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Wideband Sequential Circulator Load Modulated Amplifier with Back-off Efficiency Enhancement

Han Zhou[#1], Jose-Ramon Perez-Cisneros[#2], Christian Fager[#3]

[#]Chalmers University of Technology, Gothenburg, Sweden

{[1]han.zhou, [2]jospere, [3]christian.fager}@chalmers.se,

***Abstract*— This paper demonstrates a novel power amplifier (PA) architecture; the sequential circulator load modulated amplifier (SCLMA). The sequential configuration resulted in excellent bandwidth and extended back-off efficiency enhancement, making it suitable for modern communication scenarios with large peak-to-average-power-ratio (PAPR) signals. A wideband prototype PA based on GaN transistors and a commercial off-the-shelf circulator is employed to validate the SCLMA concept. The experimental results exhibit a drain efficiency of 55-68 % at the peak output power and 46-53 % at 8-dB output power back-off across 2.0-3.0 GHz. Combined with the measured peak output power of 42.7±0.7 dBm in the same range, make it a promising candidate for use in modern energy-efficient wireless communication transmitters.**

***Keywords*— Circulator, energy efficiency, gallium nitride (GaN), load modulation, non-reciprocal, power amplifier (PA), sequential operation, wideband.**

I. Introduction

With the increasing demand for higher data traffic and capacity of the wireless communication infrastructure, unprecedented challenges and constraints have been imposed on the power amplifier (PA). On the one hand, exponentially growing data throughput and increased spectrum efficiency require more complex modulation schemes, leading to communication signals with a high peak-to-average-power ratio (PAPR). On the other hand, the scarcity of the frequency spectrum and the need for frequency planning have resulted in a wide range of carrier frequencies being used. Therefore, PAs able to operate efficiently over large bandwidths are required.

The load modulation technique has been proven as a promising solution to transmit signals with large PAPR efficiently. Among the various load modulation PAs, the Doherty PA [1], [2] is the most widely adopted architecture in cellular base stations due to its low circuit complexity, moderate linearity performance, and enhanced back-off efficiency. However, the drawback of the Doherty PA is the operational bandwidth limitations [3], [4].

To overcome the bandwidth limitation of the Doherty PA, the load modulated balanced amplifier (LMBA) was introduced [5], [6]. Later, the distributed efficient power amplifier (DEPA) [7] was proposed to eliminate the load modulation, thereby further extending the operational bandwidth. However, the circuit complexity of both LMBA and DEPA architectures is high. Moreover, the use of extra transistors adds a high cost. Recently, a circulator load modulated amplifier (CLMA) was proposed to address some of these limitations [8]. As shown in Fig. 1, the CLMA employs a straightforward structure with two active devices and a wideband non-reciprocal output combiner. Together with correct driving conditions, the CLMA can potentially achieve high efficiency at reconfigurable power back-off levels across a wide bandwidth.

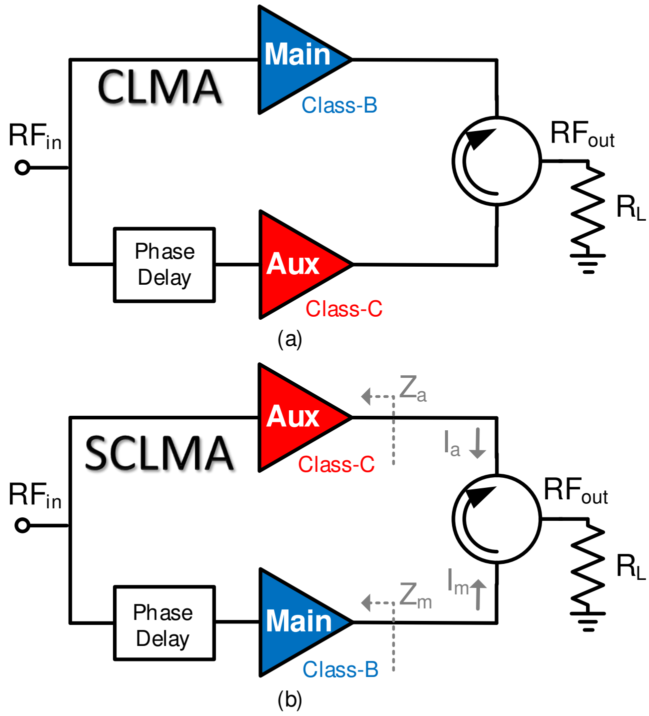

Fig. 1. Simplified block diagram of the (a) circulator load modulated amplifier (CLMA) [8] and (b) sequential circulator load modulated amplifier (SCLMA).

As an evolution of the concept in [8], [9], [10], a new active load modulation PA architecture is proposed: the sequential circulator load modulated amplifier (SCLMA). Due to the sequential type of operation, the topology can maintain high efficiency over an extensive output power range with an ultra-wide bandwidth. In this work, the theoretical foundations of the SCLMA concept are presented and validated through experimental results. This paper is organized as follows. The operational principle of the SCLMA is explained in section II. In Section III, the implementation of a GaN HEMT based SCLMA prototype, and the experimental results are shown and compared to the state-of-the-art efficient PAs. Finally,

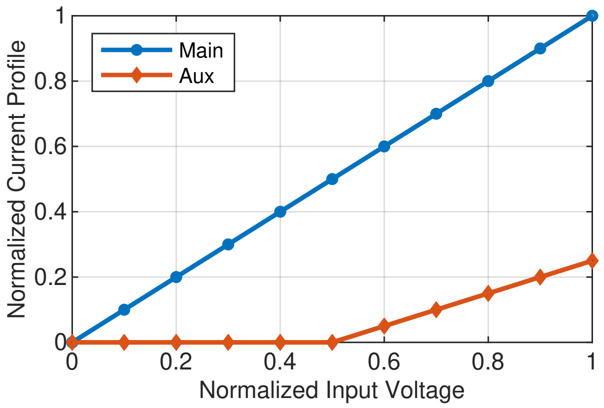

Fig. 2. Normalized fundamental current drive profile versus normalized input voltage of the circulator load modulated amplifier (CLMA).

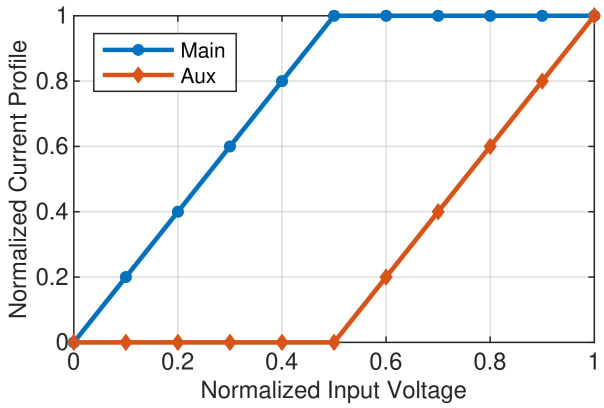

Fig. 3. Normalized fundamental current drive profile versus normalized input voltage of the sequential circulator load modulated amplifier (SCLMA).

conclusions are given in section IV.

II. Theory of Operation

Fig. 1 shows ideal block diagrams of the CLMA and the proposed SCLMA architectures. Similar to the CLMA, the SCLMA also consists of a three-port non-reciprocal circulator combiner, a class-B biased main amplifier, and a class-C biased auxiliary amplifier. However, a crucial difference is in the location of the main and auxiliary amplifiers, which are swapped between the CLMA and SCLMA architectures. Moreover, the drive conditions of the two amplifier branches are also distinctly different. In this case, the transistors are modeled as ideal current sources using a piecewise linear model [2]. Fig. 2 and Fig. 3 present the normalized fundamental current versus normalized input voltage drive profiles of the CLMA and SCLMA, respectively. As shown in the figures, the main amplifier of the CLMA operates linearly continuously. However, the SCLMA relies on the saturation of its main amplifier for back-off efficiency enhancement.

A circulator device is used in both architectures as the non-reciprocal combiner to illustrate the principle of operation. The scattering parameters of an ideal circulator are as follows:

$$[S_{circ}] = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \tag{1}$$

It is straightforward to convert the three-port scattering parameters to the admittance parameters, therefore generating a set of equations to relate the port currents and voltages.

For the sake of the theoretical analysis, and without loss of generality, the main (connected at port 3) and auxiliary (connected at port 1) amplifiers are represented by ideal current sources, having different amplitudes I_m and I_a, respectively. The output port (port 2) is terminated with a resistive load, equal to the characteristic impedance of the circulator, Z_0. By substituting the main- and auxiliary currents into the three-port admittance matrix, the resulting three equations can be solved to obtain the load impedance seen by the main (Z_m) and auxiliary (Z_a) amplifiers:

$$Z_m = Z_0, \tag{2}$$

$$Z_a = Z_0(1 + 2\frac{I_m e^{j}\theta}{I_a}), \tag{3}$$

where θ is the static phase offset between the main and auxiliary amplifier branches. Furthermore, the power relation of the main and auxiliary amplifiers, and power delivered to the load can be derived as

$$P_L = P_m + P_a. \tag{4}$$

Equation (2) reveals that the load impedance at the output plane of the main amplifier remains constant. In other words, there is no load modulation at the output of the main amplifier. Unlike other load modulated PAs, such as the Doherty, LMBA, and CLMA, the fact that the main branch is not load modulated in the SCLMA allows to considerably relax the general broadband matching Bode-Fano limitation, making the design of a much wider-bandwidth output matching network indeed possible. Moreover, it can easily be shown that the power injected by the main and auxiliary amplifiers can be fully delivered to the load. Another benefit that comes from the non-reciprocal property of the circulator combiner is that the main amplifier of the SCLMA is not affected by the off-state impedance of the auxiliary amplifier. This further simplifies the design of the circuit.

The operation of the SCLMA can be generalized. In the low-power region, before the high-efficiency output power back-off level, only the class-B biased main amplifier determines the overall output power and efficiency performance of the SCLMA. In that region, the class-C biased auxiliary amplifier is turned off. Therefore, according to (3), the auxiliary load impedance is ideally infinity. The main amplifier is designed to reach saturation and maximum efficiency when the overall output power reaches the targeted output power back-off level (OBO). In the high-power region, after OBO, the auxiliary amplifier is turned

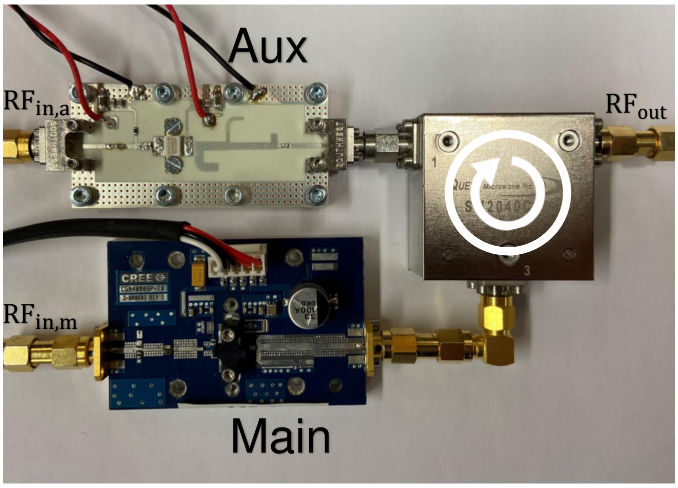

Fig. 4. Photograph of the sequential circulator load modulated amplifier prototype circuit.

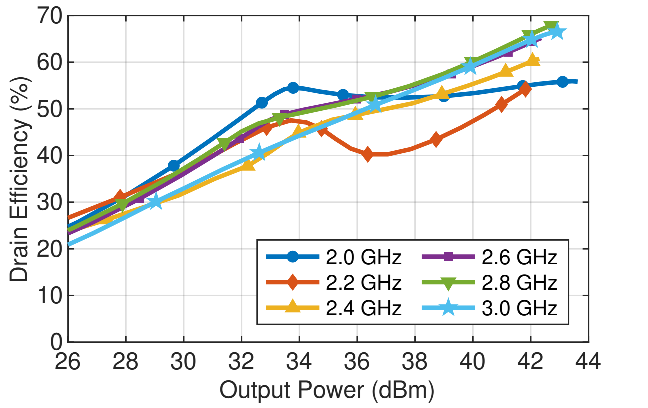

Fig. 5. Measured drain efficiency versus output power across 2.0-3.0 GHz.

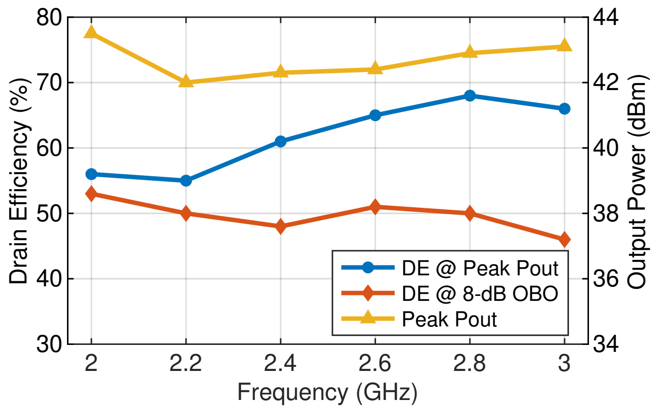

Fig. 6. Measured peak power and drain efficiency at the peak power and 8-dB OBO versus frequency profiles.

on and starts to inject current into the combiner. The loading of the main amplifier is maintained constant, according to (2). The high-efficiency of the main amplifier is therefore maintained. Moreover, the efficiency of the auxiliary amplifier can be boosted, with proper magnitude and phase delay of the currents. Consequently, overall high-efficiency can be maintained from power back-off to peak power in the SCLMA architecture.

III. Experimental Verification

A. *Prototype Design*

A prototype circuit is employed to validate the SCLMA architecture, see Fig. 4. The circuit consists of two PAs using commercially available GaN transistors and a microwave circulator, as described below.

A 25-W GaN HEMT CG2H40025F packaged transistor from Wolfspeed is employed as the active device for the auxiliary amplifier circuit. The auxiliary amplifier output matching network is designed with a multi-section low pass matching filter for high efficiency over a large bandwidth within 2.0-3.0 GHz. The circuit is implemented on a 20-mil Rogers 4350B substrate. The auxiliary circuit is designed with the proposed wideband PA technique introduced in [11]. Additionally, the 6-W GaN HEMT CHG4006P test board from Wolfspeed is selected to act as the main amplifier because of its high efficiency across a relatively wide bandwidth. Furthermore, a commercial circulator (Quest Microwave SM2040C09) with low insertion loss, wide bandwidth, and high isolation is used as the non-reciprocal output combiner.

B. *Static Characterization*

The SCLMA prototype circuit is characterized by static continuous-wave measurements. An input Wilkinson power splitter, with a power splitting ratio of approximately 40% to the main amplifier branch, has been used. Moreover, a manual phase shifter is used at the input of the auxiliary amplifier to set the optimal phase delay at each of the measured frequencies. The drain bias voltage of the main and auxiliary amplifiers are fixed to 16 V and 32 V, respectively. The main amplifier is biased in class-B mode with a quiescent current of 30 mA, while the auxiliary amplifier is biased in class-C with a fixed gate voltage of -4 V. The small signal gain of the implemented prototype is 6-7 dB within the band. The gain can be increased significantly if the commercial test board is replaced by a dedicated main amplifier design, optimized for 16V operation.

Fig. 5 presents the measured drain efficiency versus output power for several frequencies across 2.0-3.0 GHz. The results in terms of peak power, peak- and 8-dB OBO efficiency are presented versus frequency in Fig. 6. The results illustrate that a peak output power of 42.0-43.4 dBm is measured across the entire band within 2.0-3.0 GHz. The corresponding measured peak drain efficiency is 55-68 %, while the measured efficiency at 8-dB OPO is 46-53 %.

It should be noted that the back-off efficiency of the SCLMA can be easily reconfigured by simply changing the drain bias of its main amplifier, as demonstrated in Fig. 7. The figure shows the measured efficiency versus output power profiles for different drain bias voltages of the main amplifier, at 2 GHz. It can be clearly observed that a lower drain bias results in larger power back-off efficiency enhancement.

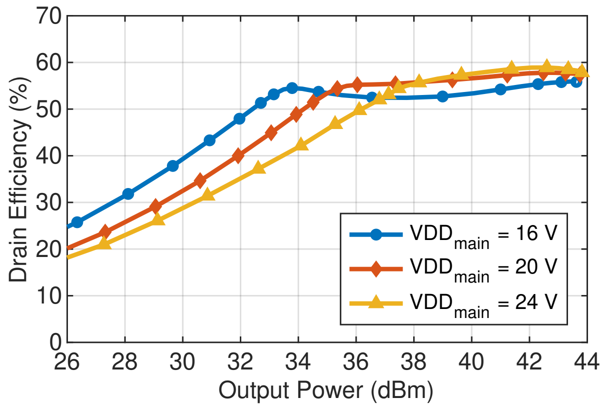

Fig. 7. Measured drain efficiency versus output power profiles, at 2 GHz, for different drain bias voltages of the main amplifier.

Table 1. Comparison with state-of-the-art load modulated PAs.

Ref.	Arch.	Freq (GHz)	P_{peak} (dBm)	η_{peak} (%)	OBO (dB)	η_{OBO} (%)
[12]	S-DPA	2.0-2.7	40.0-42.0	58-70	9.0	45-66
[13]	CM-DPA	1.6-2.7	43.8-45.2	56-75	6.0	46-64
[14]	3-DPA	1.6-2.6	46-46.0	53-66	9.5	50-53
[7]	DEPA	2.5-3.8	48.8-49.8	54-67	8.0	47-60
[15]	SLMBA	3.0-3.5	42.3-43.7	61-75	8.0	47-61
This work	SCLMA	2.0-3.0	42.0-43.5	55-68	8.0	46-53

Table I compares the measured results with those from the representative state-of-the-art load modulation PAs. The performance of the proposed SCLMA architecture shows competitive values in terms of high efficiency at both peak power and output power back-off level, over a relatively large bandwidth.

IV. Conclusion

This paper has introduced the SCLMA, a novel high-efficiency PA architecture based on two active devices and a non-reciprocal output combiner network. The use of the non-reciprocal combiner, together with the proper driving conditions for the active devices, results in the elimination of the load modulation mechanism of the main amplifier, thereby considerably relaxing the bandwidth constraint imposed on traditional load modulation PAs. Furthermore, due to the availability of wideband and low-loss circulators, the SCLMA is able to provide highly efficient operation across a large dynamic range with and an ultra large bandwidth. The proposed architecture is experimentally verified by a 2.0 - 3.0 GHz wideband circuit prototype with a drain efficiency of 55-68 % and 46-53 % at peak power and at 8-dB OBO, respectively.

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