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High Efficiency RF Power Amplifiers Featuring Package Integrated Load Insensitive Class-E Devices

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Abstract—Doherty and Mixed-mode outphasing RF power amplifiers (PAs) that make use of package integrated quasi-load insensitive (Pi-QLI) Class-E GaN transistors are presented. The package integrated harmonic terminations facilitate very simple and compact amplifier implementations. Using these proposed devices, a "Class-E" Doherty PA with 58.3% average efficiency and -49 dBc ACPR after linearization, as well as, a Mixed-mode "Class-E" outphasing PA with an average efficiency of 66.6% and -51.6 dBc ACPR, after linearization using a single carrier WCDMA, PAR=7dB at 2.14GHz, are presented.

Index Terms— High Efficiency, QLI Class-E, harmonic matching, Doherty PA, Mixed-mode outpasing.

I. INTRODUCTION

There is a growing demand for next generation communication systems that can handle high data rates, while being more energy efficient to allow reduction of their operational costs. These tasks are especially challenging for the power amplifier (PA) in the transmitter, since high average efficiency is required for high peak-to-average-power-ratio (PAR) and wideband complex modulated signals. Doherty and outphasing implementations in GaN technology have shown promising results [1]-[3]. However, even higher efficiencies can be achieved if the higher harmonic terminations can be controlled more accurately, without increasing board complexity/size.

In this paper, we present GaN transistors that are harmonically matched, based on the highly efficient QLI Class-E concept inside a standard RF package. QLI Class-E can preserve high efficiency for a varying load, which is mandatory in achieving high average efficiency in load modulated PAs such as Doherty or outphasing, shown in Fig. 1(a). Integrating higher harmonic matching networks inside standard RF packages, allow designers to easily benefit from Class-E efficiency performance in practical Doherty or outphasing designs. In this work, Doherty PA and Mixed-mode outphasing PA that use a combination of phase and amplitude modulation are presented featuring these Package Integrated QLI Class-E devices.

Section II describes the package integrated load insensitive Class-E devices and the design and implementation of Doherty and Mixed-mode outphasing amplifiers. Section III gives the static and dynamic measurement results of both architectures. The conclusions are given in section IV.

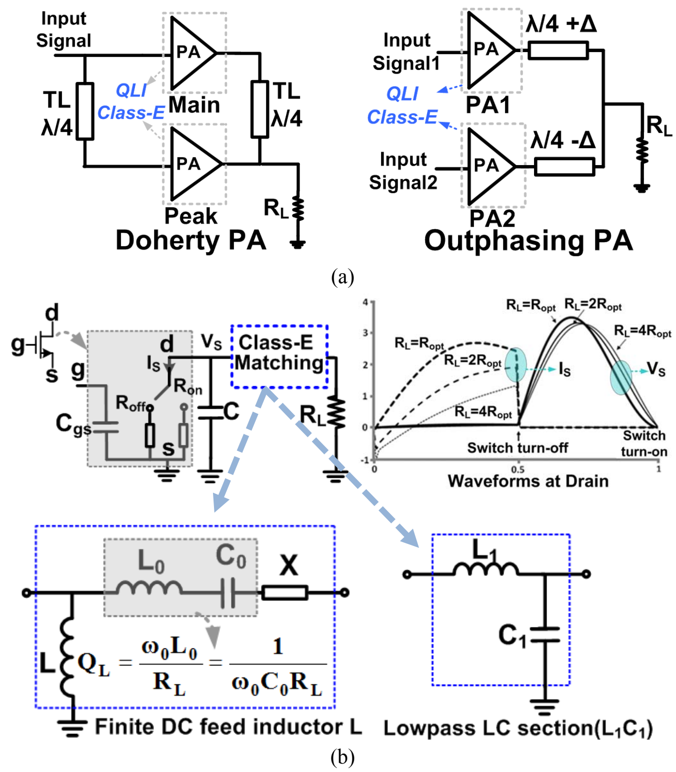

Fig. 1. (a) Simplified block diagram of Doherty PA and outphasing PA using QLI-Class-E (b) quasi load insensitive Class E: finite DC feed inductor L and lowpass LC section (L_1C_1) with related waveforms

II. DESIGN OF DOHERTY AND MIXED-MODE OUTPHASING PA USING HARMONICALLY MATCHED RF PACKAGED DEVICES

A. Package Integrated QLI (Pi-QLI) Class-E

The finite inductance implementation of Class-E has attracted the attention of RF community, due to its high efficiency and simple circuit structure. Analysis from [4] shows that there exists numerous modes of operation which, arises as the relation between load network elements and input parameters are varied as function of the resonance factor $q = 1/\omega\sqrt{LC}$, through L and C, as shown in Fig. 1(b). Among the many possible solutions, there exists a unique Class-E mode of operation for q = 1.3 which yields optimum efficiency over a wide range of load resistance, making it the best candidate for the systems

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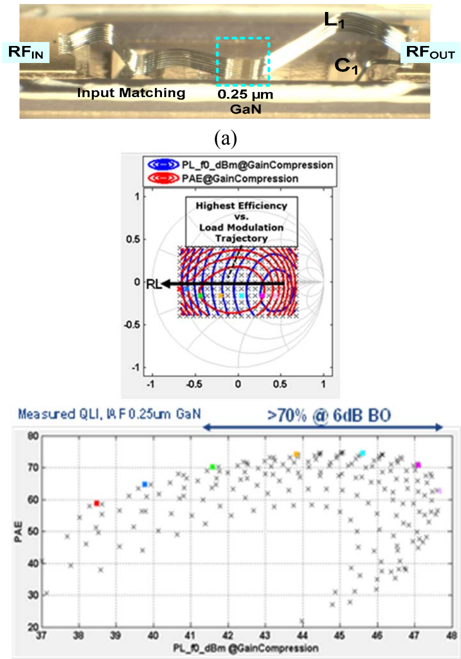

Fig. 2. QLI Class-E lowpass (L_1C_1) device (a) network implemented in package (Side view) (b) LP measurement data showing the efficiency versus load modulation trajectory (dots with "x" symbol)

based on dynamic load modulation such as Doherty and/or outphasing. The design equations for finding the circuit values for the q=1.3 condition are defined in [4]. The related admittances observed at the drain of active device can be generalized as in (1) where n indicates harmonic number:

$$Y_n = \frac{1}{R_L} * \left\{ \frac{1}{1+A^2} - \left(\frac{A}{1+A^2} + \frac{1}{nK_L} - nK_C \right) \right\} \quad (1)$$

with

$$A = nK_X + \left(\frac{n^2-1}{n} \right) \frac{\omega L_0}{R_L} \quad (2)$$

In standard RF packages, size and cost constrains allow only simple matching network topologies in practice. A series capacitor in particular is difficult to implement internally. Therefore, functionally identical transformed lowpass LC section (L_1C_1) has been derived as shown in Fig. 1(b).

Fundamental load-pull measurement data of the QLI Class-E (q=1.3) packaged devices is shown in Fig. 2. Since the higher harmonics are matched inside the package conventional fundamental load pull system is sufficient to obtain the optimum impedance for both maximum efficiency, maximum output power and BO (e.g., 6dB). The measured data shows that maximum output power and efficiency are aligned on the real axis of the smith chart. The peak efficiency is preserved while the output power is decreasing for an increasing real part of the load (R_L), which indicates that second harmonic impedance required to achieve peak efficiency during load modulation is unaffected. This property is very useful to boost the average efficiency of Doherty and outphasing PAs.

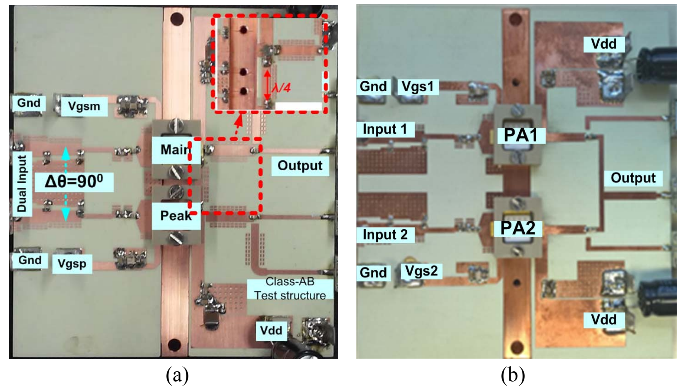

Fig. 3. Prototype (a) Doherty PA (b) Mixed-mode outphasing PA

B. QLI-Class-E Doherty PA Design

Following from the load-pull measurement results of the packaged device in Fig. 2, power and efficiency contours are aligned on the real axis which is an evidence for the *(λ/4)* internal rotation. For the design of the load network of the Doherty PA, this λ/4 internal rotation is taken into account, consequently, no additional compensation lines are required at the output. Furthermore, the fundamental load impedance required at the package leads is high enough to place the Doherty combiner directly, without the need for an extra matching network, as shown in Fig. 3 (a). Due to the termination of higher harmonics inside the package, the load network implementation of the Doherty can be very simple, compact and does not require higher harmonic matching. Furthermore, the main device is biased in "Class-AB" mode while the peak device is biased in "Class-C" mode for their quiescent currents to ensure the conventional Doherty operation, when hard driven the device will enter their Class-E like operation.

C. Dual Input Mixed-mode Outphasing PA Design

The simplified schematic and implementation for the Mixed-mode outphasing design are given in Fig. 3(b). Chireix compensation has been incorporated in the two branches by adjusting their electrical length by ±Δ instead of adding an area consuming shunt susceptance. The value of Δ determines the required outphasing compensation angle.

For the Mixed mode outphasing operation, a combination of phase and input power control is used to achieve maximum drain / PAE efficiency vs power back-off. The optimized drive profile for the best efficiency response is stored in a lookup ta-

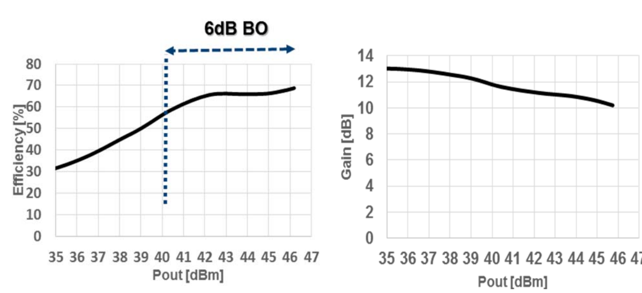

Fig. 4. Static measurement of Doherty PA at 25V

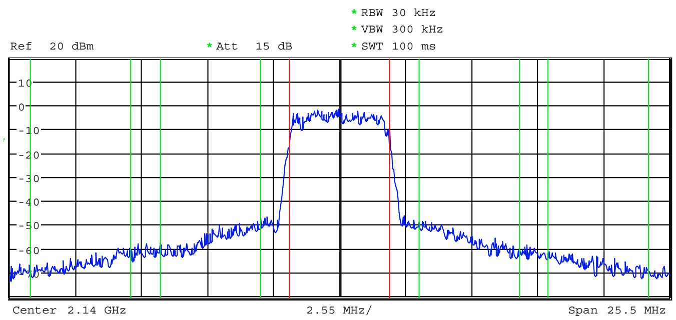

Fig. 5. Dynamic measurement of Doherty PA using single carrier WCDMA at 2.14 GHz with 7 dB PAR (after DPD)

ble. In this way, the outphasing PA can avoid the sharp efficiency /gain roll-off at larger outphasing angle and maintain high line-up efficiency.

III. EXPERIMENTAL VERIFICATION

The measurement was carried out in a dual input measurement setup capable of sweeping both input phase and amplitude. However, this work bench does not support pulsed operation, therefore devices were not pushed to high compression point to avoid thermal damage under CW operation. Therefore, it can be noticed that the peak power with modulated signals is at least 1dB higher than the static measured output power. A vector switched general memory polynomial (VS-GMP) was used in the linearization. More dedicated DPDs are expected to give better linearization.

A. QLI-Class-E Doherty PA

The static (CW) measurements of the Doherty PA are shown in Fig. 4 at 2.14 GHz and show that the peak output power

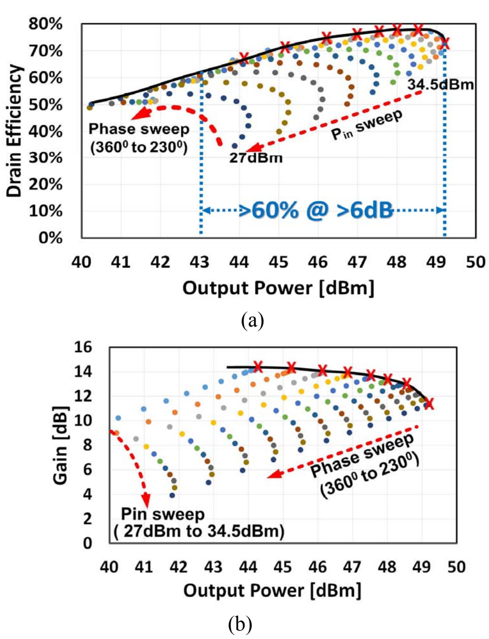

Fig. 6. Static measurement of Mixed-mode outphasing PA versus output power at 28V (a) Efficiency (b) Gain

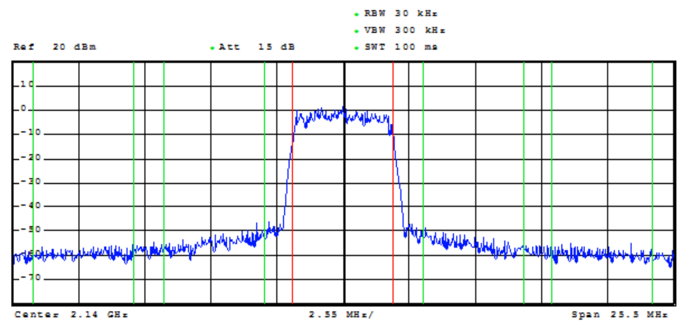

Fig. 7. Dynamic measurement of Mixed-mode outphasing PA using a single carrier WCDMA at 2.14 GHz with 7 dB PAR (after DPD)

reaches to 46.2 dBm with an efficiency of 68.79%, which is maintained above 58% at 6dB BO. The gain response is shown in Fig. 4. The Doherty PA was also tested with a single carrier WCDMA signal having 7dB PAR. The measurement results show that the Doherty PA has 58.3% average efficiency and an average output power of 40.41dBm after linearization. The power spectrum of the Doherty PA after linearization is shown in Fig. 5.

B. Dual Input Mixed-mode Outphasing PA

The measured efficiency versus output power response for outphasing PA using Pi-QLI Class-E is shown in Fig. 6. Branch PA1 is biased in Class-AB while PA2 is biased in deep Class-AB, which helped to improve BO efficiency by 3% with respect to Class-AB/Class-AB biasing. Distinct color dots show the 2-D sweep of input power and phase. The static measurement results show a peak output power of 49 dBm with 77% efficiency, which is maintained above >60% beyond 6 dB BO. The final optimum response, achieved by connecting all high efficiency points, shows >50% efficiency over a 9 dB BO with a well-behaved gain as shown in Fig. 6.

The Mixed-mode outphasing PA is also tested with a single carrier WCDMA signal, 7dB PAR. The measurement result shows that average efficiency of Mixed-mode outphasing PA is 66.6% with an average output power of 42.68 dBm after linearization. The spectrum after linearization is shown in Fig. 7.

IV. CONCLUSION

In this paper, two high efficiency load modulation based PAs using Pi-QLI Class-E GaN transistors are presented. The higher harmonics are matched inside the RF package. The Doherty and Mixed-mode outphasing PAs are designed at 2.14 GHz using the Pi-QLI Class-E RF devices, implemented on 9.6mm IAF 0.25um GaN. Due to harmonic terminations of active device inside the RF package and load insensitive property of Class-E, both PAs achieve very high average efficiency and their power combining networks are very simple and compact. The measurement results after linearization with single carrier WCDMA signal with 7dB PAR shows that the Doherty PA can maintain average efficiency above 58.3% with -49dBc ACPR, while the Mixed-mode outphasing PA achieves 66.6% average efficiency with -51.6 dBc ACPR.

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