Wideband Active Load-Modulated Amplification Using A Non-reciprocal Combiner: A Novel RF-input Circulator Load Modulated Power Amplifier Architecture

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Abstract

An RF-input highly efficient wideband power amplifier (PA) architecture based on a non-reciprocal combiner is proposed in this paper. The novel PA architecture consists of two amplifier branches and a microwave circulator acting as the output combiner, which is named circulator load-modulated amplifier (CLMA). Theoretical analysis and the design of an RF-input CLMA are presented. The analysis reveals that CLMA performs active load modulation to maintain high PA efficiency performance over a large output power dynamic range. As proof of concept, we designed a CLMA demonstrator circuit based on gallium nitride (GaN) transistors and a surface-mount circulator. The prototype circuit exhibits a drain efficiency of 62-73% at peak output power and 54-58\% at 7.5 dB output power back-off level, across 3.1 GHz– 3.7 GHz. To the best of our knowledge, this paper demonstrates the first CLMA architecture with single RF input and a surface-mount circulator combiner.

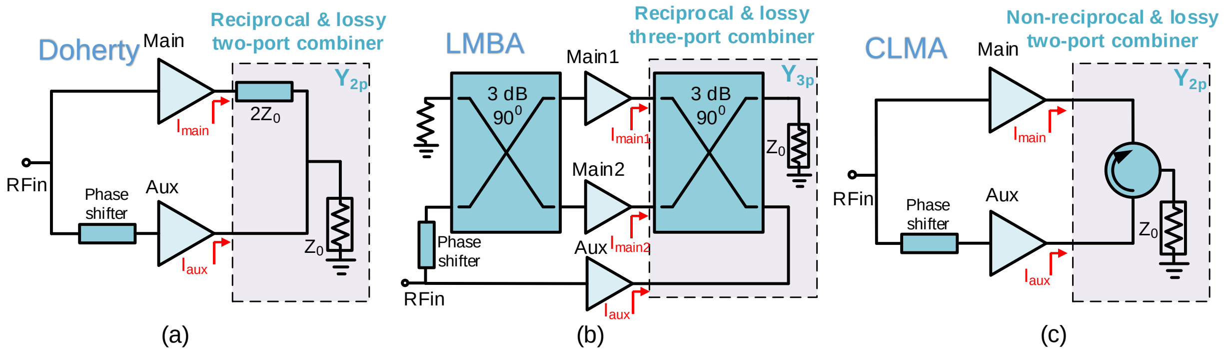

Figure 1. Active load modulated power amplifier architectures. (a) The Doherty PA, (b) the load-modulated balanced amplifier (LMBA), and (c) the circulator load-modulated amplifier (CLMA).

1. Introduction

The increasing demand for data throughput has resulted in a continuous evolution of modern communication systems to adopt more spectrally efficient modulation schemes. This inevitably results in modulated signals with a large peak-to-average power ratio (PAPR). Meanwhile, the energy efficiency of the system is extremely critical because its power consumption corresponds to a large part of the overall mobile network operational cost and environmental impact.

Consequently, active load-modulated power amplifier (PA) architectures have been proposed to improve the PA efficiency at a significantly backed-off output power. During decades of research on active load-modulated PAs, several PA architectures have been proposed and extensively analyzed. Among them, the Doherty PA is the most widely used architecture in cellular base stations due to its relatively low complexity and moderate linearity performance. However, the Doherty PA has inherent bandwidth limitations, primarily imposed by its quarter-wavelength impedance inverter. Moreover, the bandwidth limitation is also constrained by the need for precise phase delay alignment between its two amplifier branches for proper load modulation and power utilization. To resolve these fundamental problems, the load-modulated balanced amplifier (LMBA), was proposed in 2016 [1]. The LMBA comprises a balanced amplifier and a third auxiliary amplifier to inject signals to the isolated port of the output quadrature hybrid. More recently, we proposed a novel active load modulation PA architecture based on a circulator output combiner, which is referred to as the circulator load modulated amplifier (CLMA) [2]. Essentially, like the LMBA, the working principle of the CLMA architecture can be categorized as the Doherty-like linear operation [2] or sequential-type operation [3]. However, the existing CLMA prototype circuits are based on dual-input topology and a bulky microwave circulator. In this work, we propose the first RF-input Doherty-like CLMA architecture with a surface-mount circulator.

2. Theory

In its most simplified form, the CLMA architecture comprises a class-B biased main amplifier, an auxiliary amplifier biased in class-C mode, and a circulator-based output combiner network as presented in Figure 1(c). By solving the three-port admittance parameter matrix of the ideal circulator, we can obtain the expressions for the impedance seen by the CLMA main and auxiliary amplifier's output, denoted as Z_m and Z_a, as follows

$$Z_m = Z_0\left(1 - 2\frac{I_a e^{j\theta}}{I_m}\right)$$
$$Z_a = Z_0 \tag{1}$$

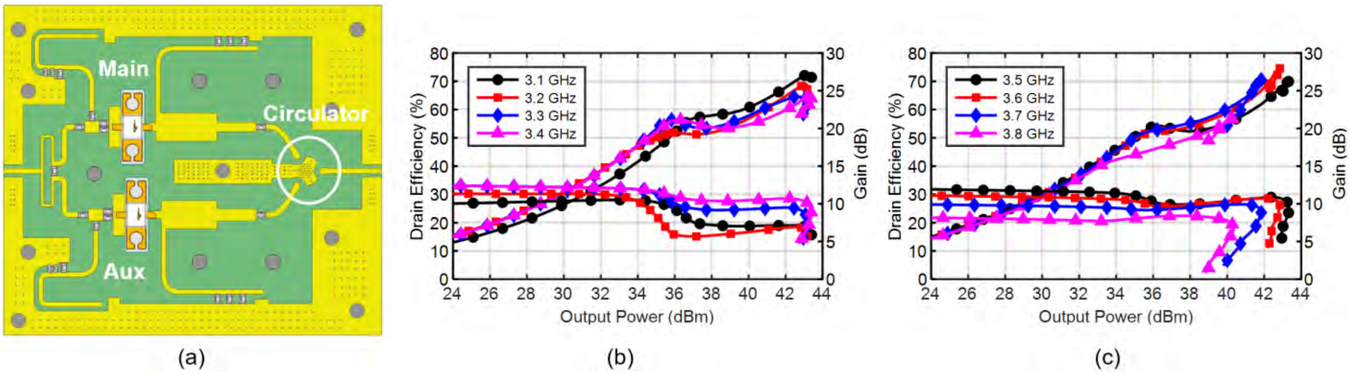

Figure 2. (a) Layout of the RF-input circulator load-modulated amplifier (CLMA) and the fully EM simulated results of the RF-input CLMA within the designed frequencies across (b) 3.1-3.4 GHz, and (c) 3.5-3.8 GHz.

Table I. Comparison with the state-of-the-art load-modulated PAs.

Ref. / Year	Architecture	Freq (GHz)	Pmax (dBm)	OPBO (dB)	DE @ Pmax (%)	DE @OPBO (%)
[4] 2022	3-way Doherty	2.14	45.3	10.0	69.0	55.0
[5] 2020	RF-in SLMBA	3.05-3.55	42.3-43.7	8.0	60.8-74.8	46.8-60.7
[3] 2022	Dual-in SCLMA	2.00-3.00	42.0-43.5	8.0	55.0-68.0	46.0-53.0
This work	**RF-in CLMA**	**3.10-3.70**	**42.2-43.5**	**7.5**	**62.0-73.0**	**54.0–58.0**

Equation (1) reveals that the load impedance seen by the main amplifier can be dynamically modulated by the magnitude and the output phase delay of the auxiliary current. It should be remarked that the impedance seen by the auxiliary amplifier remains constant to the characteristic impedance of the circulator. Therefore, the fundamental operating principle of the CLMA architecture can be described as follows: An auxiliary amplifier injects power into the output of the main amplifier through the circulator, thereby modulating its load impedance to maintain high efficiency at both peak power and power back-off. Due to the inherent non-reciprocal property of the circulator, the powers injected by the main and auxiliary amplifiers are both fully delivered to the load.

3. Prototype circuit and simulation results

To validate the proposed theory, a CLMA prototype circuit is implemented according to the theory presented above. Gallium Nitride (GaN) packaged transistors from Wolfspeed are adopted as the active devices for both the main and auxiliary amplifiers. A commercially available surface-mount microwave circulator from Skyworks is selected to act as the output combiner. A final layout and fully EM-simulated results of the designed RF-input CLMA are shown in Figure 2. The proposed RF-input CLMA achieves peak drain efficiency of 62-73% and 7.5-dB back-off efficiency of 54-58% with a saturated output power of 42.2–43.5 dBm, whose performance stands out when compared to the state-of-the-art load-modulated PAs shown in Table I.

4. Conclusion

A novel RF-input highly efficient and wideband CLMA architecture based on a non-reciprocal combiner is proposed for the first time. In addition, theoretical analysis for the RF-input circulator CLMA is presented. Furthermore, a prototype circuit based on GaN transistors and a commercially available circulator are designed and fully EM simulated. The PA achieves distinct back-off efficiency enhancement across 3.1 to 3.7 GHz, verifying the truly wideband performance. The results show the great potential of the RF-input CLMA technique as a viable alternative to other load-modulated PA architectures.

5. Acknowledgement

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