Load Modulated Balanced Amplifier (LMBA): from First Invention to Recent Development

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1 Introduction

The RF power amplifier (PA) is a unit in wireless transmitters that strengthens the signal to combat losses in transmission by converting DC electric power to the added RF output power. Over the past decades, with the rapid development of wireless communications, high-efficiency PA design has become one of the most popular topics in both academic research and industrial development, since the PA consumes a high portion of the transmitter energy and thus its power efficiency directly impacts the system performance. In addition, because the PA is the main source of distortion generated by the transmitter, linearity is another concern in PA design, particularly in wideband systems [1].

Modulated signals with high peak to average power ratio (PAPR) are commonly used in modern wireless systems to improve spectral efficiency, creating a strong demand for PAs to have high efficiency performance not only at peak power but also at back-off power level. Many PA architectures, such as Doherty power amplifier (DPA) [2], envelope tracking [3] and outphasing [4], have been introduced. Among them, the DPA has become one of the most widely used PA architectures in cellular communication systems, particularly in high power base-stations. However, with further increase of bandwidth, DPA design becomes difficult [5].

Recently, a new PA architecture called "load modulated balanced amplifier (LMBA)" was proposed, where a control signal is injected to a balanced amplifier via a commonly terminated port of a coupler at output [6, 7]. The LMBA is able to modulate the impedance seen by the balanced amplifier via varying the amplitude and phase of the external control signal. By using a wideband coupler as the load modulation network, the LMBA can potentially achieve high efficiency at different power back-off across a very wide bandwidth.

In this paper, we intend to review the recent development of LMBA to provide an in-depth look at how this PA architecture has evolved from the first invention to recent advancements. The LMBA system architecture and its operation principle are introduced first, followed by discussion of back-off efficiency enhancement techniques. Various configurations and recent developments of LMBA are then analyzed, including the RF-input structure, the inverted sequential operation and the most recent extension of orthogonal LMBA. A conclusion is given in the end.

2 The First Invention of LMBA

A coupler-based load modulated amplifier architecture, shown in Figure 1, was first disclosed in a patent filed by Paul W. Dent in 2003 [6]. In this architecture, the primary drive signal is equally split between the first and second primary amplifiers via a quadrature splitter first. The outputs of the primary amplifiers are then connected to Port 1 and Port 2 of a quadrature coupler, respectively. An additional auxiliary drive signal, amplified by an auxiliary amplifier, is injected to the auxiliary port of the coupler, Port 3. The load is connected to the output port of the coupler, Port 4. Due to the property of the quadrature splitter, there is a 90^o phase difference between the signal input to the first and second primary amplifiers. The coupler behaves in exactly the same manner as the splitter, which also introduces 90^o phase difference between the input signals. Therefore, the signals from the two primary amplifiers arrive at the load with the same phase and add constructively, while the signals arrive at the auxiliary port with 180^o out of phase and thus add destructively.

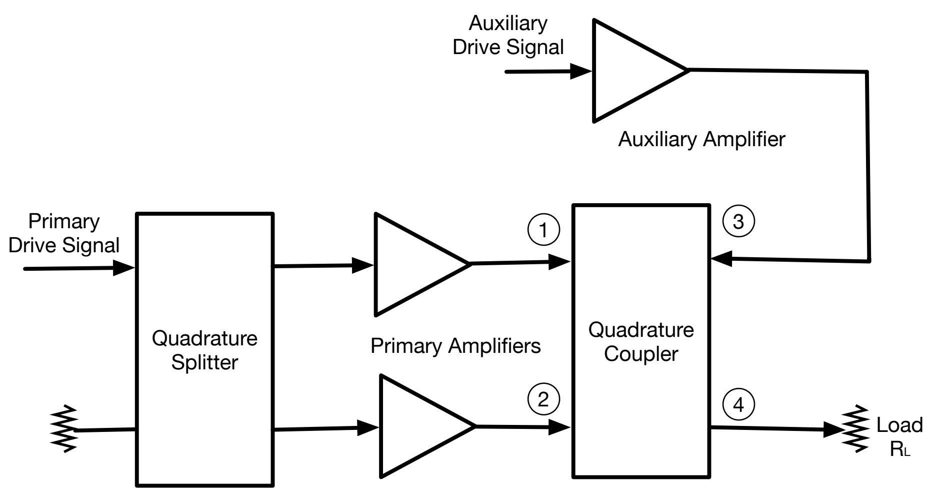

Figure 1: The block diagram of LMBA [6].

The amplifier can be operated as follows. The auxiliary amplifier is disabled while the primary amplifiers operate below the saturation point. As the primary amplifiers approach saturation, the auxiliary amplifiers is enabled and generates an reflection signal that is equally split and travels backwards into the output ports of the first and second primary amplifiers. If the auxiliary drive signal is -180^o out of phase with the original primary drive signal, the phase of these reflection signals at Port 1 and 2 will be both 180^o offset from the phase of the output signals generated by the respective primary amplifiers. As a result, the injected reflection signals appear to the primary amplifiers as a load impedance mismatch and thus can effectively reduce the load impedance of the primary amplifiers. The primary amplifiers can therefore increase their output current and deliver more power to the load. This architecture is an effective load modulation scheme for RF power amplifiers, similar to DPA. Unfortunately, this invention did not catch much attention at the time and was abandoned later. Until 2016, the first prototype, shown in Figure 2, was implemented by the group in Cardiff University [7]. In this implementation, a balanced amplifier is used as the primary amplifier and the injected signal is called Control Signal Power (CSP) that is amplified by a CSP PA. This architecture has since been formally named as LMBA.

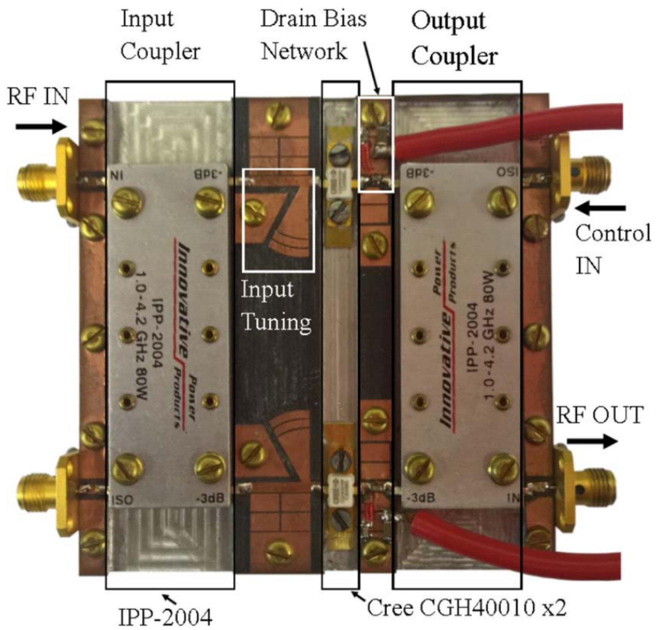

Figure 2: The first LMBA prototype [7].

The basic operation of the circuit can be analyzed by using an ideal 3 dB hybrid coupler connected with current sources, as shown in Figure 3, where the two balanced devices are represented as current sources, having equal magnitude but a 90 degree phase offset between them, i.e., $I_1 = I_\mathrm{B}$, and $I_2 = -jI_\mathrm{B}$, while the CSP signal at port 3 can also be represented by a current source, $I_3 = I_\mathrm{C}$. The output at port 4 is terminated with Z_0.

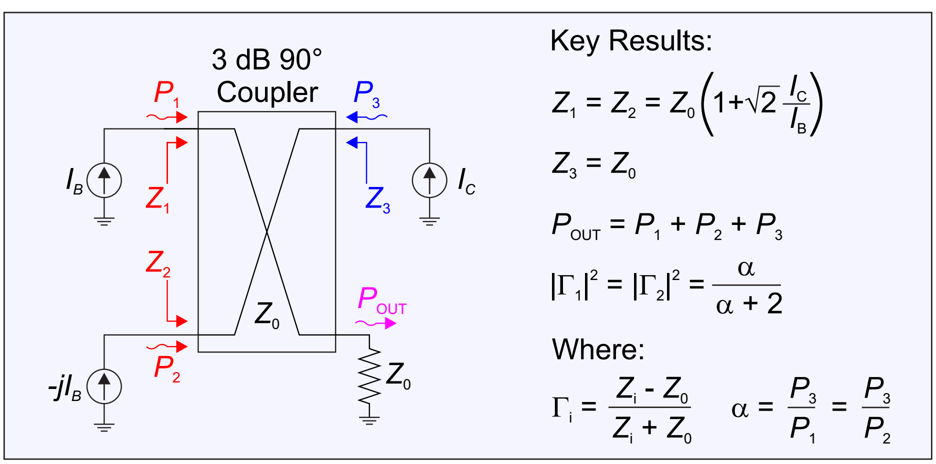

Figure 3: Simplified model of LMBA output section for theoretical analysis.

Assuming the port impedance of the coupler is Z_0, we can find that the driving impedances seen by the balanced device outputs, Z_1 and Z_2, are the same, and can be expressed as,

$$Z_1 = Z_2 = Z_0 \left(1 + \sqrt{2}\frac{I_\mathrm{C}}{I_\mathrm{B}}\right). \tag{1}$$

Furthermore, the output impedance of the CSP PA is Z_0, namely,

$$Z_3 = Z_0. \tag{2}$$

Equation (1) reveals that the impedance presented at port 1 and port 2 changes with the injected current at port 3, which means the load of the balanced amplifier can be "modulated" by adjusting the control signal. This property provides us a completely new approach to implementing "load modulation" for an RF PA, where the efficiency enhancement can be achieved by dynamically adjusting the external control signal instead of using the conventional passive networks. This removes the inherent bandwidth limitation of the usual load modulated PAs, such as DPAs, where a bandwidth-limiting network based on an impedance inverter is required. This operation makes the LMBA a very powerful and flexible load modulation technique since its bandwidth can be achieved approximately as that of the quadrature coupler, that is normally much wider than the bandwidth of a DPA combiner.

Another feature of the LMBA is that, if the coupler is lossless, the power injected at the CSP port can be fully recovered at the final output, i.e.,

$$P_\mathrm{OUT} = P_1 + P_2 + P_3, \tag{3}$$

and the CSP always positively contributes to the total output power, independent of the load modulation it is imposing [7].

The load modulation can also be expressed in terms of the reflection coefficient at the balanced ports, Γ_1 and Γ_2. If α is the ratio of the power injected at the CSP port to the power generated by a single balanced device,

$$\alpha = \frac{P_3}{P_1} = \frac{P_3}{P_2}, \tag{4}$$

the reflection coefficients can be expressed as,

$$|\Gamma_1|^2 = |\Gamma_2|^2 = \frac{\alpha}{\alpha + 2}, \tag{5}$$

where we can see that Γ lies on a circular contour for a given α. This indicates that a range of impedances can be modulated from the standard Z_0 by controlling the power ratio α.

Figure 4 shows how the LMBA active load modulation can be used for broadband matching. Frequency by frequency, the relative magnitude and phase of the CSP signal (referred to that of the principal input) can be

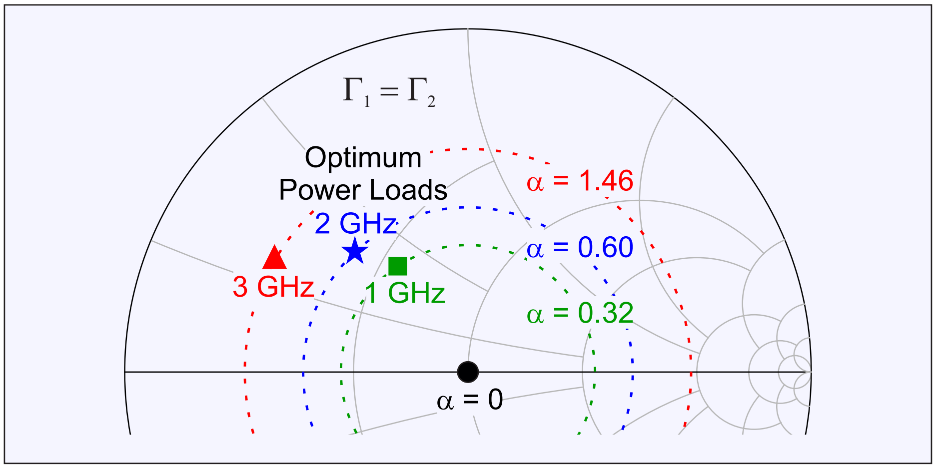

Figure 4: Example of using the LMBA load modulation for broadband matching without pre-matching.

adjusted so that the load seen by the balanced devices corresponds to the desired optimum termination. This is, in practice, a way of achieving a non-Foster response of the matching thanks to active load modulation.

In the first prototype, shown in Figure 2, the LMBA concept was pushed at its extreme: the packaged high frequency transistors were used directly in the balanced pair without any passive output matching, see the schematic shown in Figure 5. In this configuration, the PA relies completely on the "LMBA action" to achieve matching over the broad frequency band of 0.8–2 GHz. The same broadband matching capability of the LMBA was also shown in [8] for the 4–8 GHz band, by using a similar topology but this time die transistors and substrate-integrated quadrature couplers.

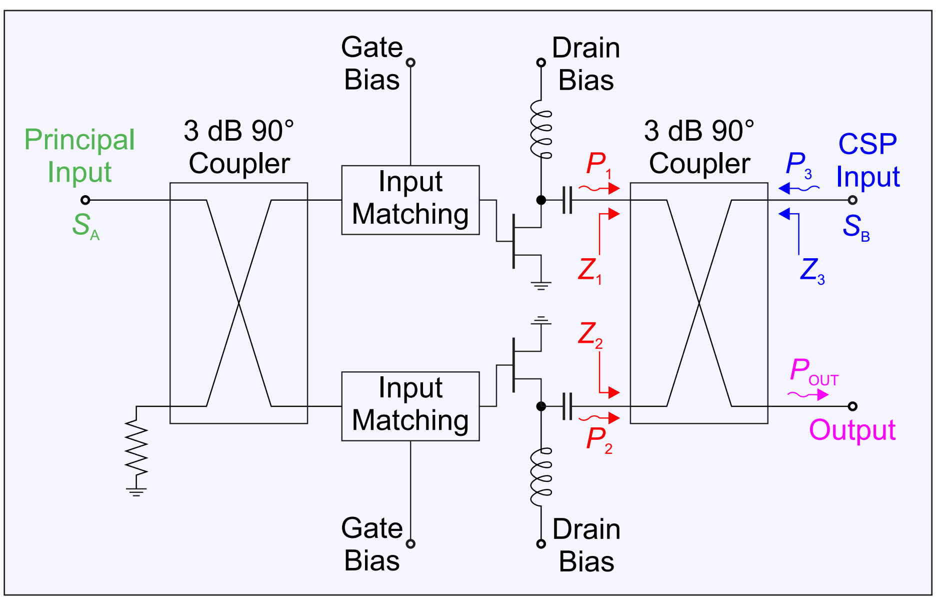

Figure 5: Schematic diagram of the first LMBA prototype, from [7].

The characterization of the first LMBA prototype relied on two separate RF sources with tunable relative amplitude and phase. However, it is very difficult to predict the precise amplitude and phase setting needed at the

RF generators to synthesize the desired loads within the LMBA. Therefore, nested sweeps of amplitude and phase settings of the signals have been used, leading to a vast dataset of results which are normally represented, frequency by frequency, by plotting the PAE vs. output power trajectory when the relative phase is varied, for different power levels. An example of these "loops" is shown in Figure 6 and such plot can be used to determine the best CSP setting for maximum power or maximum PAE. They also reveal, at some frequencies, the ability of the LMBA to maintain high efficiency over a range of output power levels.

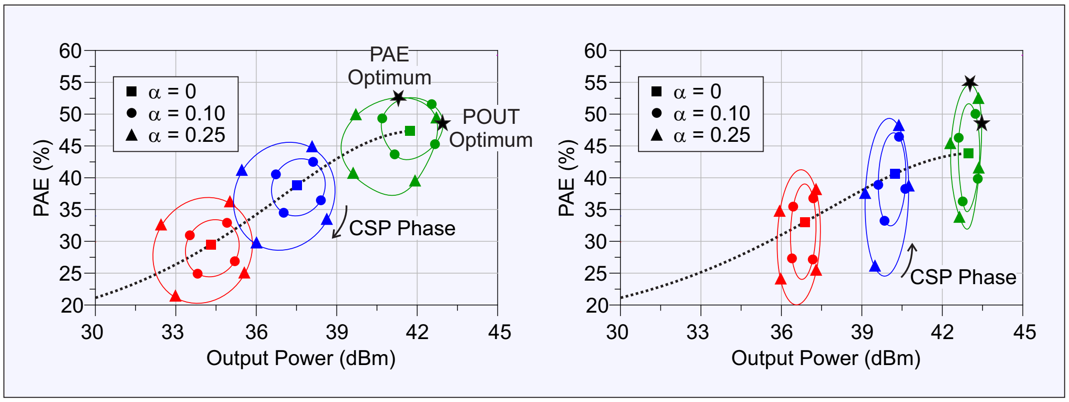

Figure 6: Examples of measured PAE vs. output power in LMBA. Dotted black line: without CSP. Colored loops: fixed principal input power, swept CSP amplitude (α) and phase.

3 LMBA for Back-Off Efficiency Enhancement

The ability of the LMBA to maintain high efficiency over an output power back-off (OBO) range is clearly interesting for applications where efficiency at reduced output power is required, such as telecom PAs where the average output power is backed-off to avoid excessive distortion due to signal peaks compression. However, the topology used for [7] could only provide a limited OBO range and the OBO efficiency enhancement was not achieved at all frequencies.

A new topology dedicated to improve the OBO efficiency was proposed in [9], with a few key additions to the first LMBA prototypes, as shown in Figure 7 (hardware picture in Figure 8). The most important difference is given by the OBO Pre-matching networks, which need to transform the coupler impedance into the optimum device terminations for OBO operation. This puts the LMBA in the condition to operate optimally at OBO without the need of any CSP signal. Similarly to what happens in a DPA, at the OBO break-point an Aux. signal starts being injected, in this case the CSP signal, leading to load modulation and positive output power contribution. By properly controlling the phase and magnitude of the CSP signal the load modulation can be imposed so that the Main amplifier (the balanced pair) is maintained efficient while its output power increases up to saturation. The matching strategy for the Main amplifier is illustrated in Figure 9.

To achieve the automatic turn-on of the CSP at a given power level, a CSP amplifier in Class C is introduced in this LMBA version, helping reducing the power need at the CSP port. The CSP amplifier can be matched for

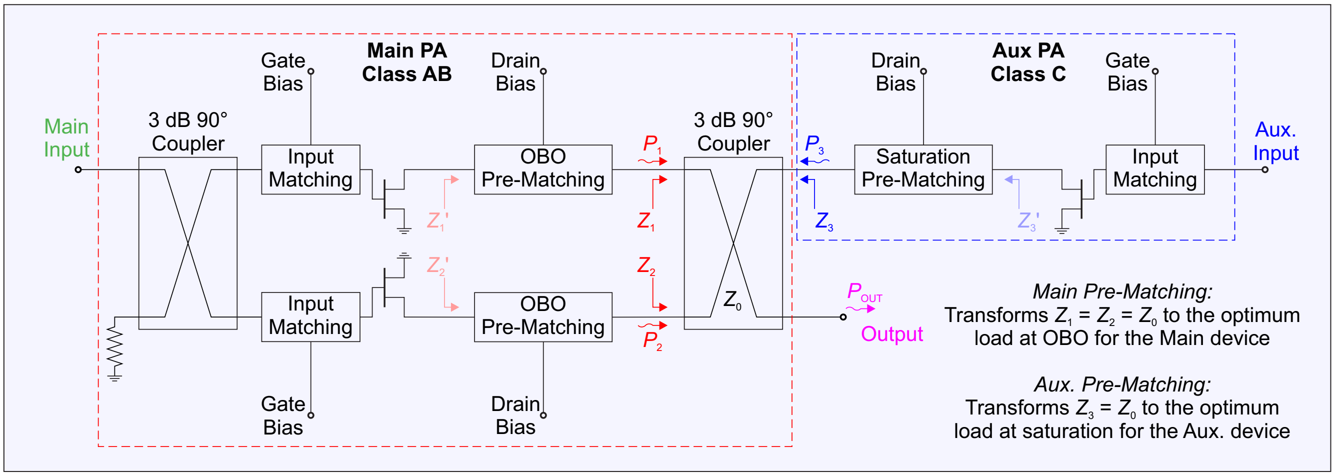

Figure 7: Schematic diagram of the LMBA for OBO efficiency enhancement, from [9].

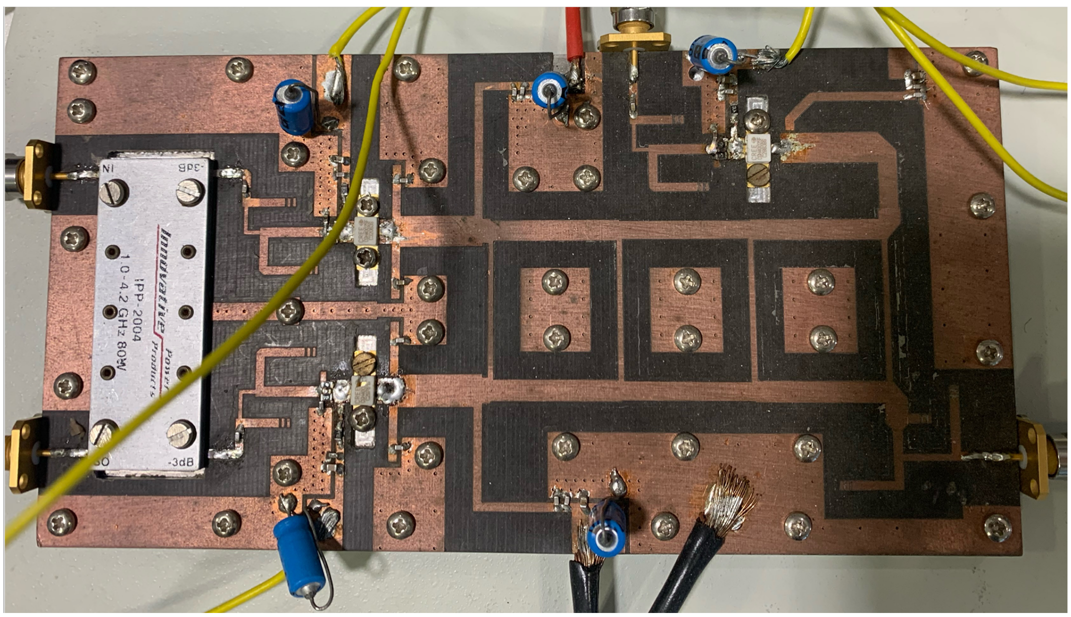

Figure 8: Picture of the LMBA for OBO efficiency enhancement, from [9].

optimum load at saturation.

The key advantage of this LMBA compared to the Doherty PAs is that the combination of the Main and Aux. stages is through the quadrature coupler rather than through a node, helping the isolation of the stages and therefore simplifying the design for broadband operation. In particular, there is no need to control the phase delay of the pre-matching networks by means of offset lines or other techniques, since the load modulation on the Main devices can be adjusted by tuning the CSP *input* phase, while the output impedance of the CSP Aux. PA before the break-point does not affect the operation of the Main PA being the CSP connected at the isolated port of the quadrature coupler.

The load modulation can be adjusted to leading to the same theoretical efficiency curve of a Doherty PA (see Figure 10). It is important to notice that the ideal LMBA does not have a linear gain if the efficiency is optimized

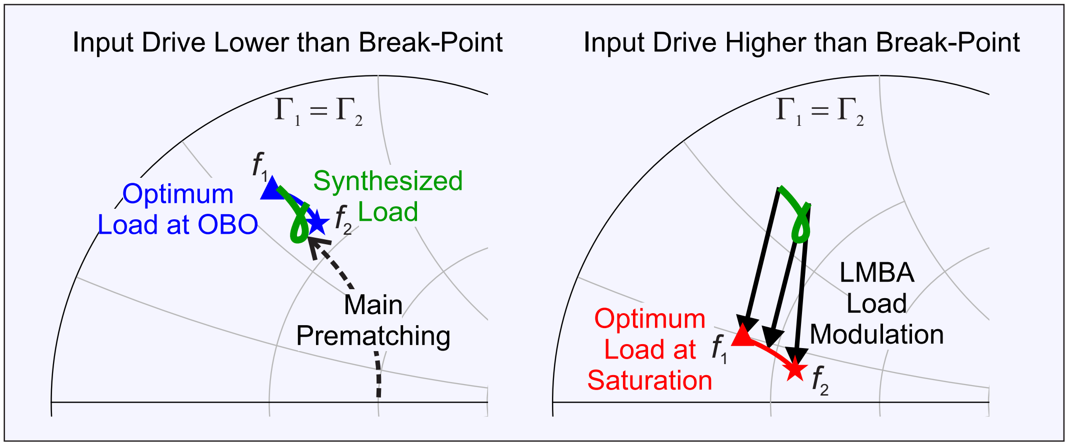

Figure 9: Design procedure for OBO efficiency enhancement LMBA.

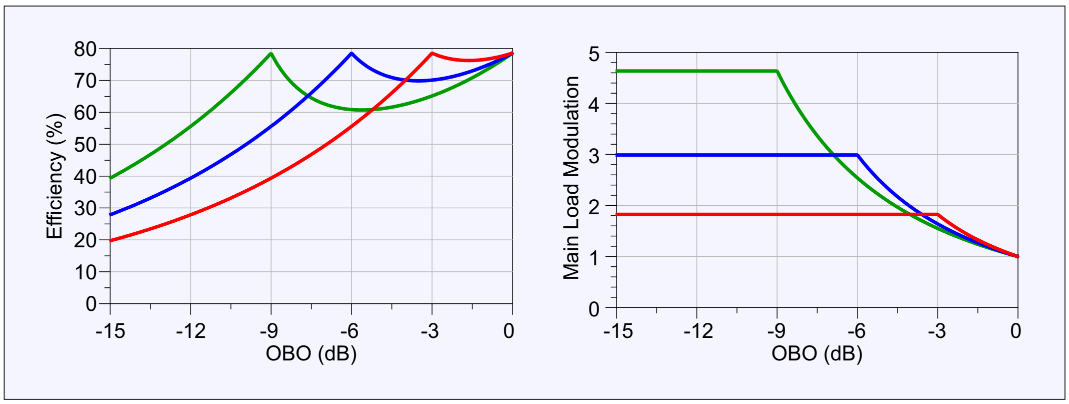

Figure 10: Theoretical efficiency (left) and Main intrinsic load modulation (right, normalized to saturated value) vs. OBO for LMBA in OBO efficiency enhancement configuration.

but a compressing response, while the ideal Doherty does have a linear response. This is due to the smaller power contribution needed from the Aux. PA to achieve the same load modulation than in a DPA, which is not sufficient to linearize the Main PA response. The practical implementation shown in [9,10] shows that in reality the LMBA is reasonably linear and easy to linearize with digital predistortion to meet linearity targets of typical telecom standards. On the other hand, the compressing behavior also means that the OBO break-point is always at reduced range compared to the input power back-off (IBO) breakpoint, meaning that extending the OBO break-point beyond 6-7 dB is very difficult with practical devices since the load modulation ratio between small signal and saturation tends to become very high.

4 RF-Input LMBA

In the originally reported LMBA, the control signal is shown as an externally derived source. Clearly, since the control signal has to be frequency and phase matched to the main signal, it has to be derived, directly or indirectly, from the main signal. The simplest way of achieving this is to split the input signal and apply suitable amplitude and phase controls to the coupled output in order to feed it to the output coupler as the control signal, as shown in Figure 11.

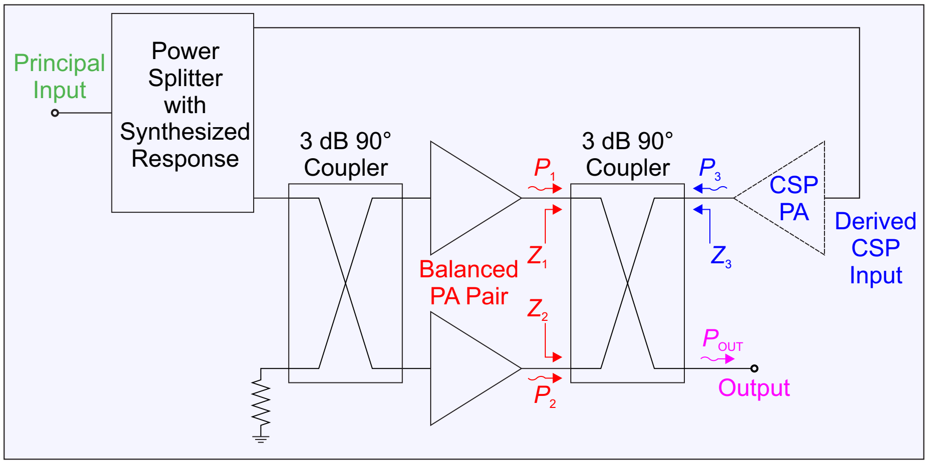

Figure 11: Schematic diagram of the RF-Input LMBA.

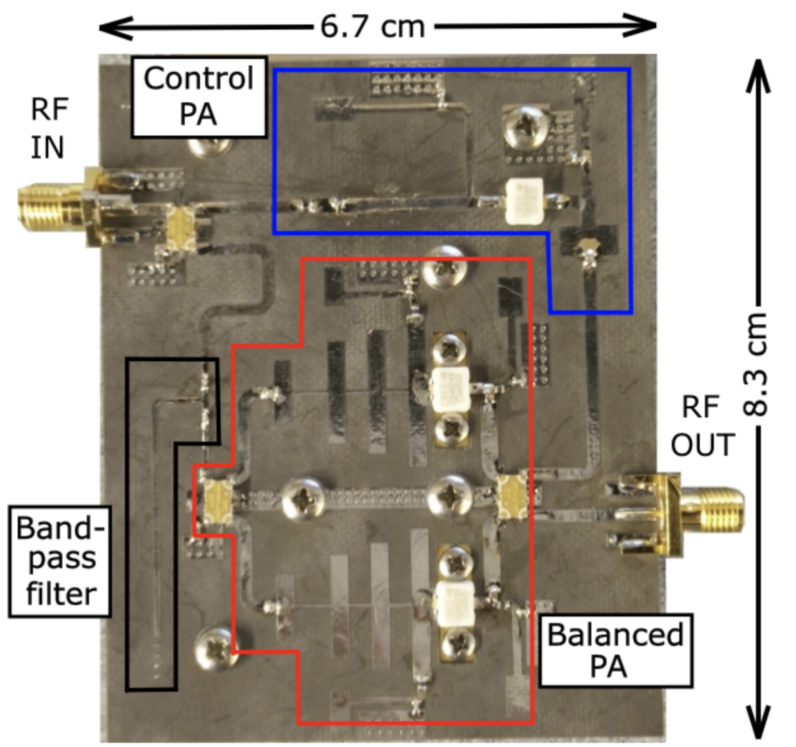

Figure 12: RF-Input LMBA Prototype [11].

This form of LMBA has been first demonstrated in [12] and then used again in [11, 13–15]. The PCB board of the RF-Input LMBA Prototype is shown in Figure 12. Ideally the amplitude and phase controls in the CSP loop would be adjusted on-the-fly to optimize power and efficiency under modulated signal conditions; in practice some compromise has to be made and [11] shows a specific approach whereby improved performance over an octave bandwidth can be achieved by suitable synthesis of a phasing network in the control signal loop. A standard splitter with proper phase delay can also be used for simplicity, at the cost of reduced performance compared to an optimized single-input or a dual-input solution [16]. Such an approach is clearly appropriate for applications in current and retro system insertions, where a PA with single RF input is standard. Future systems are expected to allow, and utilize the benefits offered by multiple input RFPAs, and an LMBA with full gain and phase controlled CSP input will offer important system design advantages.

5 Various Recent Variations

Recently, the research on LMBA continues to receive extensive attention. A variety of modified circuit architectures, load modulation configurations and continuous-mode operations have been introduced in LMBA designs to further improve the performance. Several integrated LMBA solutions based on different processes have also been developed to expand the application scenarios of this new architecture.

Different from the original LMBA configuration, an inverted architecture was proposed [17, 18], as shown in Figure 13, where the CSP amplifier is used as the main amplifier while the balanced pair is used as the Aux. amplifier. At low power, namely, when the output power is lower than the OBO level, the main PA is on while the balanced amplifier is off and the output power of the PA system is provided only by the CSP PA. When the output power is higher than the OBO level, the balanced amplifiers are turned on and the CSP PA is to be saturated. When the output power is further increased, additional power increase is mainly provided by the balanced pair due to the saturation status of the CSP PA. Similar to the original LMBA, this inverted architecture can be driven by single RF-input signals [17, 18] or by dual-input [19].

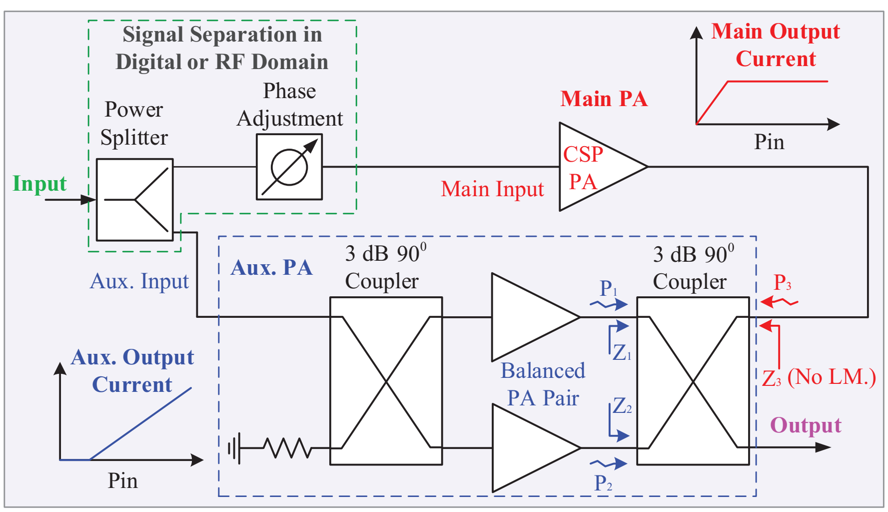

Figure 13: Schematic diagram of inverted LMBA with sequential operation.

The most important feature of this inverted architecture is that, there is no load modulation effect at the main CSP PA output, which means the CSP output power will not increase with the input power after reaching the output back-off power level. Theoretically, the additional power increase of the LMBA is entirely provided by the balanced

PA pair due to the saturation status of the main PA. This leads that the operation of the inverted LMBA is close to that of the sequential power amplifier (SPA) [20] and thus it was named as Sequential LMBA (SLMBA) in [17]. Thanks to the sequential operation and over-driven carrier PA, SLMBA can achieve high efficiency performance at deep back-off. For instance, a drain efficiency of 49% was achieved at 12 dB back-off by the prototype presented in [17] at 3.3 GHz. At the same time, ultra-wideband performance can also be easier to achieve because of the removal of carrier load modulation effect. Similar sequential operation was shown in [18] for 1.5-2.7 GHz band, with drain efficiency of 47%-58% at 10 dB back-off.

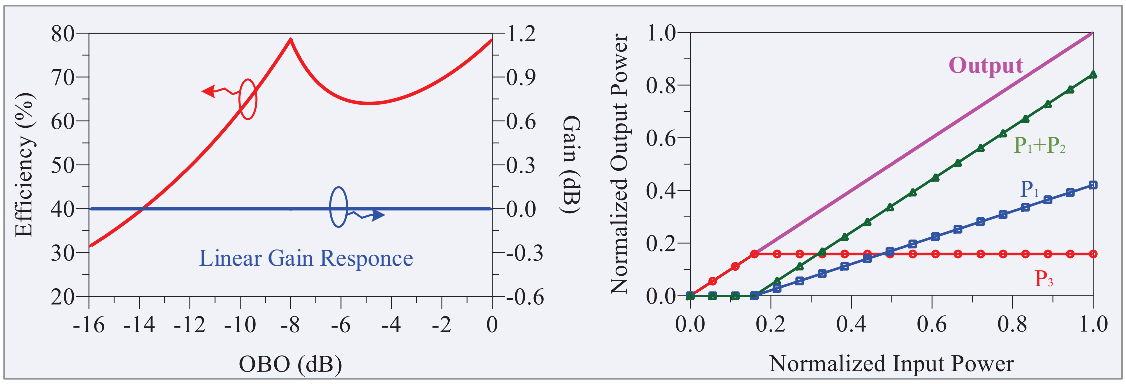

Figure 14: Theoretical efficiency/gain vs. OBO (left) and normalized output power vs. input power (right) for SLMBA with linear operation.

It is interesting to notice that, different from the original LMBA, circuit solutions with linear gain response can be obtained by the SLMBA architecture, when considering the linear piecewise current model in theoretical analysis. Figure 14 presents an example of the theoretical efficiency/gain vs. OBO and normalized output power vs. input power for SLMBA with linear operation. This is why the linearity of SLMBAs shown in [17–19] is not worse than that of Doherty PAs.

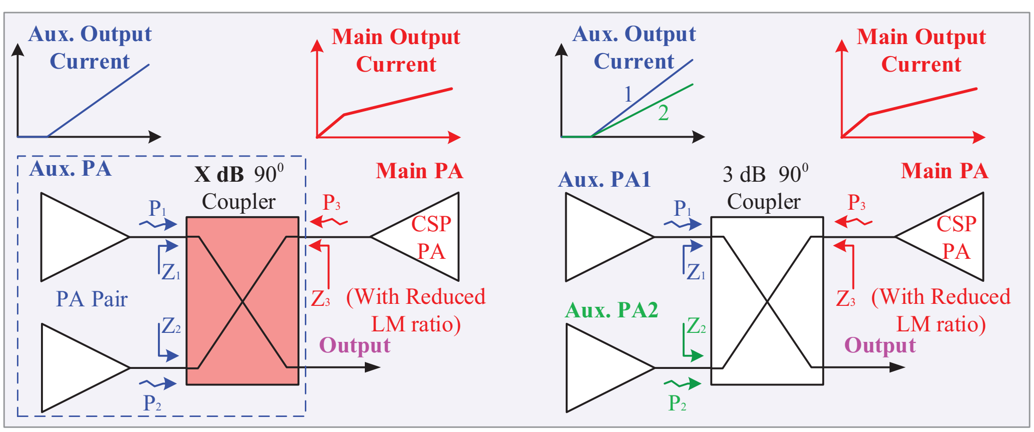

Figure 15: Schematic diagram of modified inverted LMBA with asymmetrical coupler (left) and asymmetrical Aux. PAs (right).

The employment of sequential operation in LMBA brought several advantages, however, the over-driven CSP

PA in RF-input SLMBA architecture inevitably reduce the reliability for long-term operation, which might hinder the popularization of SLMBAs in the actual communication systems. In the light of this, two different asymmetrical architectures were proposed to mitigate this impact while maintaining wideband performance as shown in Figure 15. By introducing asymmetrical couplers [21] or asymmetrical Aux. currents behavior [22], different LM ratio can be established for the CSP PA, which means the main output current can still continue to increase when the Aux. PAs turn on. Usually, it seems that the LM ratio should be set to a lower value than the Doherty PA to support wideband operation. With different asymmetrical configuration at different operation frequencies, the LMBA in [22] achieves dual-octave bandwidth.

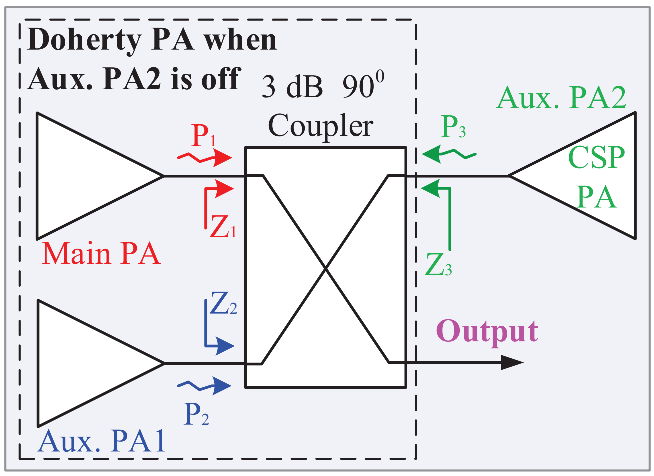

Figure 16: Schematic diagram of hybrid Doherty-LMBA architecture.

Another attempt to change the load modulation behavior of LMBAs is by combining the Doherty and LMBA operation, since the 3 dB quadrature coupler can also be used as the output combiner for Doherty operation. Figure 16 shows the schematic diagram of the hybrid Doherty-LMBA architecture introduced in [23–25]. In this configuration, the main PA and Aux. PA1 form as a Doherty PA when the CSP PA is off, while the entire PA systems become an LMBA when the CSP PA is on. This hybrid operation provides extended high efficiency range.

As the most popular wideband PA design technique, the concept of continuous-mode (CM) operation is also applied to various types of LMBA and its variants for design space expansion and performance enhancement recently [26–28]. In [26], continuous Class-B/J mode has been introduced in the balanced PA pair of RF-input LMBA, matching networks for CM PAs have been proven to be effective in LMBA designs. Continuous inverse Class-F mode has been employed in the CSP PA of RF-input SLMBA in [27] to further improve the back-off efficiency, and it has been proven that the impedance at the balanced PA ports will automatically match the continuous Class-B/J mode in this configuration. Similarly, different CM-mode impedance conditions have been used for ultra-wideband operation in the asymmetrical LMBA in [28]. In [29], the impact of the load trajectory on the AM-PM distortion of LMBA is studied. It is shown that by properly terminating the second harmonic, very high efficiency can be obtained while keeping a nearly flat AM-PM, which allows an improved efficiency and linearity trade-off.

The integration of LMBAs faces some difficulties especially in relatively low frequency applications, mainly because of the employment of couplers. In [30], the original dual-input LMBA architecture was realized in Gallium Nitride (GaN) process for X-band application by using Lange couplers. At mm-wave bands, several RF-input LMBAs were successfully built in CMOS process by using coupled metal lines based couplers [31,32]. In particular, the differential coupler presented in [31] is helpful to popularize the LMBA architecture in CMOS process with widely used differential structure. The die micrograph of the LMBA is shown in Figure 17. A lumped coupler was also employed for sub-6 GHz LMBA integration with Gallium Arsenide (GaAs) process in [33].

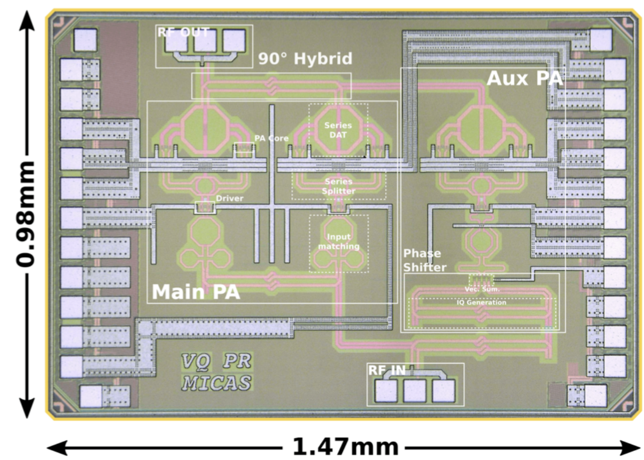

Figure 17: Die micrograph of a LMBA in 28-nm CMOS [31].

6 Further Extension

The most recent introduction among the variations of the LMBA is the Orthogonal LMBA (OLMBA) [34], whose circuit diagram and picture are shown in Figure 18 and 19, respectively. The CSP signal is injected at the isolated

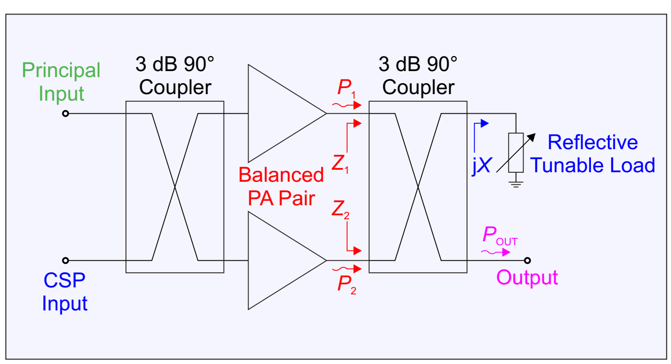

Figure 18: Circuit diagram of the Orthogonal LMBA (OLMBA).

port of the *input* coupler rather than the output, creating an orthogonal amplification path that delivers power

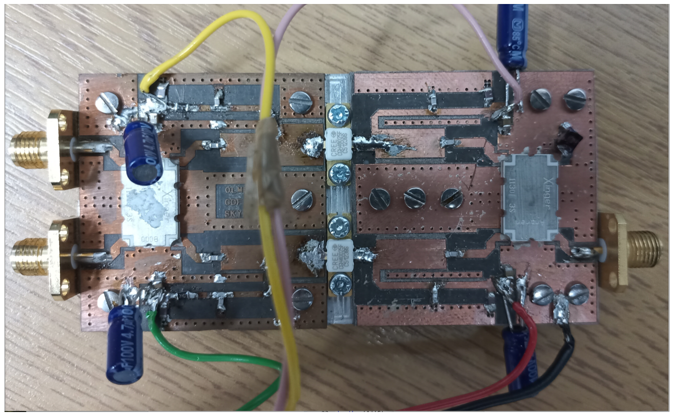

Figure 19: Picture of the first OLMBA prototype [34].

to the output isolated port. By terminating the latter with a reflective load, the signal is reflected back into the balanced pair modulating the load impedance and then transferred to the output. The main advantage of the OLMBA compared to the LMBA is that the CSP signal is amplified by the balanced pair itself, therefore it is amplified with the same efficiency of the principal signal and does not require an extra CSP amplifier. The load modulation is controlled by varying both the CSP signal relative phase and amplitude, as well as the value of the reflective load jX. The modulation obtained is not identical between the two balanced devices, neither it is as powerful and flexible as in the LMBA, however, it is still useful to improve the PA performance. The first paper showing the OLMBA [34] demonstrated the broadband tuning ability of the concept, also showing that the bandwidth of the OLMBA can exceed significantly that of the coupler in the low frequency end, meaning that a compact coupler can be used for low frequency operation. Even more important, the OLMBA has been used to improve the PA performance in presence of load mismatch, resulting better than that of an analogous balanced amplifier [35]. Together with the double-balanced LMBA structure shown in [36], it shows that the potential of the LMBA variants to tackle an important issue as that of design in presence of antenna mismatch is huge and still little explored, especially in the field of linear amplification.

7 Conclusion

It is clear from this article that the LMBA represents a new class of RF PA design, which combines some of the individual advantages of classical load modulation techniques to enable the RF PA to have high efficiency over a wide bandwidth. This opens up various applications in cellular telecom systems as well as space and military, where high power efficiency, especially at power back-off, cross a wide signal bandwidth, is desirable. The existing development demonstrated that the back-off efficiency of the PA can be significantly improved by using the electronically controlled amplifier reconfigurations rather than the bandwidth limiting passive networks that are commonly used for back-off efficiency enhancement in the conventional load modulation techniques. The applications under current development also illustrated that the LMBA architecture is beneficial to mitigation of output load variation. With further development, we expect the LMBA will play a crucial role in future broadband wireless systems.

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