A Highly Efficient Chireix Amplifier Using Adaptive Power Combining

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***Abstract* — A novel, highly efficient out-phasing amplifier with adaptive power combiner is presented. Saturated class-F operation is used for the amplifier cells. Varactor tuning is applied to make the output power combining network adaptive. Use of optimum input drive conditions and output varactor tuning, to eliminate imaginary loading introduced by the out-phasing principle, yields an amplifier efficiency of more than 50% over a 9 dB power back-off range.**

***Index Terms* — Power amplifier, high efficiency, LINC, Chireix, out-phasing, adaptive matching, varactor.**

I. Introduction

Power amplifiers (PAs) for handsets are still considered as the primary consumers of DC battery power. Therefore, improving PA efficiency is considered to be essential for extending the battery lifetime of a handset. This fact has motivated intensive PA research at both the device, as well circuit level. As a result, over the last years, high-performance (inv)class-AB, class-E, (inv)class-F amplifier implementations have been reported in literature with efficiencies approaching 80% for their peak output power operation. Unfortunately, the efficiency of these amplifiers has a strong dependence on the (RF-voltage swing / DC-supply voltage) ratio at the output terminal of the active device. As a result, the efficiency drops rapidly when the RF voltage swing decreases when the PA is backed-off from gain compression [1]. For this reason, most PA efficiency enhancement techniques focus on increasing the RF-voltage / DC-supply voltage ratio by load or supply voltage modulation. Although, very good results have been reported using these methods, there are still practical drawbacks. E.g. load-modulation requires very linear high-Q tunable capacitances and has limitations in the impedance control range that can be achieved. Supply-voltage modulation requires a fast, as well highly efficient DC-DC converter, which should not introduce switching noise in the output signal to be transmitted.

In this work, we aim to avoid the drawbacks of the methods above and improve amplifier efficiency in power back-off by combining out-phasing [2], with adaptive matching techniques [3]. Although, the basic idea of this concept has been recently proposed [4][5], to our best knowledge, no practical implementation has been reported up to date.

In this paper, Section II discusses the principles of operation, Section III gives the practical implementation of the out-phasing amplifier with adaptive power combiner and discussion of the efficiency constraints related to losses in the adaptive combiner. Finally we conclude in Section IV and V with simulated and measured results that demonstrate the efficiency improvements over the classical Chireix operation.

II. Theory

Out-phasing is quite a well known technique that has been originally proposed to increase the linearity of transmitting amplifier stages [2]. In its basic implementation, an amplitude modulated input signal is converted into two anti-phase, phase-modulated signals with constant amplitude. By feeding these signals to two, highly efficient (but not necessarily linear) amplifiers with their outputs connected to a passive power combiner, the amplified version of the original input amplitude modulated signal is recovered [2]. The block diagram of an out-phasing transmitter is shown in Figure 1.

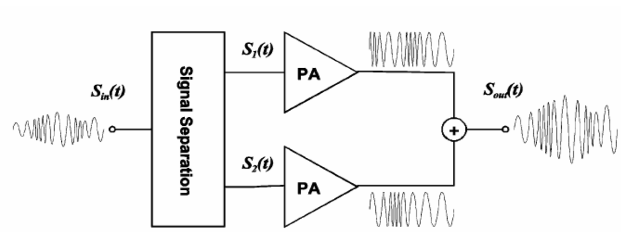

Fig. 1. shows a conventional out-phasing transmitter.

The power combiner needed to sum the signals of the amplifier cells, is one of the most important parts in the out-phasing amplifier concept. Chireix proposed a non-isolating power-combiner for an out-phasing transmitter to increase the efficiency [2]. The principle circuit diagram of an out-phasing transmitter is shown in the Figure 2, which we will use for our discussion.

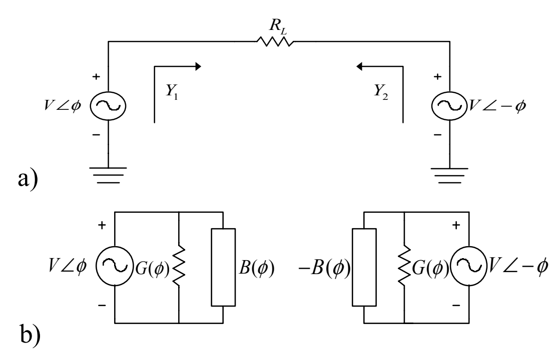

Fig. 2 a) Principle circuit diagram of an out-phasing transmitter with non-isolating power combiner. b) Complex loading conditions as seen by the active devices due to out-phasing load modulation.

In this circuit diagram, the output of the active devices behaves like a perfect voltage source, something that can be approximated in practice by saturated class-AB or class-F operation [1]. Note that in this configuration the load of the active devices (voltage sources) is modulated by the output voltage of the other device. As a result, both devices will experience a complex load that varies with the out-phasing angle (Fig. 2b) and eq. (1).

$$G(\phi) = \frac{2\sin^2(\phi)}{R_L} \quad , \qquad B(\phi) = \pm j\frac{\sin(2\phi)}{R_L} \qquad (1)$$

Note that the active devices will experience opposite susceptances as indicated by '±' sign (ϕ is the out-phasing angle). The resulting normalized conductance and susceptance are plotted in Fig. 3. In this figure, it is shown that conductance starts at 0 for a zero out-phasing angle and increases to 1 for an out-phasing angle of 90 degrees. Consequently, the current fed into the load by the voltage sources, increases with out-phasing angle.

In the basic Chireix amplifier approach, the active devices always operate with maximum output voltage swing, suggesting that maximum efficiency is achieved at all times. Unfortunately, besides the desired varying conductance, also varying susceptances are present at the output terminal of the active devices. These susceptances cause a phase shift between the device voltage and current wave, thus decreasing the efficiency. To improve for this situation, Chireix proposed to compensate these fictitious susceptances, by adding fixed susceptances with an opposite sign. As a result the susceptance at the output of a transistor stage is zero at two specific out-phasing angles (Fig. 3a), yielding high efficiency at these points (Fig. 3b).

Although the approach by Chireix is a big improvement over the classical out-phasing amplifier, it has practical limitations which degrade its efficiency performance in (far) power back-off conditions, namely:

- The susceptance is compensated only at two specific out-phasing angles. Therefore the average efficiency of the transmitter is much lower than the peak efficiency due to the uncompensated susceptance at the low and mid power levels where the conductance is small
- When the input drive power is taken constant, the power gain drops when the effective output power is reduced by out-phasing. As a result the power added efficiency (PAE) of the transmitter drops drastically under these conditions (see Fig.3b PAE curve, angle=10°).

For the reasons above, practical Chireix amplifier implementations exhibit typically much lower efficiency then what would be expected based on their operation principles.

To overcome these limitations, in this work we extend the classical Chireix amplifier concept with adaptive susceptance compensation. In this approach, the otherwise fixed compensation susceptances are now implemented as tunable resonators, which can compensate the undesired imaginary loading conditions resulting from out-phasing at each out-phasing angle. This enhancement results in a very high efficiency over a wide range of power back-off levels. This is also illustrated in Figure 3, where the dashed straight line indicates the situation when the undesired susceptances are continuously compensated by the adaptive output power combing matching network. In addition to this adaptive compensation we also will use reduced input power for the amplifier stages when operating in power-back-off, something that will be beneficial to the PAE as well.

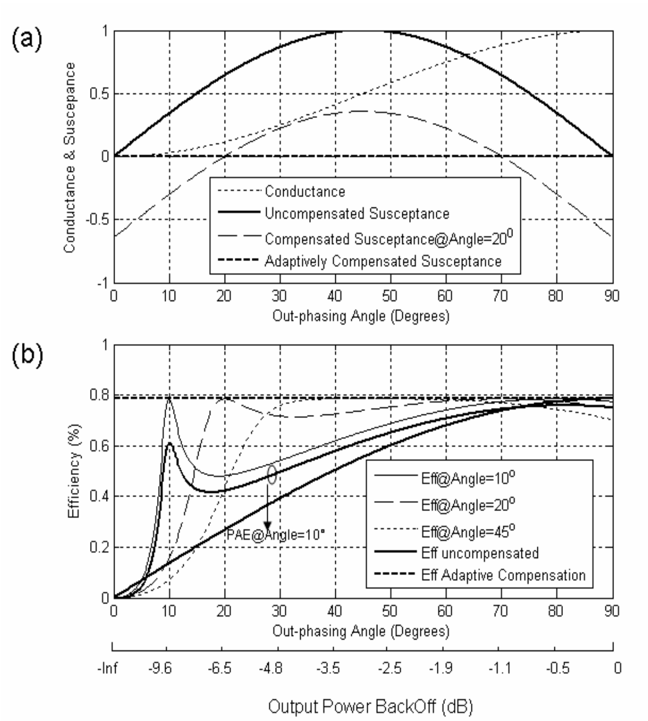

Fig. 3 a) Conductance and susceptance as seen by the active devices and b) efficiencies in a non-compensated and compensated Chireix amplifier assuming ideal class-B operation.

III. Circuit Design

A prototype Chireix amplifier with adaptive output power combing network is implemented as a hybrid. Figure 4a shows its simplified circuit diagram. The design frequency is 870MHz and the aimed maximum output power is 27dBm.

Power Amplifier Cells

The amplifier cells are based on a pair of matched SiGe NXP QUBiC transistors. To achieve a voltage source like behavior of these devices, saturated Class-F operation was used [6]. The gain of these devices for this type of operation is high (>15 dB), while providing a collector efficiency > 70% (assuming a lossless output power combiner network).

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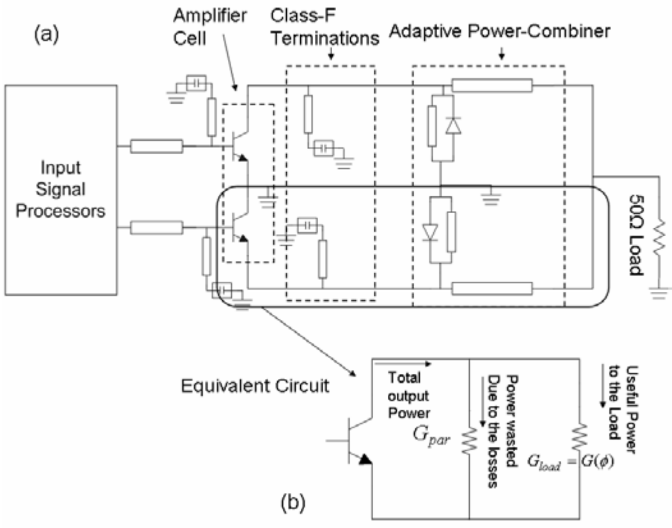

Fig. 4 a) Circuit of the implemented out-phasing transmitter with adaptive power combining network. b) Effective loading of the transistor stage, when the susceptances due to out phasing are compensated

Adaptive Output Power-Combiner Network

The hybrid power-combiner is implemented using two quarter-wave transmission lines. The electrical length of these lines is adjusted to compensate for the inductive bond-wire connection of the active devices. The line impedance is chosen such that the proper loading conditions are offered to the active devices. The resonators for the adaptive susceptance compensation are implemented by varactors (NXP BB149 varicaps) in parallel with an inductive transmission line stub. Care is taken to avoid forward biasing or breakdown conditions for these varactors under all RF drive conditions. Note that due to the power-combiner design, maximum output power for the amplifier occurs now at zero degree out-phasing angle, while minimum output power occurs at 90 degrees out-phasing angle. The proposed network is simple but effective, however its losses will restrict the out-phasing angle range over which efficiency enhancements can be achieved using this concept.

Practical Efficiency limitations

Until now, we have assumed that the compensating network is loss-less. Unfortunately, practical network elements have a limited quality factor (Q). As result the Q-factor of the inductor, the varactor and the losses related to the device parasitics of the transistor, will determine when the out-phasing principle becomes ineffective for improving efficiency. To study this limitation, we consider the simplified loading conditions of the active device (Fig. 4b), in which we have assumed that the susceptance has been properly compensated. As can been seen from Fig.4b, there will be a parasitic conductance G_{par} (representing the losses of the resonator and active device itself) in parallel with the desired loading $G_{(\ )}$ (see eq. (1)). Although, for a parallel resonator there are many combinations of L and C that can provide the desired compensating susceptance, the use of a practical varactor with a limited capacitance tuning range (r), will yield only one solution. Using this fact, G_{par} can be expressed in terms of the inductor and varactor quality factors (Q_L and Q_C) respectively, while G_{trans} represents the losses of the transistor.

$$G_{par} = G_{trans} + \left(\frac{r\omega C_{\min}}{Q_C} + \frac{1}{\omega L Q_L} \right), \; r = \frac{\left({\sin 2\phi}/{R_L} + {1}/{\omega L} \right)}{\omega C_{\min}} \quad (6)$$

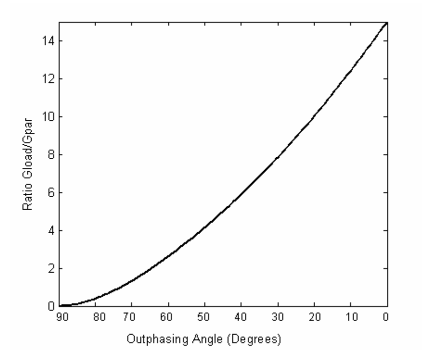

Fig. 5. Ratio desired load conductance / parasitic output conductance versus out-phasing angle.

It is obvious that the efficiency of the power amplifier is strongly dependent on the ratio of G_{load} and $G_{par,}$ e.g. if this ratio is 1, half of the output power will be dissipated in G_{par} reducing the aimed efficiency by half. Note that both conductances are dependent on the out-phasing angle. To study this, Fig. 5 shows the G_{load}/G_{par} ratio assuming an inductor and varactor Q of 30 (varactor capacitance tuning range $r = 5$). As can be observed the G_{load}/G_{par} ratio is strongly reduced at lower out-phasing angles and becomes close to 1 at 70^{o} out-phasing angle. In practice, this indicates the point where efficiency enhancement due to increased out-phasing will start to fail. This fact can be verified both by simulations and measurements as presented in the next sections.

IV. SIMULATIONS RESULTS

Fig. 6 illustrates the efficiency versus output power for the Chireix amplifier with adaptive power combiner. In these simulations, at each different out-phasing angle, the bias conditions of the varactor diodes have been optimized to obtain maximum peak efficiency. Within each curve, the out-phasing angle and the bias voltages on the diodes are kept constant, while the input power is varied. As indicated before, it can be observed, that at high out-phasing angles, which approach 70^{o} the maximum achievable efficiency is limited by the resonator losses (in this case Q~30) and the parasitics of the transistor. Overall, the adaptive Chireix concept provides a substantial improvement over conventional Chireix as can be observed in Fig 6, offering an efficiency > 50% over a 9 dB power back-off range. Note that by using out-phasing and dynamically varying the compensation susceptance, in

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combination with input power modulation for far back-off output power levels, a very efficient operation over a wide range of output power can be achieved. Consequently, Figure 6 shows the resulting curve for such an input drive condition, indicating the performance enhancement over a classic class-F operation, which is represented here by the 0 degree angle out-phasing
operation.

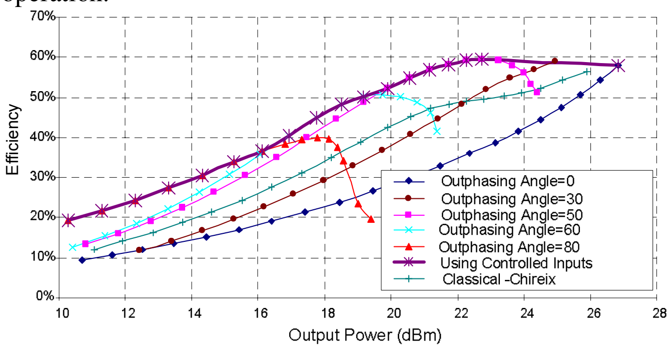

Fig. 6. Simulated efficiency versus output power for an input power sweep with different out-phasing angles

V. Measurements

To experimentally verify the Chireix amplifier with adaptive power combiner, two phase and amplitude controlled input signals along with the modulated bias signals for the varactor diodes are needed. To obtain these signals, we constructed the test setup of Fig. 7. In this setup the required RF signals are generated using a four channel arbitrary waveform generator and two IQ modulators. The resulting RF signals are pre-amplified by two amplifiers to obtain sufficient input power for the out-phasing transmitter. An additional high-voltage arbitrary waveform generator is used to generate the control voltages for the varactor diodes. The power and resulting spectrum is monitored by a spectrum analyzer. Note that this setup, by synchronization of the AWG's and coherent up-conversion, not only can perform static testing, but also facilitates dynamic modulation of the adaptive power combiner with the envelope of a complex modulated signal, an activity that is currently in progress.

The actual measurements were performed in a similar way as the previously discussed simulations. Again we have optimized the efficiency at each out-phasing angle by varying the varactor control voltages, while sweeping the input power (Fig. 8). With this information a lookup table was constructed, that provides the optimum combination of drive power, out-phasing angle and varactor control voltage for maximum efficiency over large power back-off range.

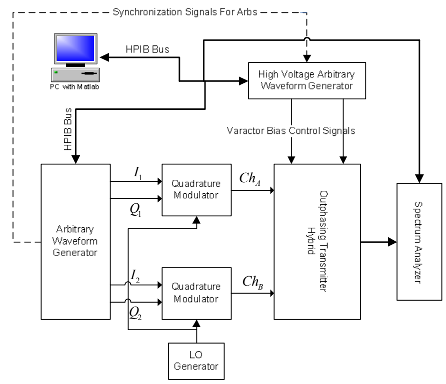

Fig. 7. Diagram of the test setup used for the Chireix amplifier with adaptive power combiner.

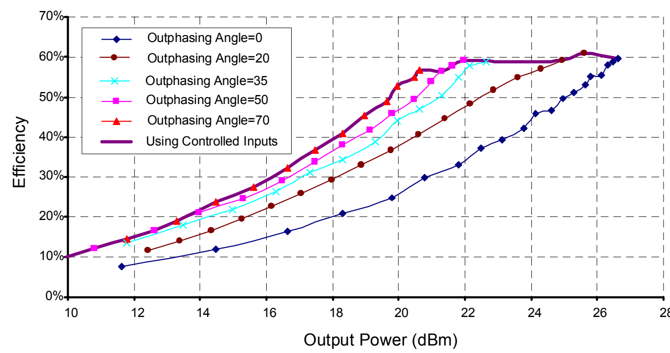

Fig. 8. Measured efficiency of the out-phasing transmitter as function of input power for different out-phasing angles.

VI. Conclusions

For the first time a hardware realization of a Chireix out-phasing amplifier with load adaptation is presented. The varactor tuned output power combiner eliminates the imaginary loading due to out-phasing of the active devices, yielding a significant improvement in amplifier efficiency for operation in power back-off. The influence of the losses in the resonator have been analyzed and experimentally verified.

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