A 20.5 dBm Outphasing Class-F PA with Chireix Architecture at 3.5 GHz for RF Transmitter Front-end

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Abstract. An outphasing class-F power amplifier (PA) with Chireix architecture is presented in Global Foundry (GF) 0.13µm Complementary Metal Oxide Semiconductor (CMOS) technology. The proposed circuit is composed of two branch class-F PA and Chireix power combiner with a floating load. The designed outphasing amplifier can provide 20.5 dBm output power from 1.8 V power supply at 3.5 GHz with 52.9 % power added efficiency (PAE). Wideband Code Division Multiple Access (W-CDMA) signal is implemented as input signal to simulate ACPR and the adjacent channel leakage ratios (ACLRs) at ±5 MHz are -20.5 dBc/-20.7 dBc. After DPD (Digital Pre-Distortion) ACLRs can achieve -44.5 dBc/-44.7 dBc at ±5 MHz. Furthermore, the chip area including testing pads is 1.98*1.62 mm².

1. Introduction

Modern wireless communication systems require high data rate, efficient spectrum utilization, necessitate low cost and power efficient solutions with high level of integration. There is a growing interest in integrating RF power amplifier (PA) in CMOS technology. Traditional linear PAs lose efficiency with power back-off for modulated signals with very high peak-to-average power ratio (PAPR). In order to solve these problem, single-branch and multi-branch PAs are proposed by researchers. Such as Envelope Elimination Restoration (EER), Envelope Tracking (ET) [1], Doherty [2] and Outphasing amplifiers [3]. Outphasing amplifier, as a PA with high efficiency and linearization and high-speed digital or analog signal processing, has become the key point of academic attention [4]. In this paper, a multi-branch class-F outphasing PA with passive non-isolated combiner is proposed which improves efficiency at 3.5 GHz. The combiner is designed to expand the operating frequency of outphasing PA system. The com-
pensating elements are selected in order to cancel the imaginary part of load modulation for 50 MHz operating frequency band centered around 3.5 GHz.

The paper is organized as follows, Section 2 introduces the outphasing theory and the Chireix combiner. In Section 3, we described the implementation of the Outphasing amplifier. The simulation result and analyzes are presented in Section 4, with conclusions following in Section 5.

2. Outphasing Theory and Chireix Combiner

The architecture of outphasing with a floating load-based Chireix combiner is demonstrated in Figure 1. And Figure 2 shows the conventional combiner and the combiner that we proposed.

2.1. The Traditional Outphasing Theory

Outphasing PA system [3], as shown in Figure 1. The input signal can be expressed as:

\[ S(t) = a(t) e^{j\theta(t)}, \quad 0 \leq a(t) \leq V_m \]  

(1)

This structure includes amplitude and phase modulation [i.e. \( a(t) \) and \( \theta(t) \)], where \( V_m \) is the maximum amplitude of \( S(t) \), is decomposed [by a signal component separator (SCS)] into two constant-envelope phase-modulated signals:

\[ S_1(t) = S(t) - e(t) = V_m e^{j[\theta(t) - \varphi(t)]} \]  

(2)

\[ S_2(t) = S(t) + e(t) = V_m e^{j[\theta(t) + \varphi(t)]} \]  

(3)

in which

\[ \varphi(t) = \cos^{-1} \left[ \frac{a(t)}{V_m} \right] \]  

(4)

\[ e(t) = j S(t) \sqrt{\frac{V_m^2}{a^2(t)} - 1} \]  

(5)

where \( \varphi(t) \) is the dynamic outphasing angle. The two signals \( S_1(t) \) and \( S_2(t) \) are separately amplified.
Figure 2: (a) With single compensation components, (b) With double compensation of components.

Figure 3: Circuit schematic of the proposed outphasing class-F PA with chireix structure.

2.2. The Design of Chireix Combiner

Figure 2 (a) illustrates the conventional chireix combiner structures with single compensation components. All of these structures use inductor $L_c$ and capacitor $C_c$ to compensate for phase-varying reactance when the two branches are different in phase. Therefore, PAs can acquire
maximum efficiency when the outphasing angle $\phi$ of two branches signal are offset each other. And the values of inductance and capacitance can be derived as [5]

$$C_c = \frac{\sin 2 \phi}{R_L \omega_0}, L_c = \frac{R_L}{\omega_0 \sin 2 \phi}$$ (6)

However, the angle $\phi_1$ from $PA_1$ and $\phi_2$ from $PA_2$ do not eliminate with each other in actual circuit test. To offset excess phase angle, double compensation of components structure is proposed in Figure. 2 (b).

3. Circuit Implementation

Figure. 3 depicts the circuit schematic of the proposed outphasing amplifier using the LC compensation Chireix combiner. Notice that two stage class-F PA provide different outphasing angle to achieve high efficiency and bandwith at both peak and back-off power levels [6]. In addition, $C_1$, $L_1$ and $C_8$, $C_8$ are the input and output resonant network. And $L_A$, $L_B$ are added into Chireix combiner to achieve outphasing angle offset each other of two branch of the PA.

4. Simulation Results and Analysis

In order to facilitate the simulation, this work plans to use PC software of MATLAB to generate digital W-CDMA data stream and then gets through DAC module to produce I/Q signals as system base-band signals. Figure. 4 shows the block diagram of simulation processing scheme. The output power and power gain with respect to input power are described in Figure. 5 for proposed outphasing amplifier. This figure manifests that the outphasing amplifier achieves 20.5 dBm peak output power with a 1.8 V power supply. Meanwhile, the 34 dB of power gain is presented when the input power is below -15 dBm. Since the proposed PA is based on the structure of the combiner, the input matching parameter $S_{11}$ and $S_{11}$ of the amplifier is considered as shown in Figure. 6. It is clear that $S_{11} = -6.5$ dB and $S_{22} = -11.8$ dB.
at 3.5 GHz frequency point. Consequently the input and output matching also realizes better matching results. Figure 7 shows that the stability factor always $K > 1$, that is, the PA is absolutely stable at 3.5 GHz frequency point. Figure 8 illustrates that the single side branch PA achieves peak PAE of 52% and maximum outphasing PAE of 52.9% with peak output power of 20.5dBm with chireix combiner. Furthermore, the output spectrum for PA is provided in Figure 9. Experimental verification is performed by two independent in-phase/quadrature (I/Q) modulating signal which are generated by MATLAB software. In this simulation experiment, pre-distortion and non-pre-distortion linearization technique are carried out respectively on PA circuit system.

Figure 6: S parameters of the proposed power amplifier.

Figure 7: K factors of the proposed power amplifier.
The designed outphasing PA is simulated with 5 MHz W-CDMA signal. Simulated lower/upper adjacent channel power ratio levels are -20.5 dBc/-20.7 dBc at 5 MHz offset from the carrier center frequency. After DPD technique of linearization, lower/upper adjacent channel power ratio levels are -44.5 dBc/-44.7 dBc and the ACPR improvement of 20/20 dB. These result indicate that the system has good linearization and less adjacent channel leakage. In the end, the layout of proposed outphasing amplifier is presented in Figure. 10, which occupies a chip size of 1.98*1.62 mm². Table 1 makes a comparison with published outphasing PA, including various signal modulation, as well as the performance of different processes. Because of the compromise, this work is still very advantageous which is based on the summary of the Table 1.

Figure 8: Power added efficiency for single side and outphasing power amplifier.

Figure 9: PA output spectrum at 3.5GHz with and without DPD technique.

Figure 10: The layout of the proposed outphasing class-F PA with Chireix structure. The total chip size is 1.98*1.62 mm²
Table 1: Performance comparison

| Ref | Pout (dBm) | PAE (%) | VDD (V) | Gain (dB) | Die Size (mm²) | f₀ (GHz) | ACPR (dBc) | Modulated signal | Technology |
|-----|------------|---------|---------|-----------|---------------|----------|------------|-----------------|------------|
| [7] | 20         | 42      | 1.8     | N/A       | N/A           | 0.81     | -45/-45    | CDMA            | 0.18µm     |
| [8] | 25.2       | 40      | 2.5     | N/A       | 1.08          | 0.8-2    | -46/-46    | WCDMA           | 0.13µm     |
| [9] | 27.7       | 45      | 2.5     | N/A       | 4             | 2.4      | N/A        | OFDM            | 65nm       |
| [10]| 29.5       | 46.7    | 2.4     | N/A       | N/A           | 2.4      | -51.08/-50.4| LTE             | 45nm       |
| [11]| 20         | 56      | 2.5     | N/A       | 1.72          | 0.9      | -50/-50    | WCDMA           | 90nm       |
| Ours| 20.5       | 52.9    | 1.8     | 34        | 3.2           | 3.5      | -44.5/-44.7| WCDMA           | 0.13µm     |

5. Conclusion

This paper presents a 0.13µm class-F outphasing PA with a non-isolated combiner, the outphasing PA based on lumped components and that also helps to improve the efficiency at back-off area. This structure can effectively overcome the problem of efficiency degradation when power is backed up. And this task achieves a peak power of 20.5 dBm, 52.9 % PAE. By comparison, the results have more advantages than other equivalent circuits and indicate the potential of the approach. Although further effort is required to linearize the input and output and PAE of the amplifier. Circuits design for improved linearity and PAE will be focused in the future paper.

6. References

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