A 5.8GHz, 47% Efficiency, Linear Outphase Power Amplifier with Fully Integrated Power Combiner

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***Abstract* — This paper presents an outphase power amplifier, consisting of two class-E power amplifiers and a power combiner. Using shielded coplanar striplines, the first low-loss, fully integrated 5.8 GHz Wilkinson combiner is realized with excellent isolation for a robust outphase PA. The outphase power amplifier, fabricated in IBM 7WL SiGe BiCMOS, achieves a peak efficiency of 47% at the maximum output power of 18.5dBm. For an Orthogonal Frequency Division Multiplexing input signal of 32 sub-channels of 64-QAM, the adjacent channel power leakage ratio is better than 32dBc.**

***Index Terms* — Chireix, LINC, power amplifiers, power combiner.**

I. Introduction

A tradeoff exists between efficiency and linearity in conventional power amplifiers (PAs). Switching class PAs, such as class-D, -E, and -F, are very efficient, but highly non-linear [1]. On the other hand, conducting class PAs such as class-A, -B, and -C are highly linear but are very inefficient [2]. Modern wireless communication systems often employ intricate modulation schemes such as Orthogonal Frequency Division Multiplexing (OFDM) with multi-channel Quadrature Amplitude Modulation (QAM) in order to maximize bandwidth efficiency. Such modulation results in amplitude- and phase-modulated signals with large peak-to-average power ratios (PAPR) that require power amplifiers with extremely good linearity. In addition, by often accounting for more than half the transceiver power budget, high efficiency power amplifiers are crucial to long battery life and manageable heat dissipation. Linear amplification using nonlinear components, or LINC, overcomes the efficiency-linearity tradeoff by enabling the use of high efficiency, non-linear power amplifiers for linear systems [3].

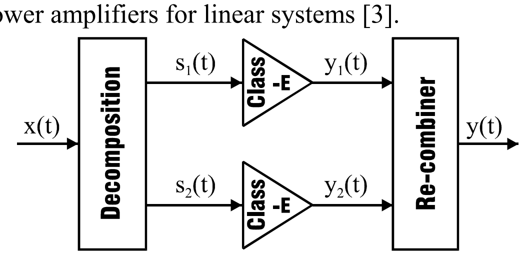

Fig. 1. LINC Principle Diagram

Fig. 1 describes the general principle of LINC. An amplitude-modulated signal $x(t)$ is first decomposed into two signals $s_1(t)$ and $s_2(t)$ that can be amplified using two highly efficient, non-linear power amplifiers. The PAs' outputs, $y_1(t)$ and $y_2(t)$, are then recombined to yield $y(t)$ for transmitting. Three conditions have to be satisfied for LINC to simultaneously achieve high efficiency and good linearity.

First, in order to employ highly efficient, non-linear switching power amplifiers, the two decomposed signals $s_1(t)$ and $s_2(t)$ can not have amplitude modulation. Second, since the overall efficiency is directly proportional to the efficiency of the recombiner, the decomposition function has to be such that its inverse function, the recombination, can be efficiently implemented. Third, for linearity, the decomposition and recombination functions must have the overall input-output characteristic close to,

$$y(t) = G \cdot x(t). \tag{1}$$

where G is the gain of the constituent power amplifiers.

One method of decomposition is outphase amplifying, which was originally proposed by Chireix in 1935 [4]. An amplitude-modulated signal can be represented as a sum of two constant-amplitude, phase-modulated signals according to the simple identity,

$$\begin{aligned} &a(t)\cos(\omega t + \theta) = \\ &\frac{A_{\max}}{2}\cos(\omega t + \theta + \phi) + \frac{A_{\max}}{2}\cos(\omega t + \theta - \phi) \end{aligned} \tag{2}$$

where $\phi(t) = \cos^{-1}\left(\frac{a(t)}{A_{\max}}\right)$ and $A_{\max} = \max|a(t)|$

Theoretically, the decomposition is an amplitude-to-phase mapping that results in two constant-amplitude signals, enabling the use of high efficiency switching power amplifiers. The recombiner is simply the addition of the two power amplifiers' outputs. An ideal recombiner fully restores the original amplitude-modulated signal, resulting in an overall outphase power amplifier with

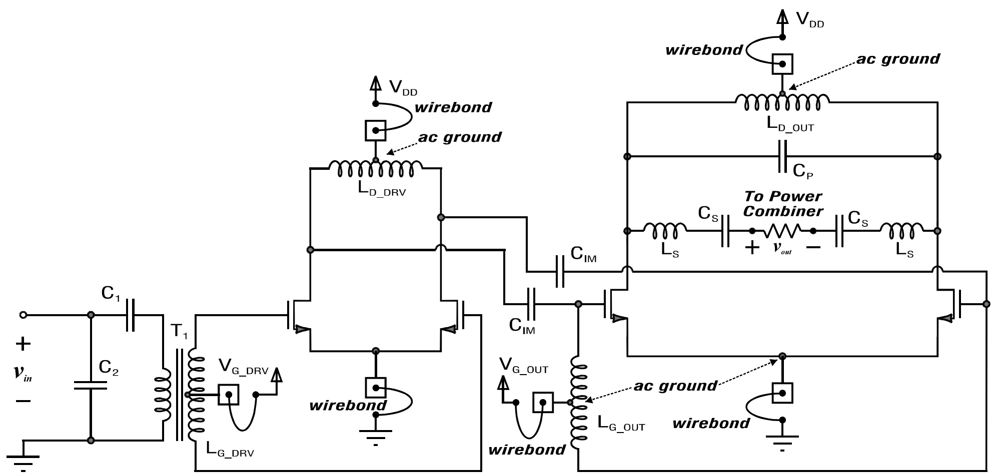

Fig. 2. Two-Stage Differential Class-E Schematic

theoretically perfect linearity. In practice, the biggest challenge of the outphase amplifying concept is the accuracy of the overall signal decomposition and recombination process, which includes the amplitude-to-phase mapping, the power combiner, and the matching between the two outphase signal paths. The overall accuracy determines the outphase power amplifier's linearity.

Another implementation challenge is the fully integrated low-loss recombiner for the best overall efficiency. A popular implementation is the "Chireix combiner", which uses readily available inductors, capacitors, and transformers [5]. However, the Chireix combiner can only be tuned for a very small range of the outphase angle ϕ. For outphase angles outside this range, isolation between the two PAs outputs is poor, resulting in significant distortion that degrades the overall linearity [6]. For a robust outphase PA, complete isolation is required between the two inputs.

A digital outphase decomposition has been reported in [7], taking advantage of the digital computational power to achieve the required accuracy and efficiency.

This paper presents a fully integrated 5.8GHz, 18.5dBm outphase PA consisting of two class-E PAs and an on-chip Wilkinson combiner that allows efficient recombining while providing the necessary input isolation. The outphase PA's performance is demonstrated in an OFDM system with 32 channels of 64-QAM. The outphase PA achieves higher average efficiency than other excellent linear PAs.

The rest of the paper is organized as follows. The differential class-E power amplifier and Wilkinson combiner designs are described in Section II and III. Measurement setups are described in Section IV, followed by measurement results in Section V and conclusion in Section VI.

II. Differential Class-E Design

The class-E topology is chosen for the simplicity of its load network. A differential configuration is used to take advantage of virtual grounds and avoid large ground-wire inductors that could limit voltage swings and degrade efficiency. A schematic of the two stage design is shown in Fig. 2. To minimize the die area, the two supply inductors L_{D_OUT} and L_{D_DRV} employ differential intertwined center-tapped design. In order to reduce the effect of the gate capacitance, a shunt inductor with a low-loss, low-impedance ground connection is chosen to resonate at the signal frequency. The differential configuration creates the required virtual ground at the center tab of the gate inductor L_{G_OUT}, which also serves as the gate bias connection. The differential gate inductor L_{G_DRV} of the driver stage is realized as part of an input transformer that transforms the differential PA input to a 50Ω single-ended signal. All differential inductors and transformers are modeled using Sonnet Suites, an EM simulator. Depending on the inductor value, a Q-factor between 18 and 25 is obtained from simulation. The class-E amplifier requires a 12Ω differential load, which is provided by the input of the power combiner in the next section.

III. Fully Integrate Wilkinson Power Combiner

A Wilkinson combiner consists of two λ/4-length coplanar striplines and a cross-input resistor. As described in the cross-sections of Fig. 3, the striplines are placed on the top thick metal while minimum-width floating metal strips are positioned underneath and perpendicular to the striplines at minimum spacing along the entire length of the striplines. The lower floating metal strips serve two purposes. First, they shield the striplines from the lossy Si-substrate, reducing substrate-coupling loss. Second, by concentrating the electric field between the two conductors of the striplines, the shields increase the

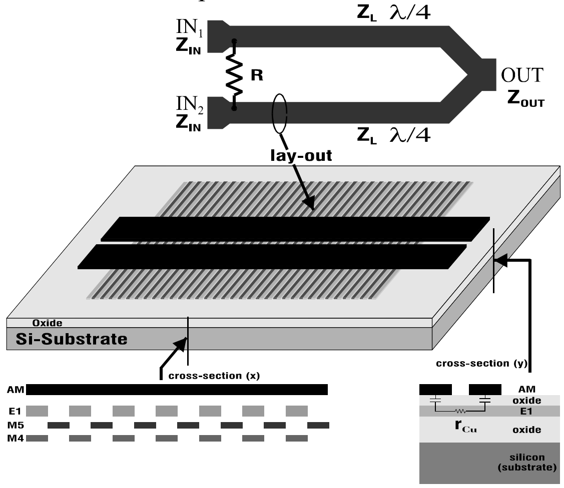

Fig. 3. Wilkinson Combiner and its Shielding Layout

striplines' effective capacitance per unit length, which in turn reduces the size of the striplines for a given frequency. Additional shields can be repeated using other metal layers. Metal strips on adjacent layers are interleaved for better shielding.

The characteristic impedance of the stripline is given in (3), with Z_{OUT} is the antenna load, and Z_{IN} is the load required by the two class-E PAs.

$$Z_L = \sqrt{2 Z_{IN} Z_{OUT}} = 34.6\Omega . \tag{3}$$

Using the metal shield technique, the λ/4-length of a coplanar stripline with the above characteristic impedance is 2.8mm or 25% shorter than an unshielded stripline. An input isolation of -35dB is achieved at the 5.8GHz frequency, while the input-to-output response is -4dB.

Fig. 4. shows the die photo of the outphase power amplifier's test chip consisting of two class-E PAs and an integrated Wilkinson power combiner.

IV. Measurement Setups

The test chip is mounted and wire-bonded directly onto a printed circuit board (PCB). In order to measure the outphase PA overall performance in a multi-channel OFDM system, the two outphase signals $s_1(t)$ and $s_2(t)$ (referring back to Fig. 1) are required to provide the inputs to the outphase PA. This can be done using two signal generators. Given a test signal in the form of a digital series $x[n]$, the two equivalent outphase series $x_1[n]$ and $x_2[n]$ are calculated using Matlab.

With additional manipulations for compatibility purposes, the two outphase series are imported into the signal generators, which then generate the two outphase input signals to the test chip.

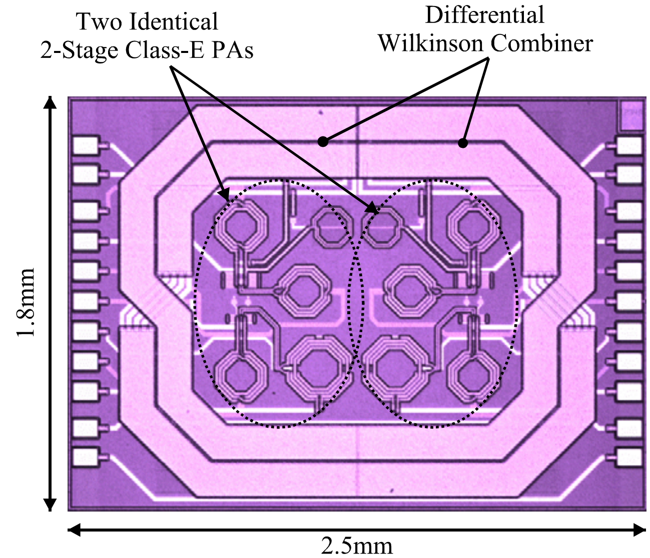

Fig. 4. Die Photo (IBM 7WL SiGe BiCMOS)

The correct timing between the two signal generators is guaranteed using 10MHz and 1MHz clocks for RF carrier and symbol synchronization, respectively.

In addition, to verify that the combiner reproduces the correct signal intended for transmitting, the outphase PA's output is fed into a custom-built receiver capable of receiving and decoding multi-channel OFDM/QAM signals. A QAM diagram of the actual transmitted signal is obtained from the receiver to evaluate the outphase power amplifier's performance.

V. Measurement Results

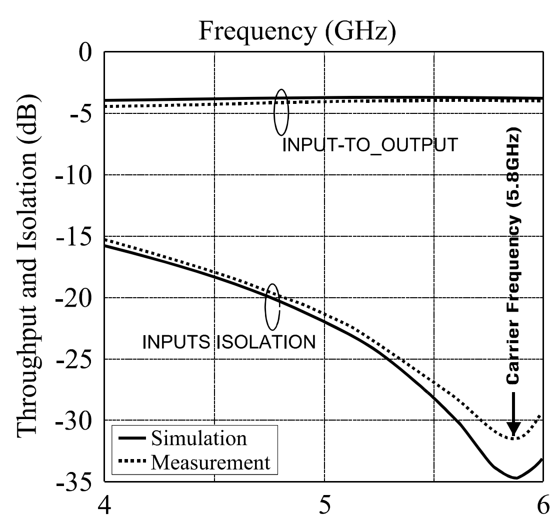

Fig. 5. Integrated Power Combiner S-Parameters

The class-E PAs and the power combiner are first measured separately to characterize their individual performance. At 1.3V supply voltage, each class-E PA has an output power of 16.5dBm at 57% efficiency. The combiner measurement is included in Fig. 5, showing 1dB insertion loss and more than 30dB input isolation.

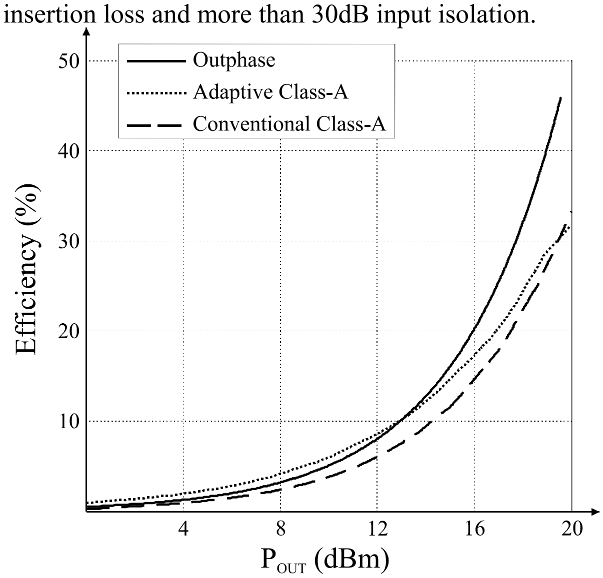

Fig. 6. Efficiency Comparison

Overall, the outphase PA achieves an efficiency of 47% at the maximum output power of 18.5 dBm. For lower output power, efficiency decreases due to dissipated power in the combiner's resistor. However, compared to a conventional and an adaptive class-A PAs with similar linearity performance [8,9], the outphase PA is generally much more efficient as shown in Fig. 6. For an OFDM input of 32 sub-channel of 64-QAM, the adjacent channel power leakage ratio (ACPR) is better than -32dBc as plotted in Fig. 7(a). Using the custom receiver, a QAM diagram of the transmitted signal is plotted in Fig. 7(b), showing the excellent accuracy performance of the outphase PA.

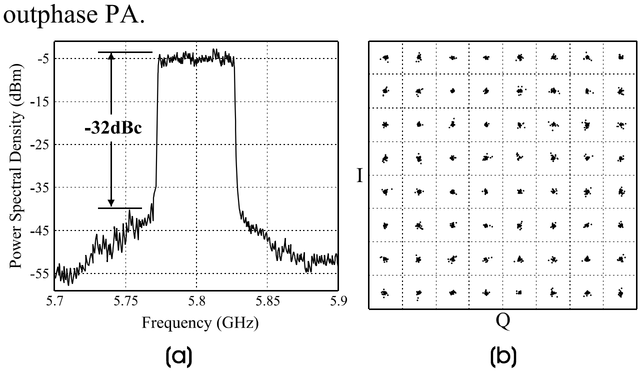

Fig. 7. (a) Linearity (ACPR) (b) Transmitting IQ Diagram

VI. CONCLUSION

The outphase amplifying technique's place in modern wireless communication has been proven in this investigation. The outphase power amplifier achieves 18.5dBm output power at 47% efficiency, with -32dBc ACPR for an OFDM input signal of 32 sub-channels of 64-QAM . By carefully designing the Wilkinson power combiner using coplanar striplines with metal shielding, the first 5.8GHz fully integrated differential Wilkinson combiner is realized. The low-loss integrated combiner allows efficient outphase recombining while providing the necessary input isolation for a robust outphase power amplifier.

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REFERENCES

[1] Steve Cripps, *RF Power Amplifiers for Wireless Communications*, Artech House, 1999, pp 47-50.

[2] [1] Behzad Razavi, *RF Microelectronics*, Prentice Hall, 1998, pp 302-313.

[3] D. C. Cox, "Linear Amplification with Nonlinear Components", *IEEE Transactions on Communication*, vol.COM-22, pp. 1942-1945, 1974.

[4] Chireix, H. "High Power Outphasing Modulation", *Proc. IRE*, Nov. 1935.

[5] Sotoudeh Hamedi-Hagh, C. Andre T. Salama, "A 1V, 8GHz CMOS Integrated Phase Shifted Transmitter for Wideband and Varying Envelope Communication Systems", *IEEE Custom Integrated Circuits Conference*, San Jose 2003, pp. 447-450.

[6] G. Poitau et al., "Experimental Characterization of LINC Outphasing Combiners' Efficiency and Linearity", *IEEE Radio and Wireless Conference*, September 2004, pp. 87-90.

[7] A. Pham, "Outphase Power Amplifiers in OFDM Systems," *Ph.D. Dissertation*, EECS Dept., MIT, Cambridge, MA, October 2005.

[8] S. Luo and T. Sowlati, "A Monolithic Si PCS-CDMA Power Amplifier with an Impedance-Controllable Biasing Scheme", *IEEE Radio Frequency Integrated Circuits Symposium*, pp 217-220, May 2001.

[9] [12] A. Pham, and C. G. Sodini, "Adaptive Biasing Technique for Linear Power Amplifiers", *TECHCON*, Dallas, TX, August 25-27, 2003.