Output Signal Re-Injection in Load Modulated Balanced Amplifiers for RF Bandwidth Improvement

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***Abstract*—This letter discusses the theory, simulation and experimental characterization of a load modulated balanced amplifier where the control signal power is obtained by re-injecting part of the output RF signal. Compared to the standard balanced load modulated power amplifier, this approach does not require an external amplification of the control signal power. The potential of this technique is explored experimentally with a balanced power amplifier working on the 1400–3400MHz band, using an external off-the-shelf directional coupler and manual phase shift adjustment. The induced load modulation can lead to a 10% increase of power added efficiency, or 1 dB of output power, across the frequency band of operation compared to the balanced power amplifier.**

***Index Terms*—Broadband, load modulation, power amplifiers.**

I. Introduction

POWER amplifiers (PAs) are key elements in wireless transmitters because of their impact on both signal transmission quality and energy consumption. Achieving high performance in PAs over a broad RF frequency in terms of output power, gain, and linearity is challenging, mostly leading to trade-offs with efficiency. Conventional RFPAs use reactive impedance transformation networks that can only approximate the optimum transistor impedance vs. frequency, and cannot vary their response to match an optimum that varies with power or any other parameter. An alternative approach is to introduce electronically tunable elements such as varactors and switches in the matching network, so that the response can be changed according to the operating conditions in what is called "passive load modulation" [1], [2], [3]. The main difficulty in this case is to achieve tunable elements with large power handling and low loss, as they must be placed directly in the output path of the PA. Another option is active load modulation, that uses the non-linear interaction between amplifiers to adapt the impedance trajectories. The Load Modulated Balanced Amplifier (LMBA) is to date the most flexible actively modulated PA, controlling the load by means of a control signal power (CSP) injected at the output isolation port of a balanced PA [4], [5]. The introduction of the LMBA has led to variations that have tried to improve on bandwidth and back-off efficiency [6], [7], [8], [9]. Another modification to the LMBA, called orthogonal LMBA (OLMBA) [10], injects the CSP at the input isolated port and uses a reflective load at the output isolated port to provide the load modulation without the need of amplifying the CSP signal separately.

This letter describes the theory of operation of a re-injection, or recursive, LMBA (RLMBA) which accomplishes active load modulation to maximize output power or efficiency at configurable frequencies across the band, by using a CSP signal which is extracted from the main RF output of the balanced PA, using a directional coupler, and with an appropriate phase delay. The RLMBA removes the need of a CSP amplifier, and compared to the OLMBA provides a simpler topology, with a single RF input, and a more symmetrical load modulation on the balanced devices. An initial proof of concept containing a manually adjusted phase is presented, showing effective tuning capabilities with significant efficiency and output power improvement, compared to the balanced PA, over a wide frequency region.

II. Theory of operation

The RLMBA (Fig. 1) constists of a balanced PA (BPA), a directional coupler placed at the main RF output to derive the CSP signal, and a phase shifter to adjust the phase of the CSP signal before re-injecting it at the BPA output isolated port.

For circuit analysis, in the first approximation, an ideal 3-dB quadrature coupler can be considered alongside active devices as voltage controlled current source, see Fig. 1. The output quadrature coupler can be represented as a 4-port impedance matrix $\mathbf{Z}$:

$$\mathbf{Z} = Z_0 \begin{bmatrix} 0 & -j & 0 & -j\sqrt{2} \\ -j & 0 & -j\sqrt{2} & 0 \\ 0 & -j\sqrt{2} & 0 & -j \\ -j\sqrt{2} & 0 & -j & 0 \end{bmatrix}. \quad (1)$$

Assuming a perfect quadrature coupler at the input, the current sources are in the following relation:

$$I_2 = -jI_1. \quad (2)$$

A matched output directional coupler leads to $V_4 = -Z_0 I_4$ while the coupling factor χ and phase shift $e^{-j\phi}$ mean that the current at the CSP port is:

$$I_3 = -\chi e^{-j\phi} I_4 = -\Psi I_4, \quad (3)$$

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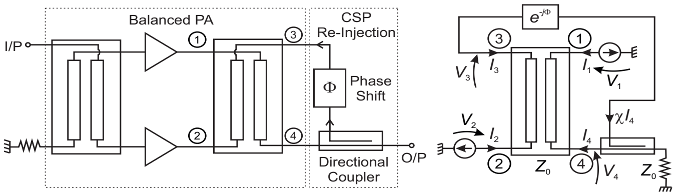

Fig. 1. Block diagram of the RLMBA and schematic diagram for circuit analysis.

where $\Psi = \chi e^{-j\phi}$ is used to simplify the notation.

By substituting (3) into $\mathbf{Z}$ (1), the impedance at the devices Z_1, Z_2 is obtained as function of Ψ:

$$Z_1 = Z_2 = Z_0 \frac{1 - j\Psi}{1 + j\Psi} \tag{4}$$

It is then possible to calculate the corresponding reflection coefficients Γ_1, Γ_2 at the devices' ports, normalized to Z_0:

$$\Gamma_1 = \Gamma_2 = -j\Psi \tag{5}$$

which clearly show that, for a fixed coupling factor χ, the reflection coefficients can be modulated on a circle of radius χ, with the phase shift ϕ that can be used to control the phase of the load. The use of any prematching between the coupler and the devices can be seen as an impedance transformation that changes the Z_0 to which the impedance are normalized to calculate Γ_1, Γ_2, but does not affect the validity of the analysis apart from a fixed phase shift on the reflection coefficient.

Assuming lossless couplers, matching networks and phase shifter, the power at the output of the BPA is

$$P_4 = P_1 + P_2 + P_3 \tag{6}$$

while the output power of the RLMBA can be written as:

$$P_{\mathrm{OUT}} = P_4 - P_3 = P_1 + P_2 \tag{7}$$

meaning that the total output power is equal to the power generated by the balanced devices independently of the coupling factor χ; an important, but somehow counter-intuitive result.

A. Impact of passive networks loss

We define the loss by using a voltage attenuation parameter $\rho \leq 1$, with no loss at $\rho = 1$, and identify three main loss contributors. Firstly, the direct loss in the output directional coupler ρ_1, which directly affects output power and efficiency. Secondly, the loss in the phase shifter ρ_2, which affects both output power and load modulation. And thirdly, the combined loss of the BPA quadrature coupler and output prematch, ρ_3, which is assumed to be the same on the direct and coupled paths, and affects both output power and load modulation. It can be shown with simple calculations that the load modulation becomes:

$$\Gamma_1 = \Gamma_2 = -j\rho_2\rho_3^2\Psi \tag{8}$$

while the output power reduces as:

$$P_{\mathrm{OUT}} = \rho_1^2\rho_3^2 \frac{1 - \chi^2}{1 - (\rho_2\rho_3^2\chi)^2}\,(P_1 + P_2) \tag{9}$$

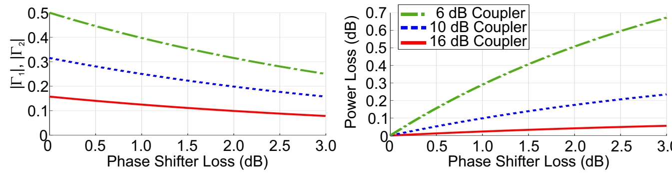

Fig. 2. $|\Gamma_1|, |\Gamma_2|$ and P_{OUT} vs. phase shifter loss ρ_2 for different values of directional coupler coupling factor χ.

By focusing on the role of the phase shifter loss which is specific to the RLMBA, Fig. 2 shows the impact of ρ_2 on load modulation and output power for different values of χ (and $\rho_1 = \rho_3 = 1$), which can be used to determine whether the RLMBA is effective with phase shifter loss.

Another factor to consider is that the re-injection of the signal might be critical in terms of the settling time of the impedance. Hence, in applications using fast, short RF pulses, the phase shifter design should target a low group delay.

III. Simulation Results

Simulations on a balanced PA prototype were run in ADS. The active devices are the Wolfspeed CG2H40025F GaN HEMTs biased at 28 V, -2.7 V, 50 mA, while the quadrature couplers are the Anaren11306-3s, nominally designed for 2–4 GHz operation. The balanced PA underpinning the RLMBA has been only slightly changed from [11]. Being based on a reasonably simple output topology, with only two-sections of microstrip impedance transformation, it leaves enough room for exploring the potential of load modulation while still providing a fair matching over the frequency band (see Fig. 3). The input matching is designed to reduce input reflection and provide broadband stability. The optimum load and BPA matching trajectory are shown in Fig. 3.

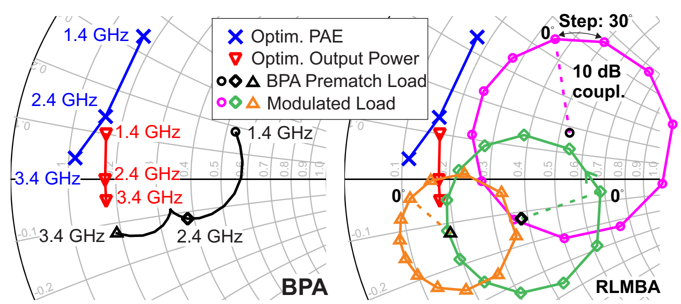

Fig. 3. Optimum load and load trajectory at the device plane for the BPA matching vs. frequency, and load modulation (RLMBA).

The measured scattering parameters of the directional coupler used, CPL-5230-10-SMA-79 from Midwest Microwave, with 10 dB coupling over 0.5–18 GHz, were used in simulation. Different values of coupling were also simulated but they did not provide a competitive advantage in this case. The ideal phase shift "ϕ" was swept on a full 360° range.

The simulated devices' impedance, both for the BPA only case and with RLMBA action at one frequency, are also reported in Fig. 3. It can be noted that the BPA pre-matching is rather good over bandwidth, but it can only approximate the optimum loads at the low impedance values required. The load modulation achievable with the RLMBA can help get closer to the optimum, as well as an option to choose priority between optimum power or efficiency. Fig. 4 shows the

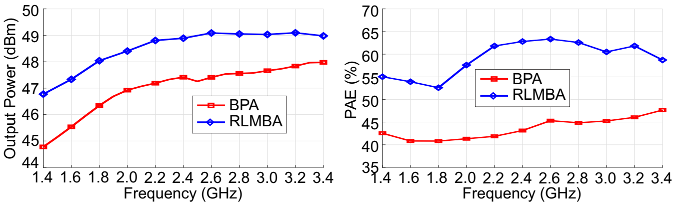

Fig. 4. Simulated best-case PAE and output power vs. frequency for the BPA only and with RLMBA action with 10 dB directional coupler and 30° phase steps. Optimum phase for PAE and output power is not necessarily the same.

simulation results over the 1.4-3.4 GHz band, comparing the BPA only and the RLMBA. For the latter, at each frequency the best phase setting for maximum PAE or output power has been chosen, respectively. The data refers to 3 dB gain compression, corresponding to a gain >10 dB over the band.

IV. Experimental Results

A photograph of the prototype board is shown in Fig. 5. For the first proof of concept of the PA, the phase shift was adjusted manually by testing coaxial cables of different lengths between the directional coupler and the isolated output of the BPA, with negligible losses. Eight different lengths of

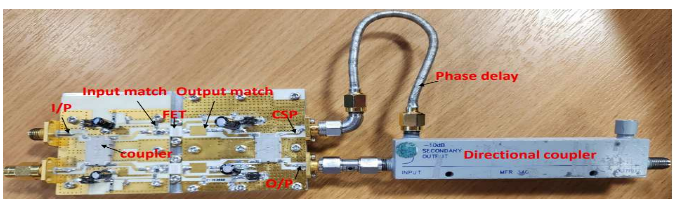

Fig. 5. Picture of the RLMBA demonstrator, the BPA board size is 90mm x 48mm.

cables were used for the single-tone measurements, resulting in selective performance improvements over the RF bandwidth.

Fig. 6 shows the PAE vs. output power at two RF frequencies, for the BPA only case and the RLMBA cases with different cable lengths. As it can be noticed, only a proper selection of the phase length leads to improvements. The best achievable results at 3 dB gain compression are selected at each frequency and reported in Fig. 7, where PAE, output power and gain are plotted from 1.4 to 3.4 GHz alongside the phase lengths of the cables tested and the optimum phase points corresponding to each performance metric.

This comparison illustrates that the RLMBA is capable of selectively improving output power or PAE compared to an analogous BPA. The output power is increased by 1 dB across the band, while the PAE is improved by at least 10% at most of the frequencies tested. In absolute terms, the RLMBA achieves 47 dBm from 1.5 to 3.4 GHz, and 50% PAE from 1.4 to 3.2 GHz. To achieve similar performance over such bandwidth, PAs in literature use matching networks with at least four sections [12], [13] or complex coupled transformers [14]. The Orthogonal LMBA in [10] shows similar results on the same band, but with higher system complexity which

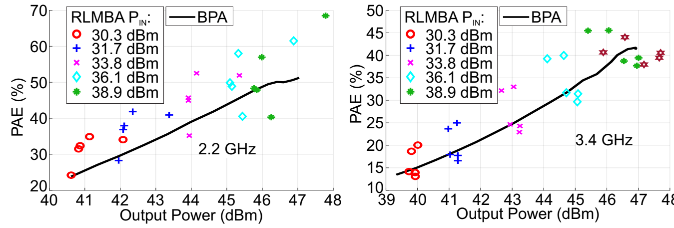

Fig. 6. Measured PAE versus output power at 2.2 GHz and 3.4 GHz for BPA and RLMBA with five different cables, at different input power levels.

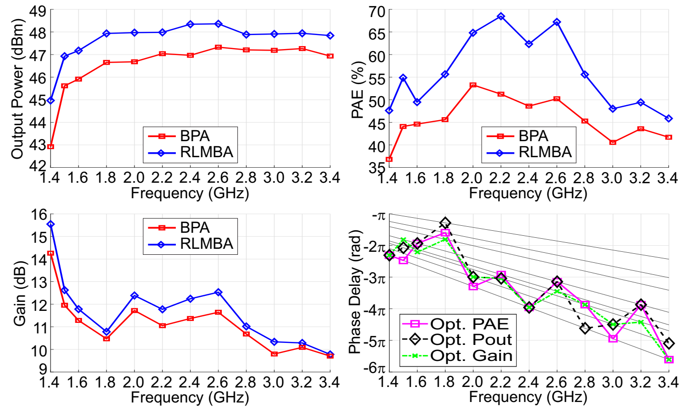

Fig. 7. Measured output power, PAE, gain and phase delays vs. frequency with BPA only (red squares) and for best phase settings in the RLMBA (blue diamonds). Optimum phase delay for each performance metric also reported vs. frequency, superimposed to the phase delay of the cable lengths tested.

allows extending the bandwidth at lower frequencies. Linearity has been tested by applying 5G New-Radio waveforms with the Amplifier Testing tool from R&S that coordinates the signal source (SMW200A) and analyzer (FSW). Normalised output spectra are reported in Fig. 8 at 2.2 GHz and 3.4 GHz, respectively, for the cable lengths providing maximum output power. The test signal is a demanding 50 MHz single-carrier downlink channel with 12.6 dB PAPR. The intrinsic linearity of the RLMBA is good, and the built-in predistortion leads to good margins from the -45 dB ACLR limit.

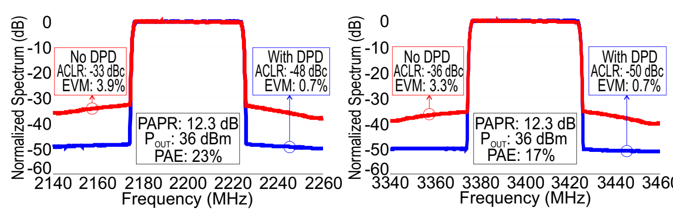

Fig. 8. Output spectra without (red) and with (blue) predistortion when applying a 50 MHz 5G NR signal. Carrier frequency of 2.2 GHz and 3.4 GHz.

V. Conclusion

The RLMBA theory of operation has been discussed and its potential demonstrated with a proof-of-concept prototype. This paper offers the starting tool for engineering the RLMBA to specific applications and technologies, encouraging further research into the design of an effective phase shifter solution that minimizes losses and group delay.

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