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Linearity Characterization of RF-input Chireix Outphasing Power Amplifier

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Abstract

This work demonstrates a complete Chireix system in which an analog signal component separator (SCS) is used to control the outphasing angle and amplitudes of the branch power amplifiers (PAs). The branch PAs are designed using load pull simulation as inverse class F amplifiers to obtain high efficiency. The branch PAs are directly connected to a signal combination network in one board to eliminate the phase error. The RF-input Chireix PA is demonstrated at 2.11GHz with peak output power 43.0 dBm and drain efficiency 73%.

Index Terms **– outphasing power amplifier, RF-input, RF-combiner, decomposer network, load pull, inverse class F amplifier.**

1. Introduction

Power amplifiers play an important role in various electronic systems, but consume a high proportion of the system's total energy. To reduce energy consumption by increasing efficiency, numerous PA structures have been introduced [1], for example Doherty, Envelope tracking, and Outphasing approaches. Among them, outphasing is an attractive approach to maintain high efficiency and linearity over a wide range of back-off output levels because this structure can employ non-linear PAs with high efficiency as its branch PAs. This feature makes outphasing PAs fit with the restrictive demands of various modern communication systems demanding high peak-to-average power ratio (PAPR).

The outphasing PA produces a variable-amplitude output by varying the outphasing phases of the RF inputs of branch PAs, which in turn modulates the PA load impedance. In conventional outphasing designs a digital SCS is used. The digital approach, however, is costly and complicated to implement. To replace this part, the RF-input outphasing approach was introduced in [2, 3] for 2- and 4-way outphasing systems with a non-isolating lossless RF combiner. In the previous experimental systems [2, 3], the branch PAs are based on a design intended for use in a Doherty amplifier [4]. Furthermore, the PAs and RF combiner are fabricated as separate PCBs, increasing loss and leading to uncertainty in the electrical length between the PAs and combiner.

In this work, a new experimental system is developed addressing the drawbacks of the connectorized system. The design of the RF power stage, comprising two inverse class F branch PAs and a power combining network, is described. Then, the completed RF-input outphasing PA is characterized using a two-tone test to evaluate its linearity and identify how linearity can be improved.

2. Experimental System design

In Figure 1, the complete outphasing system with two non-linear efficient PAs, combiner network, and RF-domain signal component separator is shown.

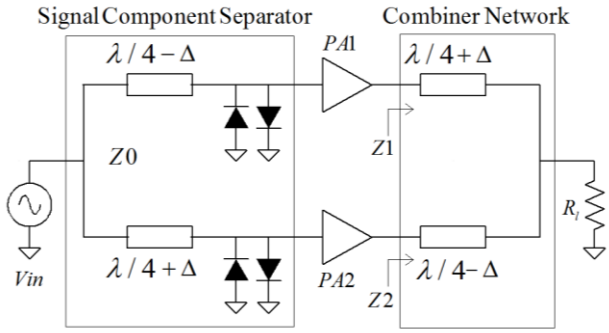

Figure 1. A complete RF-input Chireix PA block diagram with SCS, two high-efficiency PAs, and combining network.

First, the two inverse class F PAs are designed to obtain high efficiency. The fundamental load pull simulation for the Wolfspeed CGH40010F device is shown in Figure 2. The black line indicates the load impedance trajectory that connects the peak output power and peak PAE points. Because the combining network will present resistive load modulation (represented by the pink line in Figure 2), the output matching network is designed to match the black line trajectory down to the real axis. Note that this process is more complicated than for a conventional PA in which a single point, instead of a line, is matched.

To obtain high efficiency in the single PA, harmonic controls for the first three harmonics were used in both the input and output matching networks [5]. The second harmonic termination was found in simulation to have more impact on the output matching than third harmonic termination.

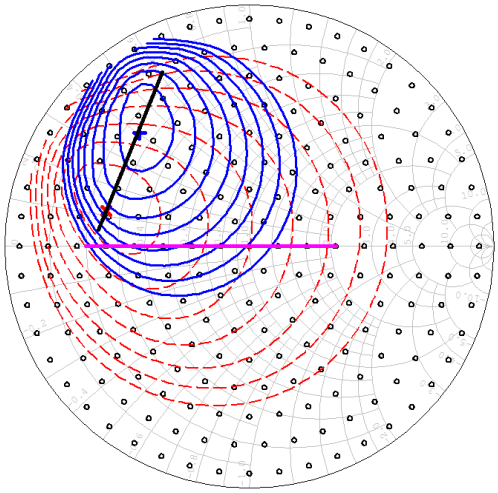

Figure 2. The original line (black line) between max PAE and max Pout and the new line (pink line) after rotating it to real axis.

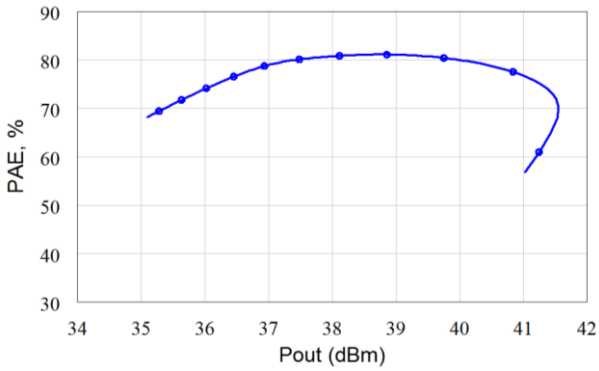

Figure 3. Simulated PAE versus output power, Pout, for a single branch PA at 2.14GHz when the load resistance is swept from 14 to 140 Ohms.

Figure 3 shows the simulated PAE when the load resistance of the branch PA is swept over 14 to 140 ohms. The PAE is at least 70% over a 6-dB output power range, corresponding to load impedance variation between 18 and 110 ohms. Based on this result, the combining network is designed to present this same range of load resistance.

The RF combiner is an ideally lossless network and can be implemented with lumped elements or microstrip-line [6]. In this work, the transmission line non-isolated lossless combiner will be design follow the principles in [6]. The output power at the load can be expressed as:

$$Pout \propto R_l.\sin^2\{\theta\}/(Z_0^2\sin^2\sigma) \qquad (1)$$

where θ is outphasing angle at two inputs, R_l is load impedance, Z_0 is characteristic impedance of transmission lines, and $\sigma = 2\pi\Delta/\lambda$. Combining the two PAs (PA1 and PA2) and the combiner network (Figure 1) in one board, the impedances Z1 and Z2, seen by the PAs are as shown in Figure 4.

Once the PAs and RF combiner are designed and combined with each other, the RF input can be designed based on the phase and impedances required to drive the PAs. The function of RF-input is that it converts amplitude modulation at the RF input signal into relative phase modulation among the inputs of the branch PAs. The RF input signal in the system is divided into two constant-envelope phase-modulated signals with the same envelopes but opposite phase. The RF signal decomposition network is designed following [2, 3] using HSMS286R diodes as the nonlinear elements, and tuned until the nonlinear behavior produced the desired impedance range of 18-110 Ohm. By integrating the two PAs and RF combiner are on one board, the effect on trajectory by cables or connectors will be eliminated or reduced compared to the previous work [2]. The RF input decomposition network and RF power stage are implemented on 30 mil RO3450B substrate with 1oz copper and dielectric constant $\varepsilon = 3.66$.

In the complete RF-input Chireix PA design with an RF input power level less than 20 dBm, pre-amplifiers after the decomposition network are needed to guarantee a sufficient RF input power level for the branch PAs. Here, two pre-amplifiers from Analog Devices, HMC457, are used.

The RF-input divides and synthesizes the RF input signals for the branch PAs through transmission lines and non-linear components diodes. The RF-input network generates two operating modes: first, with low RF input level at the input of the complete RF-input Chireix PA, the diodes are off and the resistance value, Rnl, is constant and depends on the fixed parallel resistance of the next stage. In this case, the outphasing phase is constant and this results in amplitude modulation but not in phase modulation of the branch PAs.

Second, when the RF input level of the complete Chireix PA is large, it goes beyond the threshold level of the diode, so the Rnl varies inversely proportionally with the RF input level. The relationship between Rnl and the outphasing phase, θ, can be described as in the equation (2) [2]:

$$\theta = a\tan(Z_0.\tan(\sigma)/Rnl) \qquad (2)$$

where Rnl is nonlinear resistance at output of RF-input.

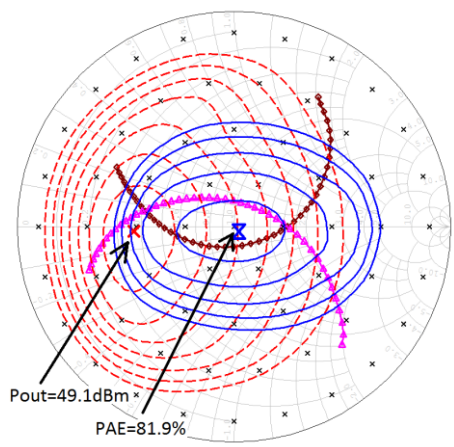

Figure 4. New positions of max PAE and Pout impedances (Pout – multiplication and PAE cone signs) and load trajectory at the combiner reference plan Z1, Z2. Blue and solid line is PAE with 5%/step and red and dash line is Pout with 1dBm/step.

3. Measurements

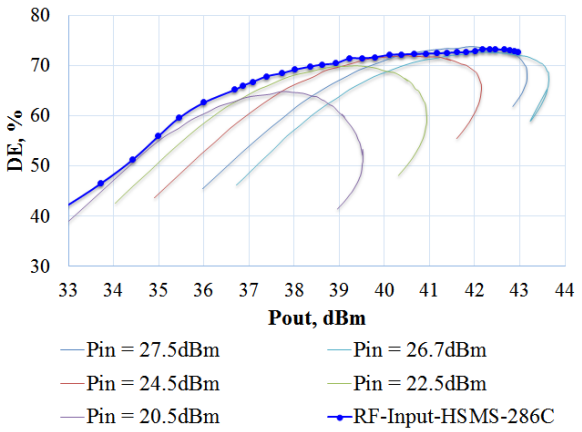

Figure 5. Measured drain efficiency (DE) of the two input signals (thin lines) and DE of the complete Chireix PA (thick line with dots).

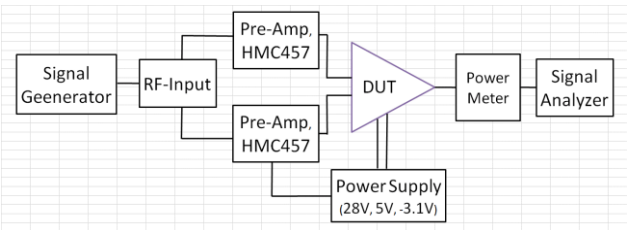

Figure 6. Block diagram of the measurement setup used to characterize the complete RF-input Chireix PA.

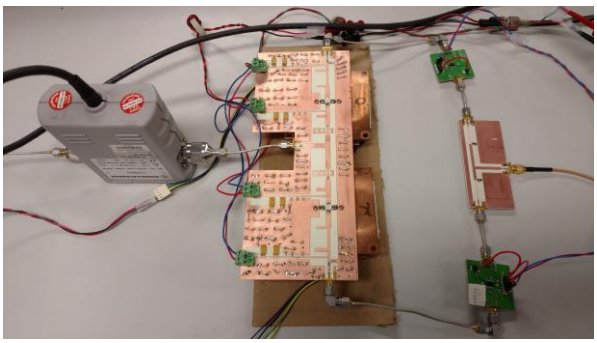

Figure 7. Photograph of the measurement setup for the complete RF-input Chireix PA.

Initially, the RF power stage was tested as a conventional, dual-input outphasing system. The PAs were biased at 27.5V and -3.1V at drain and gate, respectively. For the measurements, an SMJ 100A vector signal generator, ZHL- 42+ preamplifier, and a Wilkinson divider were used to generate, amplify, and divide an RF signal into two equal RF signals. At first, the RF input level was fixed and the outphasing angle was swept by using manually controlled phase shifters to modulate the output power. Next, the phase sweep was repeated while stepping the RF input power. The results are shown in Figure 5 with drain efficiency versus output power (thin lines).

Next, the measurements for single and two tones test of the complete RF-input Chireix PA were made using a SMJ 100A, the RF input decomposition network, two pre-amplifiers (HMC457) with gain at 2.11-2.17GHz = 24.5dB and RF power stage. A block diagram of the experimental setup is shown in Figure 6 and a photograph of the RF-input Chireix PA is shown in Figure 7.

The performance of the dual-input Chireix PA and the RF-input Chireix PA are compared in Figure 5. It can be seen that the RF-input decomposition network works as expected: it tracks the maximum value of the two RF-input Chireix system. The peak drain efficiency is 73% and it is maintained at higher than 60% over 7-dB back off range. Compared to the previous implementation in [3], the new system has a 5 percentage point improvement in peak drain efficiency and a 9 percentage point improvement at 6 dB back off.

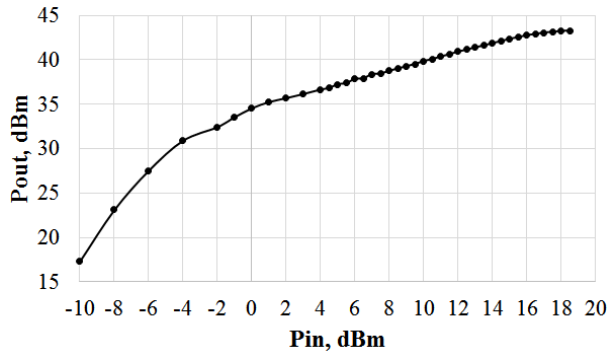

Figure 8. CW measurement of the whole Chireix PA showing Pout versus Pin.

The AM-AM characteristic in Figure 8 shows two regions of operation: first, when Pin is below -4 dBm the RF input works as power divider, in which the outphasing angle is constant. Above that input power level, the RF-input decomposition network converts the phase- and amplitude-modulated RF signal into two phase-modulated signals.

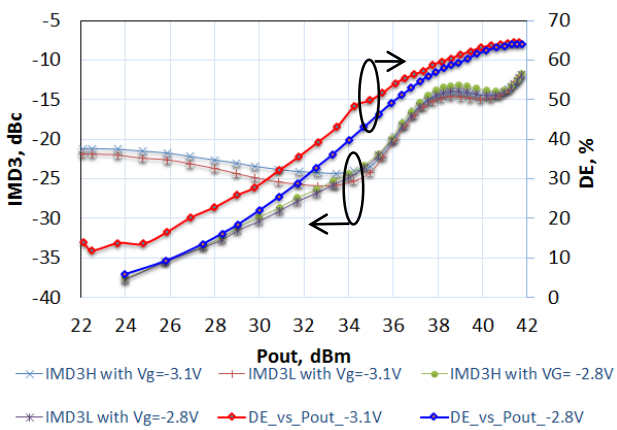

Figure 9. Drain efficiency, IMD3 (IMD3H – IMD3 above and IMD3L – IMD3 below carries tones) versus output power of the complete RF-input Chireix PA at 2.11GHz with different Vg= -2.8V and -3.1V.

In addition to demonstrating increased efficiency compared to a connectorized implementation [3], a goal of this work is to perform a linearity analysis of the complete

RF-input Chireix PA, to act as a basis for improvement in future work. Therefore, a two-tone test was performed under different gate bias conditions to understand the linearity of the system.

The two tones test results of the Chireix PA at frequency of 2.11GHz with different gate voltages at Vg=-2.8V and Vg = -3.1V are shown in Figure 9. It can be seen from the graph that, at output power less than 36dBm, the IMD3s are better than -20dBc, and at the Pout equal to 36dBm the average DE is higher than 50% for both the two gate voltages. In addition, below that output level, there is a trade-off between efficiency and linearity: when Pout is less than 36dBm, the average DE at Vg = -3.1V is better than DE at Vg = -2.8V, the IMD3 at Vg = -3.1V, however, lower than IMD3 at Vg=-2.8V.

4. Conclusions

This work describes the design of an RF-input Chireix PA with a single-board RF power stage. The performance of the RF power stage is compared when operated as a conventional dual-input PA and with the RF signal component separator. It is shown that the RF SCS tracks both phase and amplitude appropriately for high back-off efficiency. Then, the linearity of the system is evaluated using a two-tone test at different bias conditions. Future work will focus on linearity improvement.

5. References

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