A Power Reconfigurable High-Efficiency X-Band Power Amplifier MMIC Using the Load Modulated Balanced Amplifier Technique

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***Abstract*— The load modulated balanced amplifier (LMBA) technique uses a control signal, injected at the output coupler, to modulate the impedance of the balanced amplifier transistors. A 14.1-W X-band LMBA is reported, integrating for the first time the balanced, driver, and control signal amplifiers in a single microwave monolithic integrated circuit. Load modulation and bias settings are used to demonstrate that high circuit efficiency can be achieved as the LMBA is adjusted for operation in three RF-power regimes; 1.5, 5.6, and 14.1 W for a constant input power of 22 dBm. Power-added efficiencies above 37% are observed in all power regimes from 8 to 9 GHz under saturated conditions.**

***Index Terms*— Balanced power amplifier, Doherty, gallium nitride (GaN), load modulation, microwave monolithic integrated circuit (MMIC).**

I. Introduction

POWER amplifier efficiency is a critical parameter for all applications. Maintaining efficiency as the output-power requirement changes has been the subject of many inventions and papers. The Doherty technique [1], [2] has been widely adopted for its backed-off efficiency characteristic. Recently, a new technique, the load modulated balanced amplifier (LMBA) has been proposed and demonstrated [3]. In this technique, the output impedance seen by the transistors of a balanced amplifier is modulated using a control signal power (CSP) injected at the isolated port of the output coupler. It was shown in [2] that CSP power is recovered at the output.

Demonstrations of the LMBA technique have to date been confined to hybrid technologies and with a single-stage amplifier. The first published implementation [3] at 0.8–2 GHz yielded 60%–78% and 51%–67% drain efficiencies (DEs) at 42-dBm peak power and at 6-dB output-power back off (OPBO), respectively. A further hybrid LMBA [4] operated from 4.5 to 7.5 GHz with 39-dBm peak power and 47%–77% DE. In [3], it was demonstrated that using two drain bias states and three CSP power levels allows DE above 60% to be maintained at >8 dB OPBO over regions of the band of operation. An extension of this letter [5] has employed a power splitter and on-board phase shifter network to allow a single input to be used in contrast to the separated CSP inputs in [3] and [4]. In this letter, an X-band LMBA in microwave monolithic integrated circuit (MMIC) technology is demonstrated for the first time. This MMIC was designed for specific applications which require discrete, rather than continuous, switched power levels with maximum efficiency.

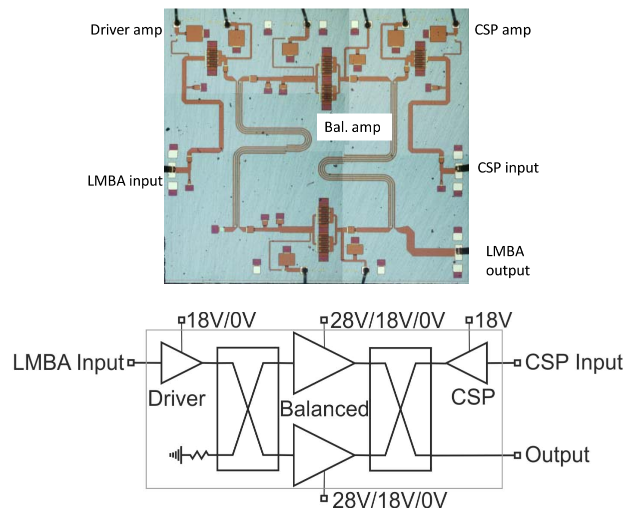

Fig. 1. Photograph of the LMBA MMIC fabricated using GaN 0.25-μm gate technology at WIN Semiconductors (4×3.55 mm^2), and block diagram representing the several integrated functions in the LMBA.

II. Design

The LMBA MMIC incorporates a balanced amplifier pair, a driver amplifier, and a CSP amplifier, as shown in Fig. 1. The design objective was to demonstrate that load modulation could be employed to enable the amplifier to maintain efficiency at three discrete output power states; 14.1, 5.6, and 1.5 W by using various bias voltage states. The design strategy was to configure the balanced amplifier circuit for peak efficiency at a drain voltage of 18 V and use the LMBA function to reconfigure the balanced amplifier output match when the balanced amplifier drain voltage is varied. In this way, the added power from the CSP will contribute to the overall higher power when the drain is increased to 28 V.

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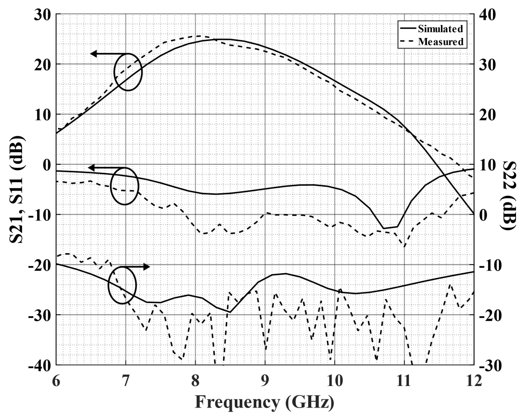


Fig. 2. S-parameter measurements for the LMBA with no CSP injected. Symbols measured compared to simulation.

We define an additional degenerate mode, where the balanced amplifier transistors are zero biased leading predominantly to the transmission of the CSP to the output due to near total reflection from the unbiased balanced amplifier transistors.

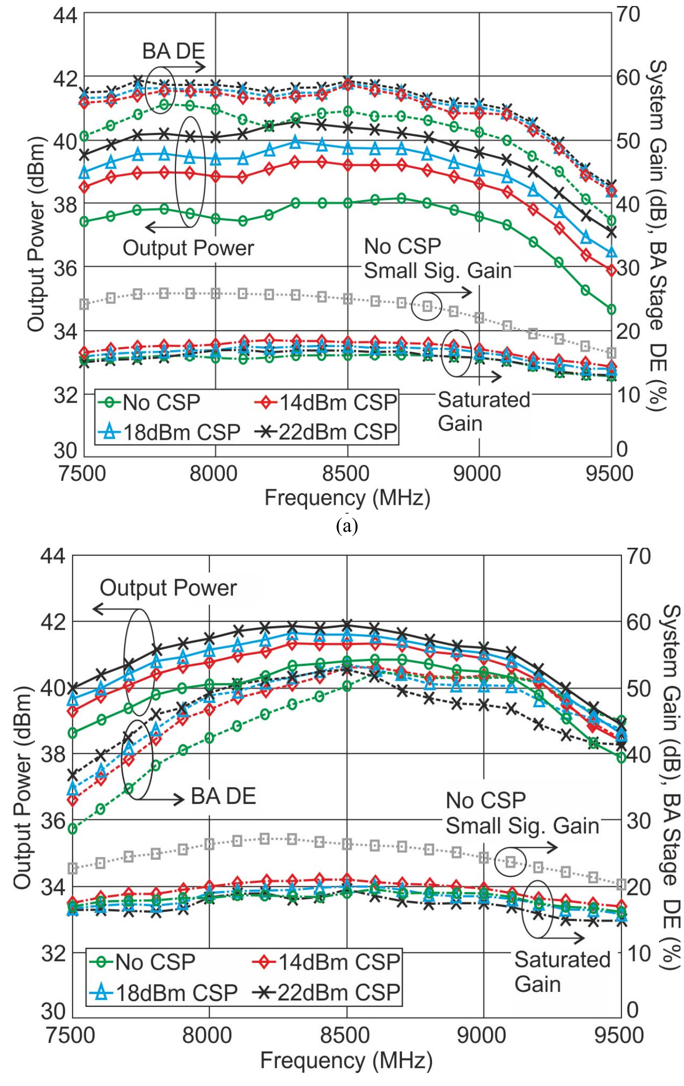
Gallium nitride (GaN) 0.25-μm gate length technology from WIN Semiconductors was used. The balanced amplifier consists of two 8 μm $\times$ 125 μm cells in each arm, while the CSP and driver amplifiers are identical and use a single 8 μm $\times$ 125 μm cell. The Lange couplers were designed in a 2.5-D electromagnetic solver.

The MMIC was mounted using high thermal conductivity epoxy on a Cu block fixture to enable bias decoupling and coaxial connector interfaces. Bias to each of the amplifiers can be monitored independently. Small-signal measurements of the amplifier, with the CSP input terminated, biased in class C, with no input power, are shown in Fig. 2, with reasonable agreement to foundry circuit models.

III. Large-Signal Measurements

Large-signal measurements of the LMBA function are performed by injecting continuous wave (CW) signals at the LMBA and CSP input ports using phase-locked signal generators [3]. Automated LMBA input-power sweeps are then performed as the CSP input signal phase is rotated through 360° , and various CSP input-power levels are used. The dc power is recorded for the amplifiers. Measurements correspond to deep class AB bias for all amplifiers and at either 18- or 28-V balanced amplifier drain voltage as stated. The 18 V is used for the driver and CSP amplifiers throughout.

Large-signal measurements for the CSP amplifier were performed using signals injected only at the CSP input and with the balanced and driver amplifiers zero biased (i.e., 0 V on the drain and gate). These measurements serve as a calibration for the CSP amplifier characteristics and allow for the balanced amplifier power, and therefore, DE to be extracted from LMBA measurements. This accuracy of this approximation has been tested with large-signal simulations and is quite good also when extrapolated to different working conditions of the balanced pair. It is also noted that this degenerate mode constitutes the lowest output-power mode of the reconfigurable amplifier reported here (Fig. 5).



(b)

Fig. 3. Large-signal performance for the MMIC LMBA showing peak performance at various CSP levels in bias states (a) and (b) as indicated. (a) 18-V driver and CSP amplifier and 18-V balanced amplifier. (b) 18-V driver and CSP amplifier and 28-V balanced amplifier.

Fig. 3 illustrates the LMBA performance of the amplifier versus CW frequency, in terms of output power, DE of the balanced pair, and gain, as the balanced amplifier bias is switched from 18 to 28 V. Each point reported is selected from the measurement data set and corresponds to an optimum efficiency phase setting for the CSP. Parameters plotted in Fig. 3 are as follows:

$$\text{BA stage DE} = P_{\text{Bal,out}}/P_{\text{dc,Bal}} \tag{1}$$

$$\text{PAE} = P_{\text{total,out}}/(P_{\text{dc,Bal}} + P_{\text{dc,drv}} + P_{\text{dc,CSP}}) \tag{2}$$

$$\text{System Gain} = P_{\text{out,total}}/(P_{\text{in,CSP}} + P_{\text{in,drv}}) \tag{3}$$

where $P_{\text{Bal,out}}$ and $P_{\text{total,out}}$ are the RF output powers for the balanced amplifier alone and for the combination of balanced and CSP amplifiers, respectively. The dc powers and RF input powers to the individual amplifiers are referenced by the parameter subscript.

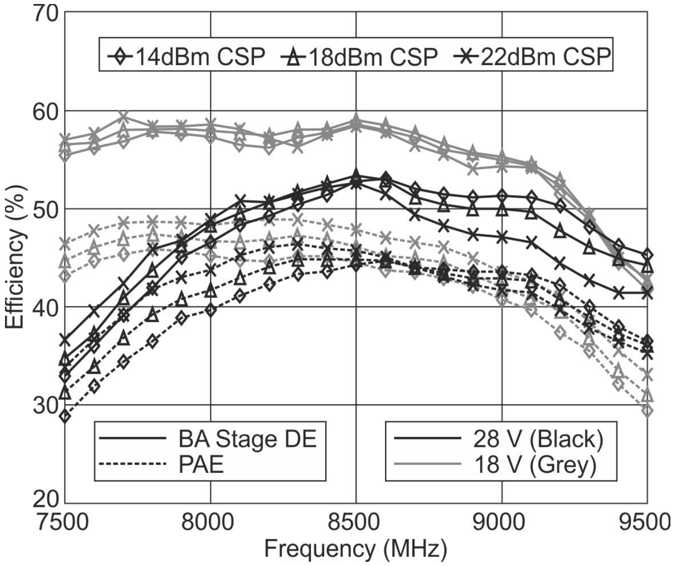


Fig. 4. Peak DE and power-added efficiency for 18- and 28-V balanced amplifier bias.

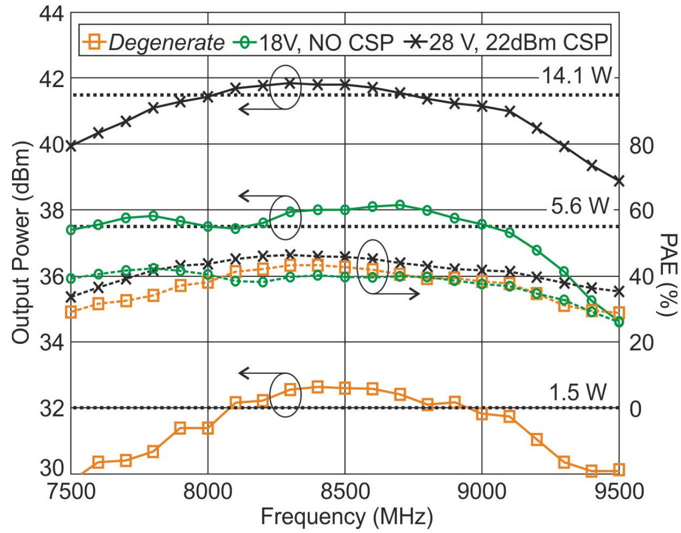


Fig. 5. Peak power (solid curve) and PAE (dashed curve) measurements for LMBA, balanced amplifier, and CSP-only (degenerate) modes. $P_{\text{in}} = 22$ dBm.

At 18- and 28-V balanced amplifier biases, application of the CSP leads to enhancement of the peak power and DE through load modulation, not simply power combining. For example, at 28-V bias and 8 GHz, a CSP input power of 22 dBm (corresponding to 1.9-W CSP after the coupler) gives rise to a 4.25-W increase in total output power. DE increased around 4% at $P_{\text{in,CSP}} = 14$ dBm and then remains unchanged as the CSP power is increased to 22 dBm.

An increase in peak output power is observed at 28 V (15.5 W) compared to 18 V (11 W), this improvement may be expected to be greater under pulsed operation [6] due to the larger thermal effects at 28 V. Circuit gain is maintained above 17 dB for 28-V operation and is reduced by around 2 dB at 18 V, found to be typical of the process. Comparing PBO, no CSP in Fig. 3 (the circuit power gain with no CSP injected and at input power in the linear operating region) with the CSP injected operation shows that the amplifiers are operated close to saturation.

DE and PAE are compared in Fig. 4 under peak efficiency conditions in saturation; the corresponding power levels are displayed in Fig. 3. Although the Bal-stage DE shows negligible improvement with the increased CSP level, the disproportionate increase in power due to load modulation is reflected in PAE improvements (for example, at 28 V and 8 GHz, PAE increases by 6% as $P_{\text{in,CSP}}$ is changed from 14 to 22 dBm).

Compared to published nonreconfigurable MMICs operating over this frequency range, the LMBA performance parameters are similar to both 18- and 28-V bias levels, see the comparison table reported in [6], namely, gains above 15-dB, 10-W class of output power and CW PAE figures in the 40%–50% range over at least 8–9 GHz. Improved LMBA performance is expected using smaller periphery or more efficient mode driver and CSP amplifiers.

Finally, the performance of the MMIC in three modes of operation is illustrated in Fig. 5. In the LMBA mode (28 V), as a balanced amplifier ($P_{\text{in,CSP}} = 0$ W) and degenerate mode (driver and balanced amplifiers unbiased; 0-V gate and drain). Three mean power levels are illustrated for the band 8–9 GHz, where 5.6 and 1.5 W correspond to 4- and 9.7-dB OPBO, respectively, relative to the 14.1-W state. PAE above 37% is observed in all modes. $P_{\text{in,drv}}$ and $P_{\text{in,CSP}} = 22$ dBm where a signal is present, meaning that the output power can be controlled without changing the input-power level while maintaining good efficiency.

IV. Conclusion

This letter has for the first time reported a demonstration of an *X*-band LMBA MMIC. Three modes of operation are illustrated which allow the amplifier to be reconfigured for 14.1-W output power and 4- or 9.7-dB OPBO; >37% PAE is maintained over 8–9 GHz. This letter describes the use of bias and CSP to optimize the efficiency of the LMBA in three bias states. It is noted that the ability of the LMBA to dynamically adjust the loading impedance of the amplifier can be achieved in further bias states to yield a wider range of power with adaptive efficiency enhancement. Furthermore, improvements in the efficiency of the driver amplifiers, which might themselves be LMBAs, die attach, and pulsed operation would further improve already impressive performance.

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