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TOPICAL REVIEW

Historical Aspect of Load-Modulated Balanced Amplifiers

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ABSTRACT This paper provides a comprehensive overview of the challenges and considerations associated with the design, implementation, and optimization of Load Modulated Balanced Amplifiers (LMBAs). Various research trends, all directed toward enhancing the benefits of the LMBA scheme and addressing its inherent limitations, are outlined. The initial focus is on maximizing efficiency and/or linearity, leveraging different techniques. Another noteworthy trend involves expanding the bandwidth of the LMBA architecture, a topic extensively covered in numerous papers. The other section delves into the most notable advancements in doherty power amplifier (DPA) and comparison with LMBAs. However, there's still a need for new load-modulation power amplifier designs that can simultaneously maximize efficiency over extended power back-off and a broad frequency range. In essence, this review underscores the ongoing need for innovation in LMBAs design to meet the evolving requirements of 5G/6G communication systems.

INDEX TERMS Auxiliary amplifier, control amplifier, high efficiency, load modulated balanced amplifier, output power back-off.

I. INTRODUCTION

The sixth generation (6G) MIMO communication systems inevitably demand the development of power amplifier architectures to achieve high efficiency at back-off, broadband operation, load mismatch tolerance, and continuum of load modulation. The high modulation order in the spectrally-efficient modulation schemes and the increasing number of subcarriers result in a high peak-to-average power ratio. This leads to the fact that power amplifiers have to operate at the extensive power backed-off range. However, the wide use of high dynamic range signals at RF and especially mm-wave carrier frequencies complicates the design of power amplifiers. Different load-modulation architectures, including out-phasing [1], [2], dynamic load modulation power amplifier [3], [4], and DPAs [5], [6], have been employed because of the complexity and bandwidth limitation of envelope tracking, [2], [7], [8]. Applying switching-mode technique results in high efficiency power amplifiers, [9], [10], [11]. However, these switching-mode power amplifiers have poor linearity and are unsuitable to replace linear power amplifiers and can be used in advanced architectures with linearization techniques. The LMBA was initially developed to address bandwidth limitations associated with conventional load modulation techniques [12], [13] and to enhance efficiency in the back-off region. Despite its potential for efficiency improvement, the inclusion of an additional control amplifier and a phase shifter contributes to an increase in circuit size. Nevertheless, LMBA has garnered significant research interest due to its efficiency enhancement in back-off regions. However, challenges persist, such as maintaining maximized efficiency over extended power back-off and mitigating the effects of load mismatch in LMBA applications. The LMBA technique allows dynamic control of amplifier characteristics over wide signal amplitude and frequency ranges. In [14] and [15], LMBA implementations required an external low-power control signal for efficiency enhancement but did not operate on a single modulated RF input. The work in [14] was expanded upon in [15], demonstrating the reconfiguration of the operating frequency by modifying the phase of the control signal. In [16] and [17], the control signal was directly generated from the single modulated RF input, resulting in a RF-input LMBA. While [16] focused on amplitude

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control of the control signal for efficiency enhancement, [17] extended the control signal generation approach to include the automatic generation of the correct phase, enabling octave-bandwidth operation. Moreover, the authors in [17] achieved greater than one octave bandwidth using a bandpass filter as a broadband phase shifter. Another approach was presented in [18], where an envelope-tracked load-modulated balanced amplifier over a wide frequency range was introduced. The supply voltage of the balanced power amplifier was dynamically varied for efficiency enhancement using a multi-level power digital-to-analog converter, albeit requiring an extra supply modulator. In [19], a high-efficiency Doherty-like single RF-input LMBA was proposed as an alternative to the DPA. Additionally, [20] proposed a wideband DPA using wideband sandstone power amplifiers and 2-section wideband quadrature couplers with reactive termination at the isolation port. Further innovations include the reconfigurable balanced to doherty power amplifier demonstrated in [21] and [22]. For the first time, a commercial switch was utilized to convert the balanced amplifier to a DPA. However, in [21], efficiency in balanced mode was significantly degraded due to the absence of load modulation. The purpose of [22] was to achieve high linearity and efficiency in both balanced and Doherty modes. A Sequential LMBA (SLMBA) achieved a wider bandwidth than the conventional LMBA, [23]. In SLMBA, the control amplifier serves as the carrier amplifier, and the balanced amplifier acts as the peaking amplifier, facilitating the load modulation process. Introducing a configuration with dual-octave bandwidth and multi-band operations, [24], [25] referred to this as Pseudo-Doherty LMBA (PD-LMBA). However, reliability concerns and severe nonlinearity were noted in these techniques, particularly in the control amplifier. In [26], researchers demonstrated that introducing asymmetry in the auxiliary transistors of the balanced amplifier allows for a continuum of load modulation ratios in the control amplifier. However, in an Asymmetrical LMBA (ALMBA), one of two identical auxiliary transistors cannot achieve full power utilization. This under-utilization is considered impractical in industrial applications due to the complexity of the supply chain and cost considerations. A novel approach is presented in [27] and [28], where wideband Quasi-Balanced DPAs (QB-DPAs) are designed through reciprocal main/auxiliary PA with strong mismatch tolerance. In comparison to power amplifiers in [21] and [22], a novel linearity-enhanced combiner [28] is proposed to improve linearity in both Doherty and balanced modes. However, both Sequential LMBA (SLMBA) and QB-DPA face challenges as the control amplifier saturates at the output back-off level, causing dependability issues and nonlinearity. To address these challenges, a Hybrid LMBA (HLMBA) in [29] combines a QB-DPA and a control amplifier, offering high efficiency, an OBO range of 9 dB, and good linearity. Another innovative design is presented in [30], introducing an asymmetrical HLMBA with different threshold voltages for BA1 and BA2, enhancing efficiency between two peaks. In [31], a straightforward automatic design is proposed to calculate the optimum impedance, efficiency, and output power levels for SLMBA. Overcoming the difficulty of maintaining constant resistive load modulated impedance, a novel Waveform-Engineered Sequential LMBA (W-SLMBA) is introduced in [32]. W-SLMBA utilizes continuous Class-B/J PAs in the peaking branch and continuous Class-F^{-1} PA in the carrier branch to expand the design space for the BA. Similarly, in [33], high-efficiency harmonic-tuned continuous Class-F/F^{-1} is combined with H-ALMBA to achieve broadband performance. The authors in [34] proposed a broadband three-stage pseudoload modulated balanced amplifier with enhanced power back-off efficiency. Another approach to achieving load modulation continuum is presented in [35], introducing a RF-input symmetric LMBA with a properly selected coupling factor of the output coupler, enabling full power utilization of two identical auxiliary transistors compared to [32]. The first significant evolution of LMBA, known as Orthogonal LMBA (OLMBA), is introduced in [36] and [37]. In OLMBA, the Control Signal Power (CSP) buffer and main power amplifier are combined in a single balanced amplifier. However, OLMBA requires an external control signal similar to an Envelope Tracking system, though the needed CSP power is much lower than in conventional LMBA. There is a review paper on LMBAs published in [38]. However, in this paper a complete review with more details on design techniques for the LMBA, an essential subject for 5G/6G wireless transmitters, is presented. The article describes the conventional LMBA architecture and operation principle in Section II. In Section III, the article highlights several major categories of efficiency improvement in LMBAs. The objective of this section is to determine how different techniques can enhance the performance or efficiency of LMBAs in the OBO region. The advancements in DPA and comparison with LMBAs is presented in Section IV. Finally, Section V focuses on the potential advancements and areas of further research in LMBAs in RF/microwave applications.

II. CONVENTIONAL LMBA ARCHITECTURES AND OPERATION PRINCIPLES

In this section, we provide a technical description of the LMBA and its advantages over conventional techniques like doherty and outphasing amplifiers. The LMBA is designed to address the bandwidth limitations of these traditional techniques while enhancing efficiency during power backoff. Doherty amplifier is a technique where two PAs are combined, one acting as a main (carrier) amplifier and the other as an auxiliary (peaking) amplifier. The carrier amplifier operates continuously, while the peak amplifier is activated only when higher power levels are required. The load modulation in a doherty amplifier occurs by varying the impedance seen by the peak amplifier. However, the load modulation range is typically limited to around 2:1, which might not provide as much efficiency improvement in deep back-off conditions. In an outphasing amplifier, multiple PAs generate two or more signals with varying phases. These signals are then combined to produce the desired output signal. This technique allows for load modulation with load variations up to 10:1 or even more. This characteristic makes outphasing amplifiers more suitable for achieving efficient operation in deep back-off conditions. While outphasing amplifiers offer significant load modulation potential, they do face challenges. One of these challenges is the mismatch in loading trajectories experienced by the different PAs in the system. When the PAs have different load conditions, it can lead to suboptimal performance and reduced overall efficiency. To address this issue, one approach is to use more than two PA paths in the outphasing configuration. By increasing the number of PA paths, you can improve the load distribution and mitigate the performance mismatch problem. However, this comes at the cost of increased complexity in the amplifier design and potentially higher power consumption.

A. BASIC STRUCTURES

The basic LMBA structure is shown in Fig. 1. Some points can be summarized as

- The LMBA is based on a classical balanced amplifier configuration, employing wideband input and output quadrature couplers.
- A control signal is injected into the normally terminated isolation port of the output coupler. This control signal modulates the load presented to the two power transistors, allowing for an active and controllable match.
- The control signal can be generated from the modulated RF input using an input splitter and a specifically designed control power amplifier. This results in an RF-input LMBA.
- The LMBA's load modulation can be applied over a wide bandwidth, primarily limited by the 90-degree coupler. This wide bandwidth capability makes the LMBA potentially more versatile than conventional doherty and outphasing techniques.
- The LMBA can modulate the impedance seen by the power transistors in a quadrature balanced configuration., power and efficiency of the LMBA can be dynamically optimized at specific power backoff levels and frequencies by varying the amplitude and phase of the external control signal.
- The LMBA is presented as a potentially disruptive technique that enables dynamic control of amplifier characteristics over wide signal amplitude and frequency ranges.
- Unlike the doherty PA, the LMBA allows the load seen by the active devices to be modulated both upwards and downwards, resistively and reactively, with minimal loss of power combination efficiency.

Overall, the LMBA offers a unique solution to address bandwidth limitations, enhance efficiency, and provide dynamic control over amplifier characteristics. Its ability to modulate the impedance seen by power transistors allows

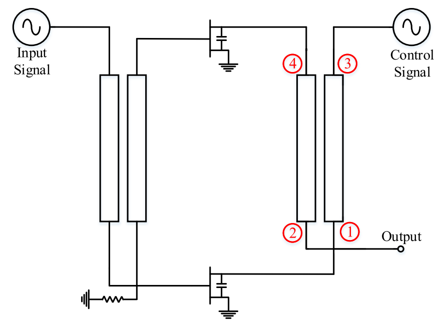
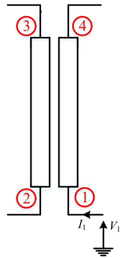


FIGURE 1. The LMBA structure [14].



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

FIGURE 2. 4-port Z-matrix of 3dB coupler.

for optimization in various operating conditions, making it a promising technique for next-generation RF power amplification systems.

B. OPERATION PRINCIPLE

Based on Fig. 1, two balanced devices are represented as current sinks with equal magnitude of I_b, and an appropriate quadrature phase offset, so that $I_2 = -I_b = -jI_c \times e^{j\phi}$ and $I_4 = -jI_b$. The control device output can also be represented as a current sink on port 3, which has a stipulated phase offset ϕ, so that $I_3 = -I_{con}$. Output port 1 is terminated, so that $V_1 = -Z_0 \times I_1$. Based on Fig. 2, the impedances seen by each balanced device is

$$Z_A = Z_0\{1 - \sqrt{2}\frac{I_c \times e^{j\phi}}{I_b}\} \tag{1}$$

$$Z_B = Z_0\{1 - \sqrt{2}\frac{I_c \times e^{j\phi}}{I_b}\} \tag{2}$$

Eqs. (1) and (2) show that the load impedance presented to each of the balanced device outputs has the same magnitude and phase and can be modulated by adjusting the magnitude and phase of the control signal. Furthermore, the power generated by each of the balanced current sources P_{bal} is given by

$$\begin{aligned} 2P_{bal} &= I_b^2 Z_0 Re\{1 - \sqrt{2}\frac{I_c \times e^{j\phi}}{I_b}\} \\ &= Z_0\{I_b^2 - \sqrt{2}I_b I_c \cos(\phi)\} \end{aligned} \tag{3}$$

Considering $I_1 = \sqrt{2}I_b - I_c e^{j\phi}$, the output power P_1 is

$$\begin{aligned} P_1 &= \frac{1}{2}Z_0|\sqrt{2}I_b - I_c\cos(\phi) - j\cos(\phi) \\ &= Z_0|I_b^2 - I_b I_c\cos(\phi) + \frac{1}{2}I_c^2|^2 \end{aligned} \tag{4}$$

The control power signal into port 3 is given by

$$P_{con} = \frac{1}{2} Z_0 I_c^2 \tag{5}$$

Finally

$$P_1 = P_{con} + 2P_{bal} \tag{6}$$

The control current is $I_{con} = I_c e^{j\phi}$. The ratio of control power to the power generated by a single balanced device α is obtained by Eq.(1)-(4) as

$$\frac{P_{con}}{P_{bal}} = \frac{|\frac{Z_b}{Z_0} - 1|^2}{2Re(\frac{Z_b}{Z_0})} = \alpha \tag{7}$$

where Z_b represents the device plane impedance Z_A or Z_B. The corresponding reflection coefficient is

$$\rho_b = \frac{z_b - 1}{z_b + 1} \tag{8}$$

where $z_b = \frac{Z_b}{Z_0}$. Substituting (8) in (5) gives

$$\alpha = \frac{|\frac{2\rho_b}{1-\rho_b}|^2}{2Re(\frac{1+\rho_b}{1-\rho_b})} \tag{9}$$

So the reflection coefficient is

$$\rho_b = \frac{\alpha}{2 + \alpha} \tag{10}$$

III. EFFICIENCY AND BANDWIDTH IMPROVEMENT

In this section, different techniques to improve the efficiency of LMBAs at power back-off conditions, where the amplifier operates at reduced power levels, will be discussed. The architecture in [16] involves generating a control signal directly from a single modulated RF input. The focus of this architecture is to manipulate a reflection coefficient magnitude ($|\Gamma|$) using the generated control signal. In this variation of the architecture, the control signal is derived directly from a single modulated RF input, which is termed an "RF-input LMBA." Increasing the power of the control signal ($|P_{ctrl}|$) increases the magnitude of the reflection coefficient and causes a counter-clockwise rotation of the reflection coefficient on the smith chart. This trajectory includes providing the correct phase and adjusting the amplitude of the control signal. The amplitude of the control signal should increase as the desired output power decreases. The correct phase in the control signal can be achieved using fixed or variable phase shift networks. The challenge lies in managing the power level of the control signal ($|P_{ctrl}|$). There's an inverse relationship between the input power P_{in} and the control signal power ($|P_{ctrl}|$), meaning that as the desired output power decreases, the control signal power needs to increase. The architecture introduces a control PA that exhibits a nonlinear input-output characteristic. This characteristic is depicted in Fig. 3. The control PA is intentionally designed to saturate at a low power level. This design choice ensures that the relative control power (P_{rel}) decreases as the input drive power increases.

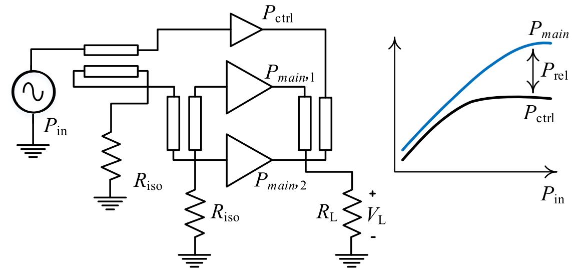


FIGURE 3. The RF-input LMBA [16].

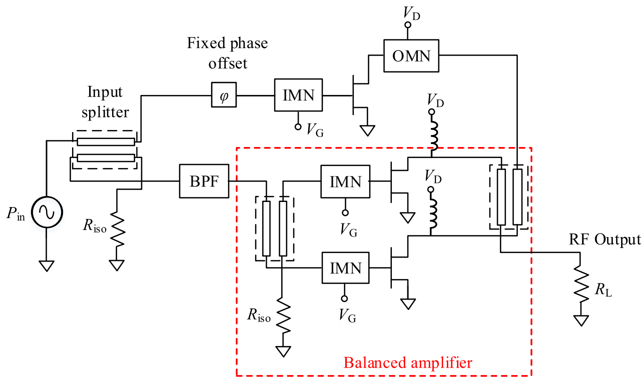


FIGURE 4. The RF-input LMBA [17].

In [17], the control signal amplitude of the LMBA is dynamically adjusted based on the amplitude modulation of the RF input signal, Fig. 4. This dynamic modulation technique enables better control of the amplifier's behavior and performance. Compared to conventional LMBA, the RF-input LMBA offers several notable advantages.

1) Using RF circuits on the board to generate the control signal eliminates the need for extra baseband computations that would be necessary in the case of a modulated signal. This simplifies the overall signal processing and reduces complexity.
2) The dynamic modulation of the control signal in the RF-input LMBA enhances its back-off efficiency, enabling it to perform better even at lower power levels.
3) The dynamic modulation of the control signal extends the dynamic range of the amplifier. This means that the amplifier can handle a wider range of input signal amplitudes effectively, accommodating varying signal strengths and adapting to different communication scenarios.

The advantages offered by the RF-input LMBA make it particularly well-suited for use with complex modulation schemes that have high PAPR. These modulation schemes tend to generate signals with significant amplitude variations, which can challenge traditional amplifiers. The dynamic control mechanism of the RF-input LMBA helps mitigate these challenges and ensures better signal quality. In [18], the authors focused on utilizing supply modulation to enhance the back-off efficiency of a broadband LMBA, highlighting its advantages over traditional amplification techniques. The study presents the architecture, implementation details, and characterization results to demonstrate the viability

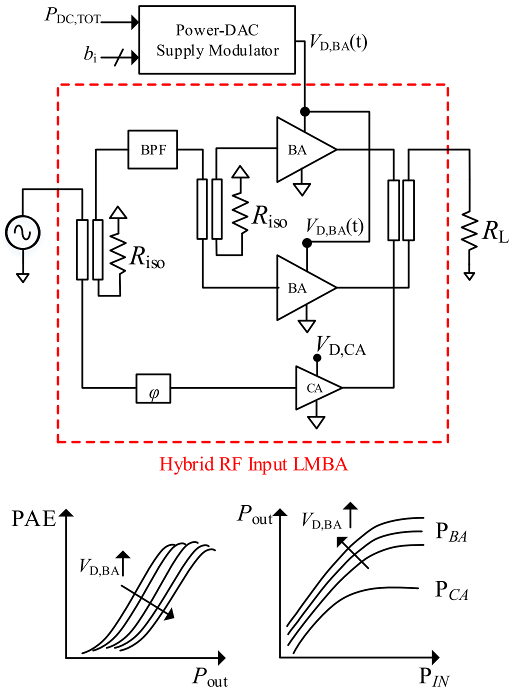


FIGURE 5. The RF-input LMBA with supply modulation [18].

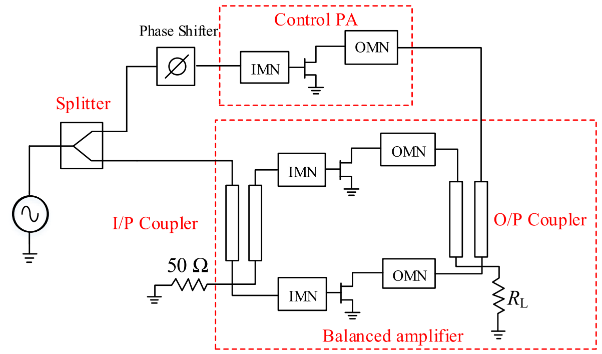


FIGURE 6. The RF-input LMBA [19].

of the proposed approach. In Fig. 5, a hybrid multi-level converter, acting as a power DAC, is used to produce different supply voltage levels ranging from 10 V to 30 V for modulating the drain of the balanced amplifier. Supply modulation's advantage lies in its independence from the carrier frequency of the RF signal. This makes it a natural candidate for enhancing back-off efficiency in a broadband power amplifier. The configuration of the Doherty-like RF-input LMBA has been introduced in [19]. Fig. 6 shows the arrangement of components and connections within this specific type of amplifier circuit. In this version of the RF-input LMBA, there is a control power amplifier that shares similarities with the auxiliary amplifier in a DPA. The behavior of the control PA in the RF-input LMBA is compared to the functionality of the auxiliary amplifier in a DPA. In a DPA, the auxiliary amplifier works in conjunction with the main amplifier to improve efficiency and linearity, particularly at lower power levels. Similar to the behavior of the auxiliary amplifier in a DPA, the control PA in this RF-input LMBA operates by turning ON only during the high-power regime. This means that the control PA is engaged selectively, activating when the output power of the amplifier is at higher levels. This design strategy aims to enhance the efficiency and performance of the LMBA during high-power operations.

The sequential LMBA in [23] employs a balanced power amplifier pair. This means that two identical amplifiers are used in a balanced configuration, where the signals are split and fed into each amplifier with a phase difference of 180 degrees. This configuration helps cancel out even-order harmonic distortions and improves linearity and efficiency. The concern mentioned about efficiency and parallel losses refers to the efficiency of the power amplifier at back-off and saturation power levels. Inefficient parallel paths can limit the overall efficiency of the amplifier, particularly when operating away from its peak efficiency point. The architecture mentions the challenge of designing output matching networks (OMNs) that satisfy load conditions across a wide bandwidth. The difficulty in designing OMNs over a wide bandwidth suggests that the architecture's performance might be constrained in terms of frequency range. The architecture combines different amplifier classes for the carrier and peaking amplifiers. Class-B operation offers good efficiency at the cost of some distortion, while Class-C operation offers high efficiency but with significant distortion due to signal clipping. This combination may be chosen to balance efficiency and linearity requirements. Fig. 7 shows a 90-degree directional coupler used in the architecture to split the signals between the carrier amplifier and the peaking amplifiers. The isolated port is connected to the carrier amplifier, and the through and coupled ports are connected to the peaking amplifiers. The architecture might also involve a sequential approach to load modulation, where the carrier amplifier operates in Class-B mode, and the balanced PA pair operates in Class-C mode. This could be a strategy to balance the efficiency and linearity requirements of the overall system. In [24], the authors aim to address the efficiency-bandwidth trade-off that is often encountered in amplifier designs. This trade-off suggests that improving efficiency could lead to a limited bandwidth, and vice versa. The pseudo-doherty LMBA (PD-LMBA) is proposed as a solution to break this deadlock. The PD-LMBA is introduced as a mode that combines the benefits of Doherty-like amplifiers and LMBAs. It appears to be a unique configuration that aims to offer enhanced efficiency and wide bandwidth simultaneously. The distinguishing feature of the PD-LMBA seems to be its ability to operate independently of the impedance of the main amplifier using specific bias settings of both the control amplifier and the BA. This independence from BA's impedance is claimed to result in theoretically unlimited bandwidth. These bias settings allow the CA to operate without being constrained by the impedance variations of the balanced amplifier. This could contribute to the proposed unlimited bandwidth capability. Fig. 8 depicts the configuration or circuitry of the PD-LMBA,

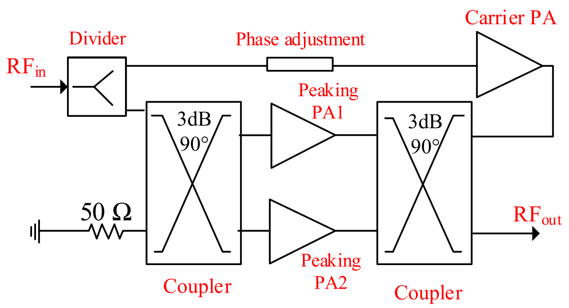


FIGURE 7. The sequential LMBA [23].

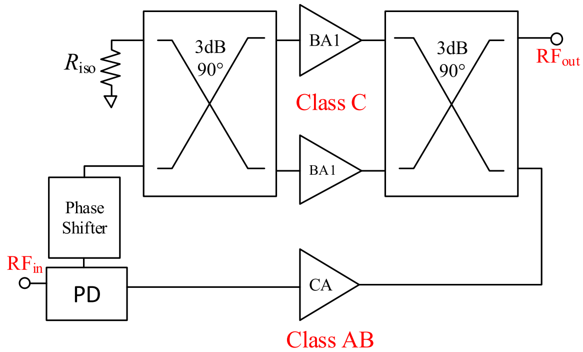


FIGURE 8. The proposed PD-LMBA [24].

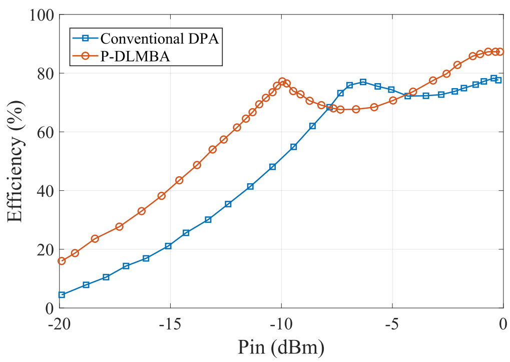


FIGURE 9. Simulated efficiency [24].

showing how the bias settings and amplifier components are connected. As shown in Fig. 9, with proper settings of BA-CA power scaling ratio and phase offset, the power back-off range of PD-LMBA can be greatly extended beyond the 6 dB of conventional DPA.

Fig. 10 shows a schematic that conceptualizes the design scheme of the wideband Quasi-Balanced Doherty Power Amplifier (QB-DPA) in [27]. This type of power amplifier is likely intended to balance power efficiency and linearity, and its design might include specific reciprocal interactions between amplifiers. The main and auxiliary amplifiers are reciprocally exchanged, suggesting that their roles might be switched based on the operating conditions. This design strategy could optimize the amplifier's efficiency and linearity at different power levels. The analysis addresses the impact of a realistic wideband coupler on the operation of a QB-DPA and proposes strategies to overcome bandwidth limitations by adjusting the coupler's configuration. The analysis then evaluates the transmission response of the coupler in

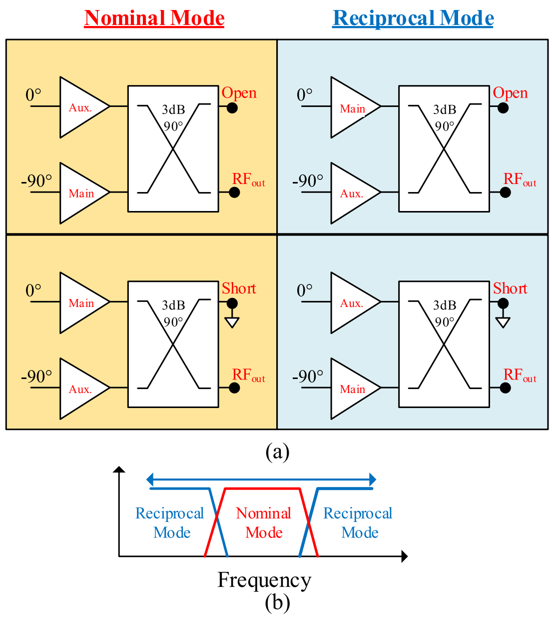


FIGURE 10. (a) The reconfiguration between series/parallel QB-DPA, (b) frequency response [27].

this doherty-like configuration. The red curve in Fig. 11 represents the transmission response. It's mentioned that the bandwidth is compromised compared to the original coupler, which suggests that the coupler's frequency response is not ideal for Doherty-like operation. To address the bandwidth limitation, the analysis suggests exchanging the main and auxiliary port settings. By doing this, a complementary frequency response can be achieved (blue curve in Fig. 11), which potentially helps extend the bandwidth of the parallel QB-DPA.

The schematic and operation of a Hybrid Load-Modulated Balanced Amplifier (HLMBA) in [29] are shown in Fig. 12. This HLMBA appears to be an advanced version of a standard BA, combining elements of a QB-DPA [27], [28] and a CA. Fig. 13 shows that the HLMBA operates in different regions based on the state of the CA. When CA is turned off, the amplifier operates in QB-DPA mode with either series or parallel configuration. When QB-DPA saturates, CA is turned on to power-equalize BA1 and BA2, re-establishing the quadrature balance and entering the LMBA region where the CA is not load modulated.

A Hybrid Asymmetrical Load Modulated Balanced Amplifier (H-ALMBA) in [30] is shown in Fig. 14. It combines aspects of doherty power amplifier and load-modulated power amplifier designs to improve efficiency and linearity over a wide range of output power levels. Let's break down the operation into three regions:

Low-Power Region: In this range, the peaking amplifiers (BA1 and BA2) are turned off, meaning their bias currents (I_{b1} and I_{b2}) are set to zero. Only the carrier amplifier is active, operating as a standalone amplifier.

Doherty Region: BA1 is turned on, and its bias current I_{b1} increases. The carrier amplifier is load-modulated by the increase in I_{b1}, similar to the operation of the carrier amplifier

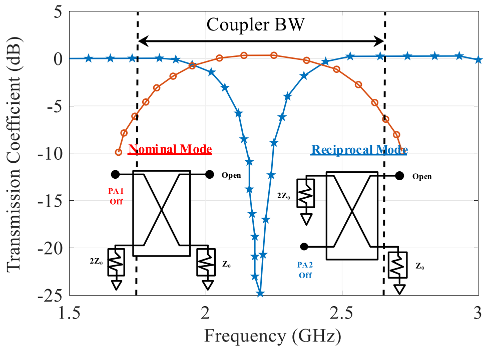


FIGURE 11. Low power equivalent circuit of QB-DPA [27].

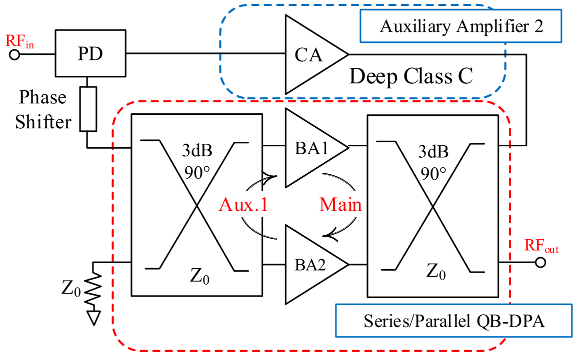


FIGURE 12. Shematic of HLMBA [29].

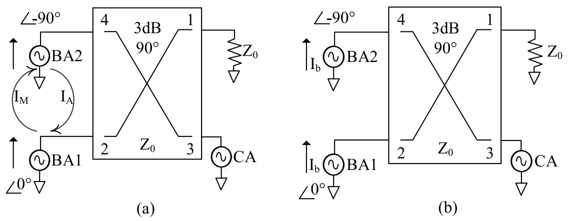


FIGURE 13. Operation of HLMBA at (a) QB-DPA, and (b) LMBA region [29].

in a DPA. The main goal in this region is to achieve a balance between the carrier amplifier and BA1 to maintain good efficiency and linearity.

ALMBA Region: Both BA1 and BA2 are turned on. I_{b2} starts to increase sharply, and I_{b1} continues to grow as well. Notably, I_{b2} increases at a larger slope than I_{b1}, and both currents eventually reach their maximum values.

The H-ALMBA design attempts to combine the benefits of both Doherty amplifiers and load-modulated amplifiers to provide enhanced performance across a wide range of output power levels. This architecture is particularly useful in applications where the transmitted power needs to be dynamically adjusted while maintaining high efficiency and linearity, such as in wireless communication systems. Fig. 15 shows that BA1 and BA2 need to be turned on at the target low-back-off and high-back-off, respectively, which can be achieved by setting the power dividing ratio between BA and CA and correctly choosing threshold voltages of BA1 and BA2. In [32], a systematic procedure to automatically design the output combiner of a sequential LMBA (SLMBA) has been presented. The method aims to find impedance

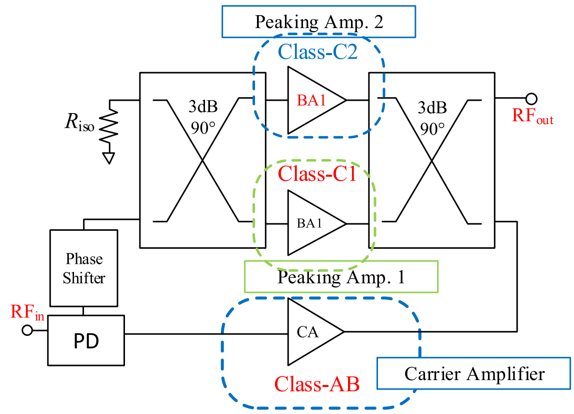


FIGURE 14. The H-ALMBA [30].

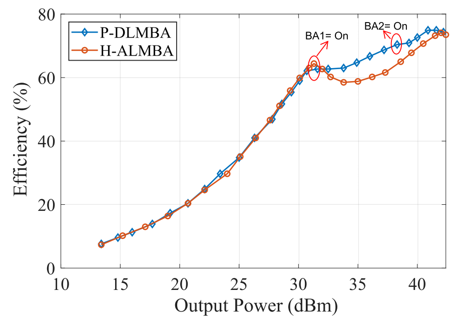


FIGURE 15. Phase and amplitude of H-ALMBA [30].

profiles that optimize the performance of the amplifier, considering factors like power, efficiency, linearity, and harmonic suppression. The approach is based on load-pull data, S-parameter analysis, impedance calculations, and objective function optimization.

The SLMBA and the P-DLMBA share a common design requirement: achieving a purely resistive load modulation trajectory for the PA. This design requirement ensures optimal power combining and maximum overall power amplifier efficiency, as depicted in Fig. 16(a). However, maintaining a constant resistive load modulation over a wideband operation is challenging in practice. To address this challenge and expand the design possibilities for power amplifiers, a novel approach is introduced in the proposed W-SLMBA architecture, as discussed in [33]. In the W-SLMBA architecture, load modulation is achieved by varying the injection of the fundamental current component from the continuous inverse Class-F carrier amplifier. This injection is accomplished through the second-harmonic load reactance of the carrier amplifier, as illustrated in Fig. 16(b). In the W-SLMBA architecture, the carrier branch employs a continuous inverse Class-F PA, while the peaking branch utilizes continuous Class-B/J PAs. This configuration removes the limitation of requiring purely resistive load modulation for the balanced amplifier, thereby expanding the available design space for amplifier implementations. This innovative approach enables more flexible load modulation characteristics and wider operational bandwidth for power amplifiers.

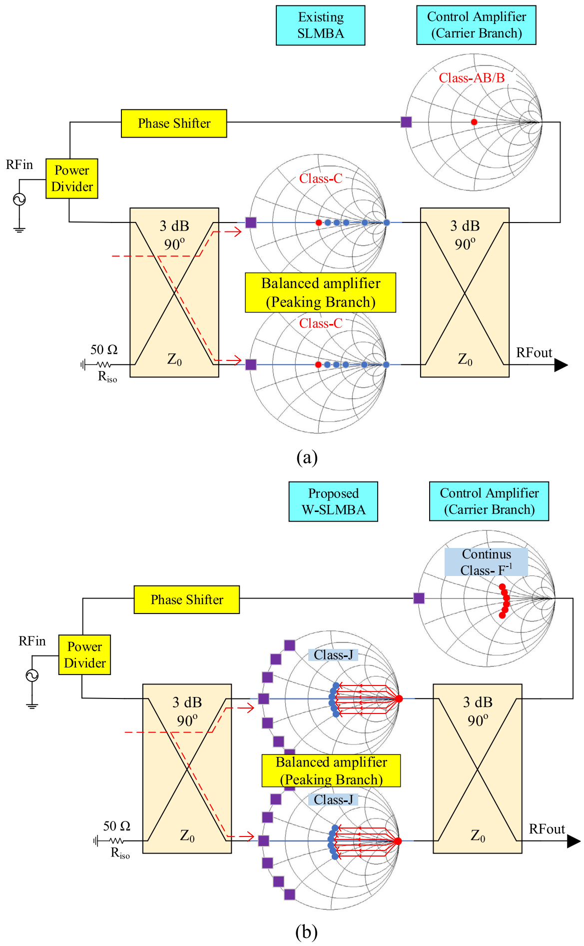


FIGURE 16. (a) The SLMBA, (b) The W-SLMBA [33].

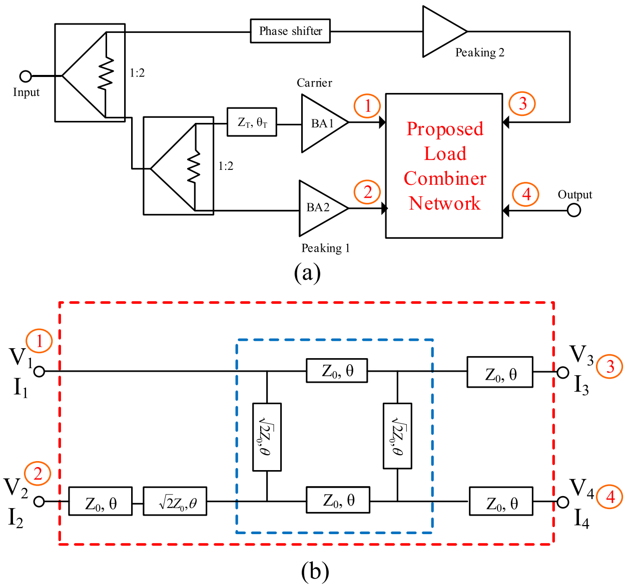


FIGURE 17. (a) The proposed P-LMBA, (b) The proposed load combiner [34].

The authors in [34] present a broadband three-stage Pseudo load modulated balanced amplifier (P-LMBA) with enhanced power back-off efficiency. The P-LMBA is a three-stage amplifier designed for broadband performance. It seems to utilize a combination of balanced amplifiers and a control amplifier to achieve its desired characteristics. The proposed P-LMBA operates in three different modes: single-PA mode, doherty mode, and LMBA mode. These modes likely correspond to different power levels and efficiency targets. As shown in Fig. 17(a), one of the balanced PA pairs is modified to function as the carrier amplifier, while the other balanced PA pair, along with the control amplifier, acts as a peaking amplifier. This suggests a configuration where one set of amplifiers handles the main signal, while the other set assists during higher power levels. The load combining network, illustrated in Fig. 17(b), consists of a branch-line coupler cascaded with multiple transmission lines. This network likely plays a crucial role in achieving proper power combining and impedance matching in different operating modes. The Peaking 1 and Peaking 2 power amplifiers are sequentially turned on as the input power increases. This strategy could be used to optimize the efficiency and linearity of the amplifier across different power levels. Unlike a conventional LMBA, the gate voltages of the three power amplifiers in the proposed design differ. This differentiation might be part of the optimization process to achieve the desired performance characteristics. The drain efficiency of the P-LMBA is plotted against the output power back-Off (PBO) in Fig. 18. This graph likely illustrates how the amplifier's efficiency varies as the output power is reduced from its maximum level. The main focus of the design appears to be enhancing the power back-off efficiency, which means maintaining relatively high efficiency even when the output power is reduced. This is a desirable feature for power amplifiers used in communication systems to conserve energy during periods of lower transmission power.

The proposed technique in [35] degenerates into the SLMBA [23], [25] when the coupling factor of the output coupler is set to 3-dB. When a 3-dB coupler is used as the output power combiner, the auxiliary amplifiers are in a balanced configuration, leading to perfect power cancellation at the isolated port. In this scenario, the main amplifier doesn't experience load modulation because the balanced setup eliminates any net power entering the main amplifier. When the coupling factor of the output coupler deviates from 3-dB, the power from the auxiliary amplifiers can't completely cancel each other at the isolated port. As a result, there's a residue power component that affects the loading condition of the main amplifier. Fig. 19 provides equivalent circuit representations of the proposed LMBA at output PBO and peak envelope power (PEP). When the coupling factor is not 3-dB, the residual power from the auxiliary amplifiers contributes to modulating the loading condition of the main amplifier. This modulation can impact the overall behavior and efficiency of the amplifier.

In [36] and [37], the concept of the OLMBA has been introduced. The OLMBA schematic is depicted in Fig. 20. The OLMBA configuration involves combining the functions

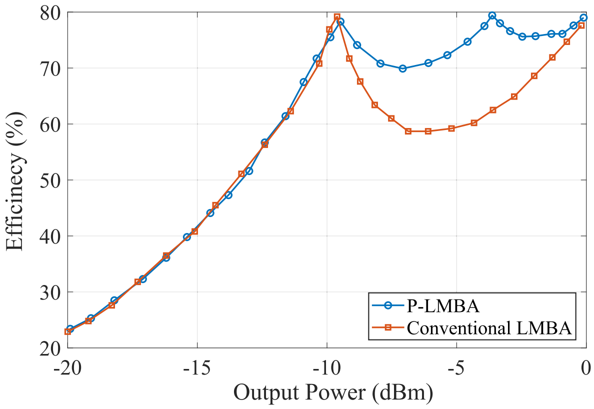


FIGURE 18. Drain efficiency proposed P-LMBA [34] and conventional LMBA.

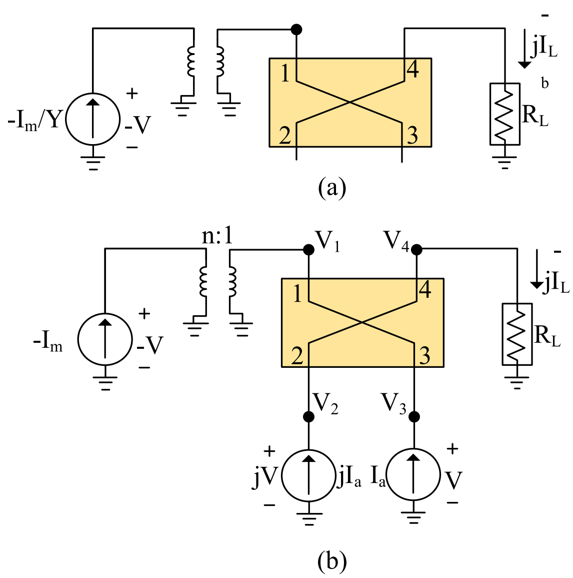


FIGURE 19. Equivalent circuit of the proposed LMBA at (a) OBO, and (b) PEP [35].

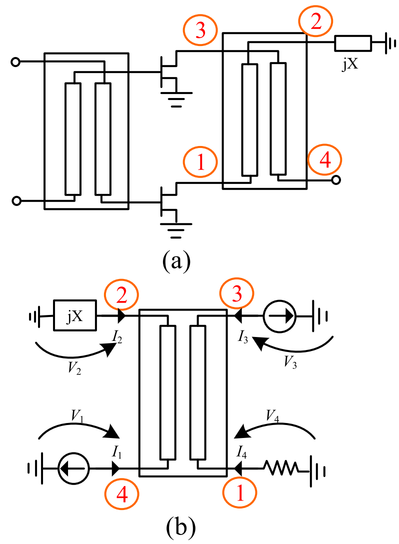


FIGURE 20. (a) OLMBA structure, (b) Output section [36].

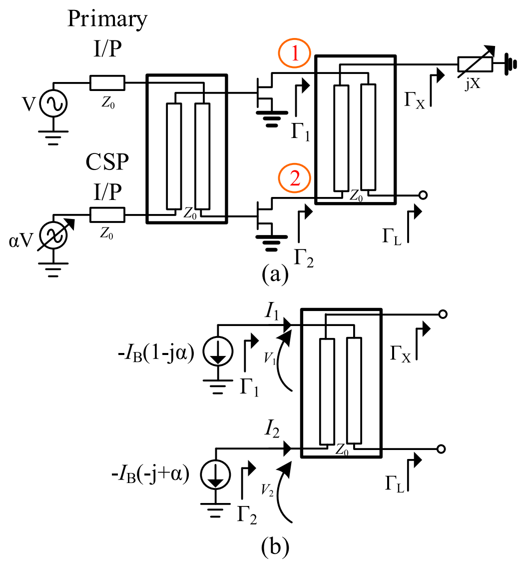


FIGURE 21. (a) OLMBA structure, (b) OLMBA schematic for analysis [37].

of the CSP buffer and the main PA into a single balanced amplifier setup. This is achieved by terminating the output coupler with a reactive element, allowing the CSP signal to be added to the main signal's amplification process. The CSP signal is injected into the OLMBA by feeding a lower-level CSP signal into the isolated port of the input coupler. This configuration ensures the CSP signal is added to the main signal's amplification process. One significant advantage of the OLMBA is that it requires much lower CSP power than traditional LMBA designs. This reduced CSP power requirement makes it easier to generate the necessary control signal efficiently. In the OLMBA configuration, the output port that receives the amplified CSP signal is terminated reactively. This arrangement causes the CSP signal to be reflected into the balanced stages of the amplifier. This reflective behavior effectively performs a load modulation function, contributing to the amplification process. The OLMBA configuration ensures that the CSP signal is always amplified with the same efficiency as the main signal power. Additionally, the CSP signal remains at a much lower level since it is scaled down from the signal input rather than from the output. A reflective tunable load is connected to the isolated output of the OLMBA. This load is adjustable and reflects a portion of the signal back into the circuit, allowing for further control and tuning of the amplifier's behavior.

IV. DOHERTY POWER AMPLIFIER

In this section, a brief review of DPAs and the comparison with LMBAs is presented. Traditional DPAs are inherently narrowband, and the incorporation of high-order load modulation becomes essential to enhance efficiency between two peaks. To achieve broadband performance, asymmetrical DPAs [39], and multi-way DPAs [40], involving multiple amplification paths, have been employed. Furthermore, for significant back-off efficiency enhancement, the QB-DPA [27], [28] is a viable option. The other techniques for bandwidth extension in DPAs include post-matching

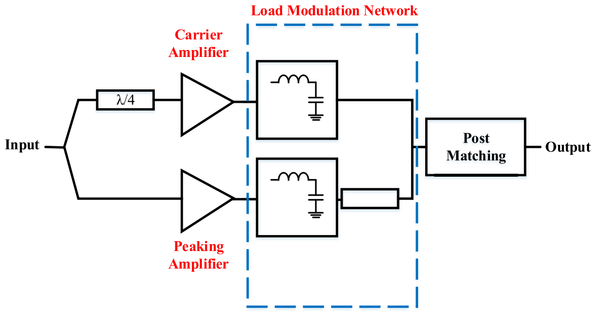


FIGURE 22. **The post-matching DPA proposed in [59].**

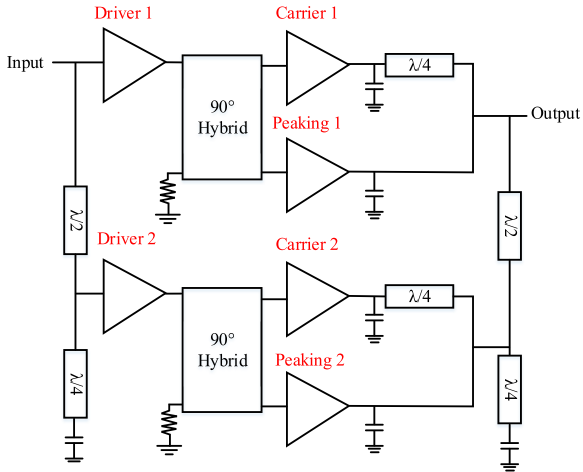


FIGURE 23. **The distributed two-way DPA architecture in [61].**

structures [41], [42], [43], continuous mode modulation [44], [45], [46], impedance compensation [47], [48], and complex combining loads [49]. These innovations collectively contribute to the ongoing evolution of power amplifiers, addressing the limitations of traditional DPAs and paving the way for improved efficiency and performance across diverse operating conditions. The recent advances in wideband asymmetrical DPAs, such as increased power-added efficiency and broader bandwidth, have started to overcome the challenges faced by traditional DPAs with limited OBO range and narrow bandwidth. In the conventional DPA, the two transistors exhibit variations in drain current profile, gain, and input impedance. To address these discrepancies, several analog techniques have been proposed, including uneven input power splitting, an asymmetric DPA architecture, and adaptive gate biasing [50]. A general approach is to treat the DPA as a dual-input amplifier, allowing independent control of the magnitude and phase of each input signal to achieve optimal operation. The bandwidth of the DPA can be extended by employing a frequency-dependent input signal distribution. Moreover, the efficiency and gain of the DPA can be enhanced through adaptive input signal splitting, where a majority of the input power is directed to the carrier transistor at back-off, while a larger portion is routed to the peaking transistor at peak power [51], [52]. The bandwidth of the DPA may face limitations due to the presence of parasitic capacitances in the transistors. Additionally, output parasitic components can modify the impedances presented to the intrinsic drain nodes of transistors, causing fluctuations in output power and efficiency across the bandwidth. Various techniques for compensating for these parasitic effects in the DPA have been introduced, as outlined in [53] and [54]. In [53], broad-spectrum reactive networks are sequentially connected with the output of the carrier and peaking amplifiers to counteract the impact of their output parasitic components. The compensation network is meticulously designed to ensure that the cascaded networks exhibit scattering parameters of $S_{11} = S_{22} = 0$ and $S_{21} = S_{12} = \pm 1$. However, achieving these conditions, particularly the phase response, across a wide bandwidth is a non-trivial task. A transformer-less load modulation architecture is introduced in [55], [56], and [57], eliminating the need for bandwidth-limiting transmission line impedance transformers or offset lines. The load modulation is achieved through broadband output matching networks, transforming two load impedances into optimal values at both peak power and back-off [55]. In [58], a "real frequency" technique is employed for the synthesis of matching networks. The DPA output network is characterized by three two-port networks. The scattering parameters are determined based on conditions that must be satisfied by the impedances at both saturation and back-off. In the DPA architecture introduced in [59], the impedance-matching networks of the carrier and peaking amplifiers are implemented using simple low-pass networks to enhance the bandwidth. Additionally, a broadband impedance matching network is employed at the DPA output to convert the load resistance into the optimal resistance for broadband operation (see Fig. 22). This approach differs from the conventional impedance matching network at the DPA output, which transforms the 50 Ω load resistance to a fixed resistance of $2R_{opt}$. The post-matching network ensures a suitable frequency-dependent impedance for the low-order impedance inverters. A distributed amplifier can provide broad bandwidth by absorbing the transistors' input and output parasitic capacitances into the transmission lines connected to the gate and drain, [60]. A broadband distributed DPA architecture was proposed in [61], in which two DPAs with their driver amplifiers are used in the single-ended dual-fed distributed structure without the need for a two-way power divider and combiner, shown in Fig. 23. This architecture inherits some features of the distributed amplifier including absorption of the peaking amplifiers' output capacitance into the output transmission line. However, the output parasitic capacitance of the carrier amplifiers and the impedance inverters still limit the bandwidth. In [62], the typical load impedance underwent an augmentation from $R_{opt}/2$ to an elevated value, such as $\sqrt{2}R_{opt}/2$. This alteration results in a diminished impedance transformation ratio of approximately 2.8 at a 6-dB back-off. Consequently, the bandwidth of drain efficiency expands when compared to the traditional DPA. An alternative strategy for designing a broadband DPA was introduced in [63], outlining a methodology in which the characteristic impedances of the two transmission lines are carefully selected to achieve impedance transformation while maintaining a maximally flat frequency response. A further modified DPA architecture, illustrated in Fig. 24, incorporates two $\lambda/4$ transmission lines in the peaking network. Notably, the output impedance transformation network is omitted, and the characteristic impedances of the transmission lines are configured to attain a broadband response. This particular design has undergone thorough investigation, leading to the derivation of various design criteria for its optimal operation, as detailed in [64], [65], and [66]. Complex load modulation networks, utilizing branch-line couplers, were put forth in [67] and [68]. Nevertheless, the reported bandwidths are observed to be inferior compared to those achieved through the implementation of a simpler two-section peaking network structure. In [69], a $\lambda/4$ shunt short-circuited stub was introduced at the output of the peaking amplifier to enhance the bandwidth of the load modulation network, as depicted in Fig. 25. The purpose of this stub is to alter the impedance presented to the impedance-inverting transmission line, thereby compensating for the impedance decrease experienced by the carrier amplifier.

Despite these advancements, there is an ongoing need for new load-modulation power amplifier designs that can optimize efficiency across an extended OBO and a wide frequency range. The emergence of LMBAs is noteworthy in this context, as they exhibit high efficiency over an extended OBO range while maintaining high linearity. For instance, within the context of a three-way DPA, a systematic design methodology to ensure linearity in the single RF-input three-stage PAs remains an unexplored challenge within the complex load-modulated circuitries. DPAs and LMPAs are both techniques employed in RF power amplifier design, but they differ in their architectures and operational principles. Here's a comparison between DPAs and LMBAs:

- Architecture: The Doherty architecture involves the combination of a main amplifier and a peaking amplifier. The main amplifier operates at a constant power level, while the peaking amplifier assists during high power demand, improving overall efficiency. LMBAs utilize load modulation to achieve power amplification. The impedance of the load is modulated to improve efficiency and linearity. This technique often involves dynamically adjusting the load impedance based on the input signal characteristics.
- Efficiency Improvement: DPAs are known for their high peak efficiency, especially in scenarios with varying power requirements. The architecture allows for improved efficiency at both high and low output power levels. LMBAs aim to enhance efficiency by dynamically adjusting the load impedance, and optimizing the power transfer under varying operating conditions.
- Operational Flexibility: DPAs are particularly effective in scenarios with varying power demands, making them suitable for applications where the input power levels can change dynamically. LMBAs provide flexibility by adapting the load impedance based on the input signal characteristics, contributing to improved efficiency across a range of operating conditions.
- Bandwidth Considerations: DPAs are generally designed to operate efficiently within a specific bandwidth. While some modifications can be made for broader bandwidth, the primary focus is often on optimizing efficiency within a narrower frequency range. LMBAs may offer a broader bandwidth because the load modulation technique can be adapted to different frequency ranges, allowing for versatility in various communication standards.
- Complexity and Implementation: Implementing a DPA can be relatively complex due to the need to combine the main and peaking amplifiers effectively. Proper tuning and matching are essential. Load modulation introduces its own set of challenges in terms of control circuitry and modulation mechanisms. However, the overall complexity may vary depending on the specific implementation.

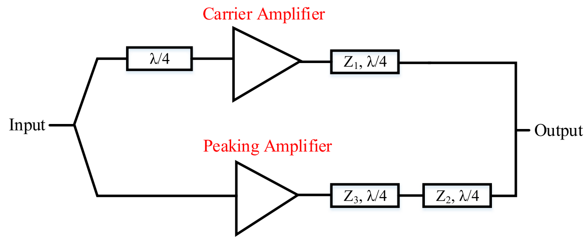


FIGURE 24. The Proposed DPA architecture in [64].

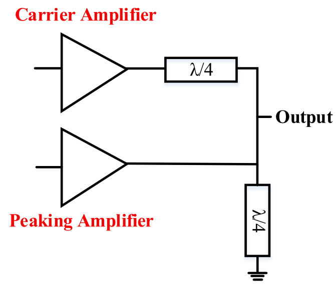


FIGURE 25. The DPA bandwidth extension using short-circuited stub in [69].

However, while both DPAs and LMBAs aim to enhance RF power amplifier performance, they do so through different architectural and operational approaches, each with its strengths and considerations. The choice between them depends on the specific requirements and constraints of the application.

V. CONCLUSION AND FUTURE WORKS

LMBAs represent a significant leap in RF circuit design, providing solutions to persistent challenges in power efficiency and output. Historically, conventional RF amplifiers struggled with achieving high efficiency and output power across diverse frequencies. While push-pull configurations improved matters, challenges like impedance matching persisted. The breakthrough came with load-pull analysis, allowing identification of optimal load impedance for maximum efficiency and power transfer. LMBAs build upon this by dynamically adjusting the load impedance, ensuring consistently high efficiency and power output across various operational conditions and frequencies. Their applications are extensive, spanning wireless communications, radar systems, and satellite communication. LMBAs' ability to maintain efficiency across a broad frequency spectrum aligns with the demands of modern communication systems. However, challenges remain, including nonlinear behavior and impedance matching issues, necessitating continuous research and development. Despite these challenges, LMBAs symbolize the progress in RF circuit design, overcoming historical efficiency and power output limitations. The historical journey of LMBAs is closely intertwined with advancements in semiconductor technology and the ongoing pursuit of more efficient RF amplification methods. As their impact continues to grow across various applications, ongoing research promises more refined and effective LMBA designs in the future.

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