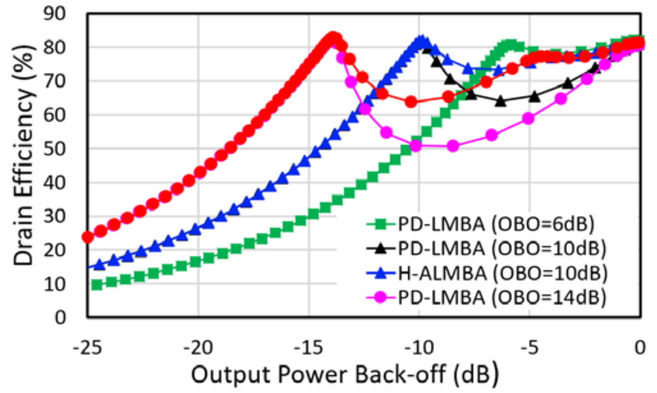

Fig. 3. LMBA with different settings to accommodate various PBO ranges and efficiency enhancement.

III. Practical Design Methodology

Advanced design methodologies for developing ultra-wideband LMBA with extended power-back-off range are discussed in this section.

A. Extended Power-Back-off Range

Compared to DL-LMBA, PD-LMBA utilizes two PAs (BA1 and BA2) as its peaking amplifiers instead of one, inherently providing a wider output power back-off (OBO) range. However, as the OBO increases, the efficiency of PD-LMBA across the OBO to peak power range significantly diminishes due to the low efficiency contributed by the peaking amplifiers. This is because the peaking amplifiers, BA1 and BA2 in this case, only reach their maximum efficiency at peak power. To address this challenge, hybrid asymmetrical LMBAs (H-ALMBA) [7], [8] have emerged as a viable solution. The core concept of H-ALMBA involves activating BA1 and BA2 at different OBO levels to enhance the overall efficiency through high-order load modulation, akin to a three-way DPA [11].

To illustrate the theory, emulation models of PD-LMBA and H-ALMBA are simulated at various OBO levels, and the normalized efficiency curves at different OBO levels are plotted in Fig. 3. Notably, for H-ALMBA, a stronger behavior of efficiency enhancement is observed, as depicted in Fig. 3.

B. Signal-Flow-Based Phase Alignment

As discussed in section II, the traditional LMBA theory involves with the use of Z-matrix to derive the impedances

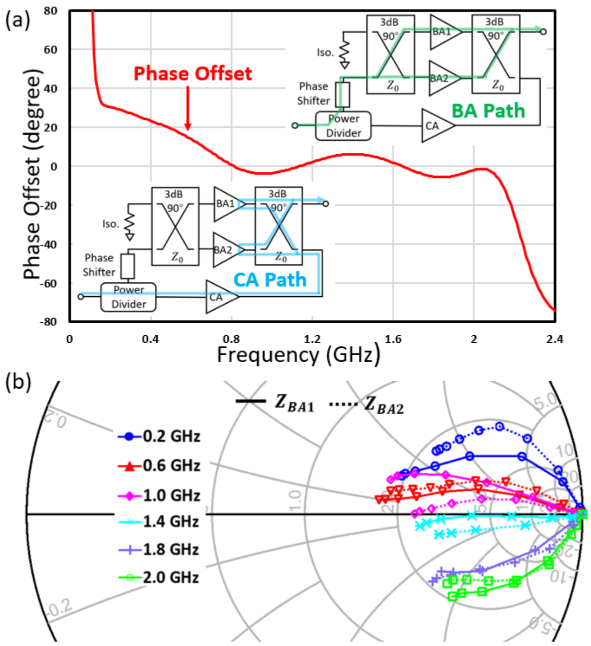

Fig. 4. (a) BA and CA signal path phase offset reported in [12] across the design bandwidth. (b) BA Intrinsic load impedance trajectories.

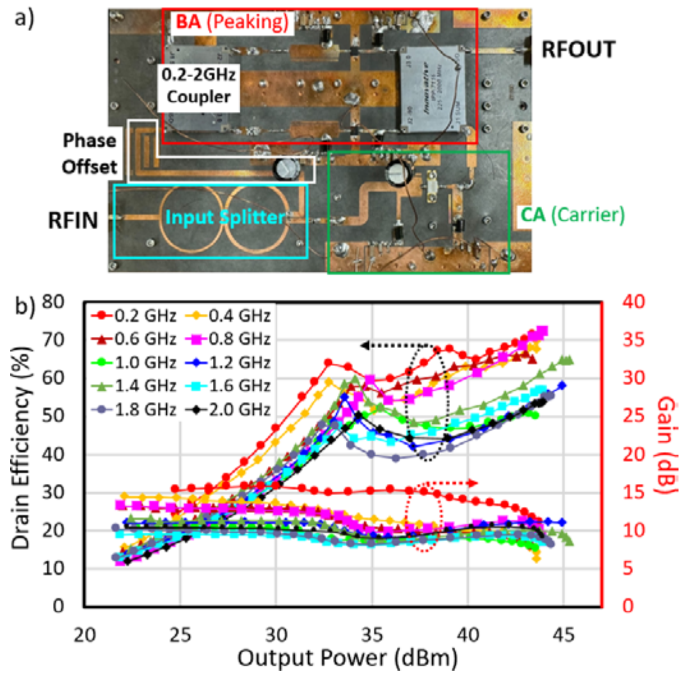

Fig. 5. Demonstration of the first-ever decade-bandwidth LMBA: a) hardware prototype, b) CW measurement results from 0.2–2 GHz.

equations. Although this approach provides a concise explanation of the load modulation behavior of LMBA, it only applies for a single frequency and does not account for the frequency-dependent nature of couplers and other building blocks. Additionally, such theory is not able to provide a systematic design methodology for the phase-alignment problem of LMBA.

To address this problem, a signal-flow-based theory was proposed in [12]. It accounts for the frequency-dependent nature of all building blocks and applies for all in-band frequencies of LMBA by constructing the full signal-flow graph of LMBA. Furthermore, a unique phase-alignment condition is found to be critical in [12] to ensure the load modulation behavior of LMBA: CA signal and BA signal should be in-phase combined at the output.

The phase offset of the PD-LMBA prototype reported in [12] between the BA and CA signal paths is plotted in Fig. 4(a), indicating that the phase difference is below 30 degrees. Fig. 4(b) displays the intrinsic load trajectories of BAs, revealing a desired load modulation behavior across all in-band frequencies.

IV. Design Examples

In this section, several design examples will be reviewed to showcase the state-of-the-art LMBAs.

A. Ultra-Wideband PD-LMBAs

The first example was reported in [3], an PD-LMBA/ ALMBA prototype developed using GaN technology and commercial quadrature couplers. The prototype experimentally demonstrated a 4:1 RF bandwidth from 0.55 to 2.2 GHz and high efficiency, i.e., 55%–82% at peak power and 40%–61% at 10-dB power back-off, as depicted in Fig. 5(a).

The second example, reported in [12], presented a PD-LMBA prototype designed using the signal-flow-based design methodology. Utilizing GaN technology and commercial couplers, the prototype spanned a frequency range from 0.2 to 2 GHz, marking the broadest bandwidth achieved among all reported load modulated PAs to date. Experimental results demonstrated an efficiency of 51% to 72% for peak output power and 44% to 62% for 10-dB OBO, respectively, as shown in Fig. 5(b).

B. Highly Linear and Load-Insensitive H-ALMBA

Derived from the horizon of PD-LMBA [2] and other Doherty-like LMBAs, which predominantly utilize two-way modulation, the innovative H-ALMBA architecture provides a three-way load modulation by sequentially turning on the transistors in balanced amplifier [7]. This new mode can offer enhanced efficiency over extended power back-off range. More importantly, H-ALMBA also perfectly inherits the wideband nature from PD-LMBA, while offering a nearly unlimited frequency span.

The H-AMLBA mode is then extended to linear enhancement operation by exchanging the gate biasing of BA1 and BA2 together with linearity-optimal phase control [8]. This reconfiguration effectively improves the linearity profile of H-ALMBA without any DPD. Additionally, it is theoretical proven that this linearity enhancement reconfiguration is load-dependent, together with the load-dependent biasing of CA [9], the overall PA performance in terms of power back off range, efficiency and linearity can be sustained under arbitrary load mismatch.

Fig. 6(a) shows the fabricated H-ALMBA with the proposed linear enhancement operation including load-dependent biasing and trimmable phase-shifting TL. With such reconfiguration, the prototype is first measured using a 20 MHz modulation-bandwidth single-carrier 64 QAM LTE signal

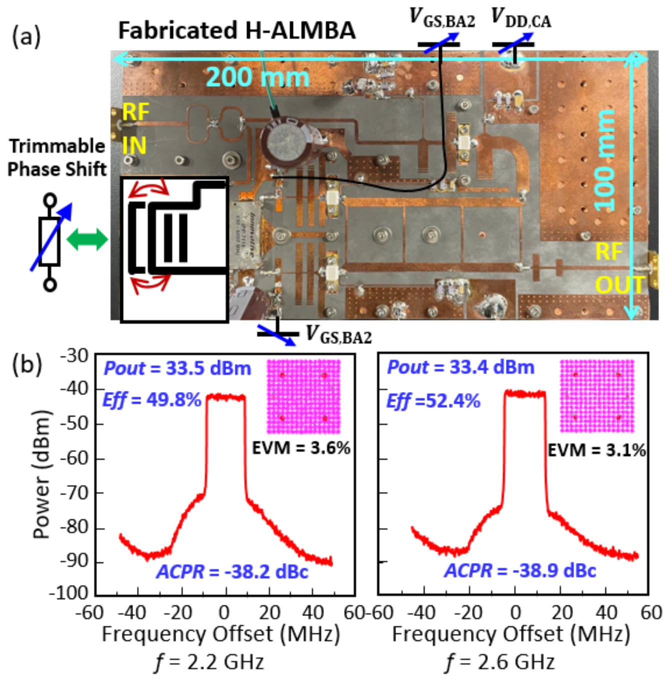

Fig. 6. Reconfigurable H-ALMBA [8] with wide bandwidth and high linearity: a) prototype, b) modulated measurement.

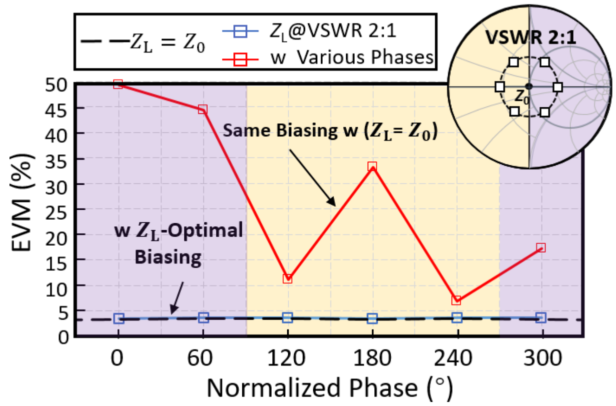

Fig. 7. Resilience to antenna impedance mismatch (2:1 VSWR).

under matched condition. As depicted in Fig.6 (b), the measured ACPR of the two selected frequencies are both lower than -38 dBc without any digital pre-distortion which solid prove the effectiveness of our proposed linear operation. The board is further measured under the 2:1 VSWR load mismatch to present the mismatch-resilient feature. As shown in Fig. 7, over the entire 2 : 1 VSWR circle, the EVM can be perfectly recovered through the proposed reconfiguration. Such a successful demonstration highlights its substantial potential for integration into array-based massive MIMO systems.

Moreover, by further incorporating another balanced amplifier [13] or magnetic-less non-reciprocity [14] into the LMBA circuit, it can offer intrinsic insensitivity/isolation to load variations without any reconfiguration. This can eliminate the necessity for closed-loop control with minimized complexity at system level, promising an ideal solution for future massive MIMO systems based on large-scale antenna arrays.

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