A Power Re-Use Technique for Improved Efficiency of Outphasing Microwave Power Amplifiers

Robert Langridge, *Member, IEEE,* Todd Thornton, Peter M. Asbeck, *Senior Member, IEEE,* and Lawrence E. Larson, *Senior Member, IEEE*

Abstract—An improved power re-use technique is introduced for application to outphased microwave power amplifiers. The technique allows a significant portion of the wasted out-of-phase components of the signal to be returned to the power supply, resulting in substantial improvements in overall power-amplifier efficiency. A peak re-use RF-to-DC efficiency of 63% was obtained at 1.96 GHz.

Index Terms—linear power amplifiers, LINC, outphasing amplifiers.

I. INTRODUCTION

THE out-phased power amplifier concept dates back to the early 1930's as an approach for the simultaneous realization of high-efficiency *and* high-linearity amplification [1]. It has been revived recently for wireless communication applications under the rubric of linear amplification with nonlinear components (LINC) [2], and many recent papers have developed the concept further [3], [4]. The LINC concept takes an envelope-modulated bandpass waveform and resolves it into *two* out-phased constant envelope signals, which are applied to highly efficient—and highly nonlinear—power amplifiers, whose outputs are summed. The advantage of this approach is that each amplifier can be operated in a very efficient "switching" mode, and yet the final output can be highly linear—a key consideration for bandwidth-efficient wireless communications. This is shown schematically in Fig. 1.

However, one of the major disadvantages of the approach is the power wasted in the summing network when the two amplifiers are operated substantially out-of-phase, which dramatically compromises the power-added efficiency of the overall amplifier [5]. This problem has been addressed previously through the use of a Chireix power combiner [6], and adaptive termination of each amplifier output depending on the phase [7]. Though these techniques represent a significant improvement, each still suffers from limitations, including efficiency, bandwidth, and linearity.
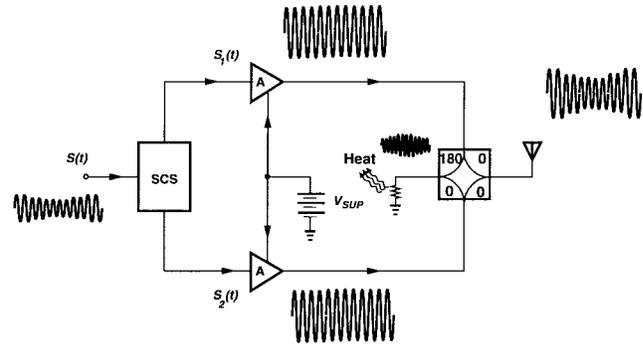
Fig. 1. Outphased power amplifier illustrating power wasted in combining network.

A new technique is proposed here for partial recovery of the wasted power in the summing network, similar to recently reported results of adiabatic digital VLSI circuits [8]. The potential resulting improvement in overall power-added efficiency is significant, without an excessive loss of design flexibility.

II. THEORY

The outphased amplifier of Fig. 1 takes a general baseband representation of an RF signal

$$s(t) = a(t)e^{j\phi(t)} \tag{1}$$

where $a(t)$ is the instantaneous amplitude and $\phi(t)$ is the instantaneous phase and resolves it into two *constant envelope* vectors $s_1(t)$ and $s_2(t)$ through what is known as a signal component separator (SCS), such that

$$s_1(t) = s(t) + x_1(t) \tag{2a}$$
$$s_2(t) = s(t) - x_1(t) \tag{2b}$$

where

$$x_1(t) = js(t)\sqrt{\frac{a_{\max}^2}{|s(t)|^2} - 1}.$$

The hybrid combiner of Fig. 1 takes $x_1(t)$ and $-x_1(t)$ and sends them to the load resistor at the termination of the difference port as waste heat. This process preserves the envelope of $s(t)$ at the output of the sum port, but reduces the overall power-added efficiency, especially for higher order modulations that involve significant envelope variation. In fact,
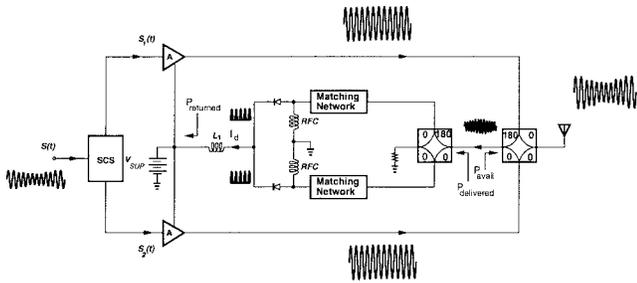
Fig. 2.   Power recycling circuit applied to out-phased power amplifiers.

the total power-added efficiency can drop to as low as 20% for the case of 64 quadrature amplitude modulation (QAM) [5].

In this paper, we propose to convert as much of the wasted power as possible delivered to the difference port termination *back* to the power supply. This is, in some ways, the "mirror image" of the traditional power-amplifier design challenge—where the goal is to convert as much of the DC power to RF as possible. A simple example of this approach is shown schematically in Fig. 2, where an RF–DC converter is implemented with high-speed Schottky diodes and an optimized matching network. The efficiency of the conversion is highly dependent on the power-supply voltage, as well as on the series resistance of the diodes and their intrinsic cutoff frequency and built-in voltage. Furthermore, the power conversion is a strongly nonlinear process, requiring the diodes to switch fully in order to achieve the best efficiency.

Assuming a simple resistive model of the diode, the power delivered *back* to the power supply can be approximated by

$$P_{\text{returned}} = V_{\text{sup}} I_{d_{\text{dc}}} \tag{3}$$

where V_{sup} is the power-supply voltage and $I_{d_{\text{dc}}}$ is the DC value of the current from the converter. At the same time, the power *available* from the hybrid is given by the familiar expression

$$P_{\text{avail}} = \frac{V_{\text{source}_{\text{rms}}}^2}{4R_s} \tag{4}$$

where V_{source} is the source voltage of the power-amplifier output combiner. Thus, we define the overall efficiency of the power re-use circuit as

$$\eta = \frac{P_{\text{returned}}}{P_{\text{avail}}}. \tag{5}$$

The efficiency can be calculated by first determining the instantaneous current through the converter, which can be approximated by

$$I_d(t) \approx \begin{cases} \left(V_{\text{pk}} \sin \omega_c t - (V_{\text{sup}} + V_d)\right)/R_{\text{di}}, \\ \qquad\qquad V_{\text{pk}} \sin \omega_c t \geq (V_{\text{sup}} + V_d) \\ \left(-V_{\text{pk}} \sin \omega_c t + (V_{\text{sup}} + V_d)\right)/R_{\text{di}}, \\ \qquad\qquad V_{\text{pk}} \sin \omega_c t \leq (-V_{\text{sup}} - V_d) \\ 0, \qquad |V_{\text{pk}} \sin \omega_c t| < (V_{\text{sup}} + V_d). \end{cases}$$

where V_{pk} is the magnitude of the peak voltage of the input signal at the diode network, V_d is the built-in diode voltage, R_{di} is the series "on" resistance of the Schottky diode, and ω_c is the carrier frequency.

The DC value of the converter current is, therefore, approximately

$$I_{d_{\text{dc}}} \approx \frac{2\left(\sqrt{V_{\text{pk}}^2 - (V_{\text{sup}} + V_d)^2} - \theta(V_{\text{sup}} + V_d)\right)}{\pi R_{\text{di}}} \tag{7}$$

where $\theta = \arccos((V_{\text{sup}} + V_d)/V_{\text{pk}})$ for $V_{\text{pk}} > (V_{\text{sup}} + V_d)$.

At the same time, the impedance at the carrier frequency of the converter can be approximated by

$$Z_{\text{detector}} \approx \frac{\pi R_{\text{di}}}{2}\left[\theta - \frac{(V_{\text{sup}} + V_d)\sqrt{V_{\text{pk}}^2 - (V_{\text{sup}} + V_d)^2}}{V_{\text{pk}}^2}\right]^{-1}. \tag{8}$$

Since this value of the impedance varies with input power (through V_{pk}), the converter circuit can only be ideally matched at its input at *one* input power level. At other powers, there will be some loss in the recovery due to impedance mismatch effects. If the impedance transformation is given by n^2, then the source voltage will be given by

$$V_{\text{source}_{\text{rms}}}^2 \approx \frac{n^2 V_{\text{pk}}^2}{2}\left[\frac{(R_s + Z_{\text{in}})}{Z_{\text{in}}}\right]^2 \tag{9}$$

and the power *delivered* to the detector is approximately

$$P_{\text{delivered}} \approx \frac{V_{\text{source}_{\text{rms}}}^2 Z_{\text{in}}}{(R_s + Z_{\text{in}})^2} \tag{10}$$

where $Z_{\text{in}} = n^2 Z_{\text{detector}}$.

Hence, inserting (9) into (7) and (4) allows us to determine the overall power re-use efficiency in terms of (5), the available input power, diode resistance, power supply, and built-in diode voltage.

III. Measured Results and Discussion

The power re-use circuit of Fig. 2 was fabricated with Hewlett-Packard surface mount Schottky diodes, on a 0.5-oz 32-mil Rogers 4003 board, and was fed by a hybrid power amplifier constructed from NE8500R599 and NE6 500 278 MESFET's. A resistive load of 11 Ω was used to simulate the equivalent load of a power amplifier on the power supply, and allowed for adjustment of the power-supply voltage. An impedance-matching network was employed at the input to the detector to optimize performance, and the circuit was evaluated at 1.96 GHz, a typical personal communications system (PCS) frequency.

Figs. 3 and 4 show the measured results for re-use efficiency and measured VSWR as a function of the input power for three different power-supply voltages: 3, 4, and 5 V. The best measured re-use efficiency was found to be approximately 63% at a power level that varied with supply voltage, and the efficiency was greater than 40% over a range of a decade in input power. This can result in a significant increase in the overall efficiency of an outphased power amplifier, although there are some limitations on the use of this approach. The experimental agreement with the simplified prediction of (5),
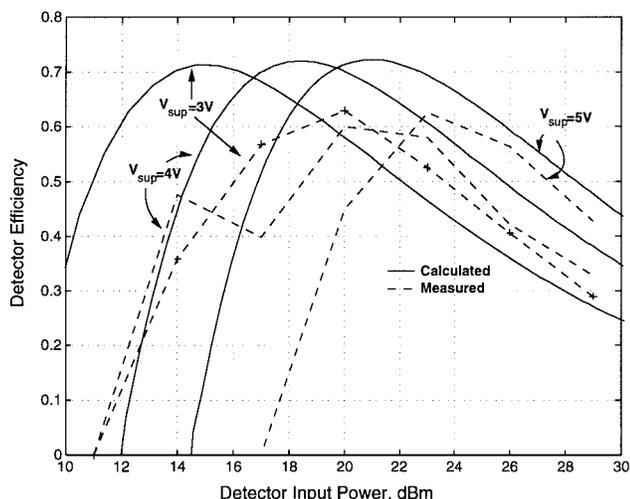
Fig. 3. Measured variation of re-use efficiency at 1.96 GHz as a function of input power level for $V_{\mathrm{sup}} = 3, 4,$ and 5 V. The agreement with (5) is shown for comparison.
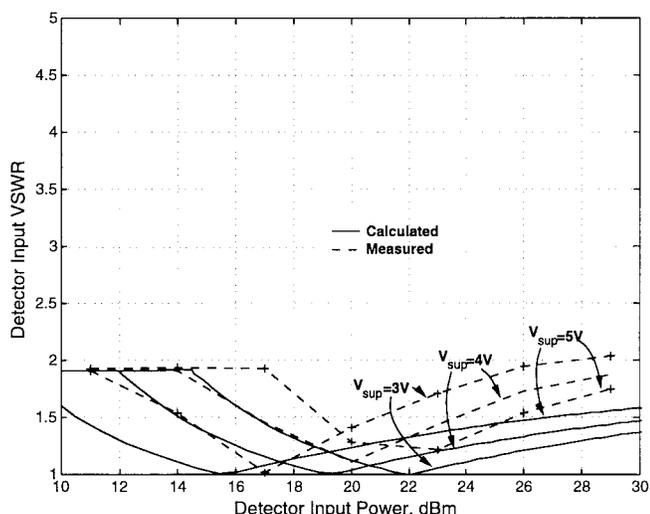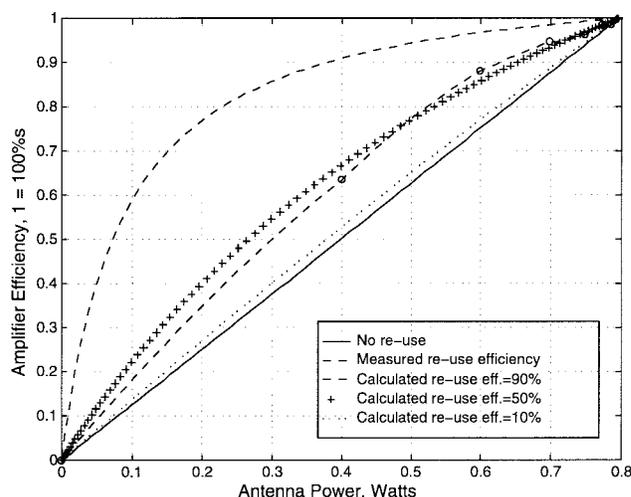

Fig. 5. Calculated power-amplifier efficiency as a function of power delivered to the antenna for 0.8-W peak outphasing power amplifier, showing the effect of re-use efficiency. The re-use efficiency data from Fig. 3 is included.

Fig. 4. Comparison of calculated and measured variation of input VSWR at 1.96 GHz as a function of input power level for $V_{\mathrm{sup}} = 3, 4,$ and 5 V.

assuming 1-dB loss in the input matching network, is excellent over a wide range of input powers and power-supply voltages.

At *low*-input power levels, the efficiency drops because the diodes are unable to turn "on" and overcome the combination of supply voltage and built-in potential of the diode. However, this loss in efficiency does not degrade the overall system efficiency because most of the total RF power in the circuit is delivered to the antenna anyway at these power levels. The efficiency drops at *higher* powers because of the increasing mismatch loss of the circuit as more power is delivered to the diodes, and the input impedance to the converter continues to drop. This would mean that the improvement in efficiency could be compromised for modulation schemes that exhibit very deep variations in envelope power on a regular basis—like QAM.

Fig. 5 shows a plot of predicted power-amplifier system efficiency in a LINC system with and without power re-use. For illustrative purposes, the power amplifiers in the system are assumed to have 100% efficiency. The re-use

efficiency was varied between 0.9–0.1 to show the effects of power re-use on the overall power-amplifier efficiency; the data from the detector circuit is also superimposed on the plot to compare it to the various contours of constant re-use efficiency. The "measured" data in this figure refers to measured re-use efficiency data of Fig. 3; the power-amplifier system efficiency was then calculated based on that data. As can be seen, the overall power-amplifier system efficiency can be enhanced significantly by re-using the "wasted" power from the difference port of the 180° hybrid. The amount of improvement will depend on the modulation scheme and data-filtering technique applied.

The variation in measured VSWR as a function of input power follows a similar pattern: at low input powers, the diodes appear to be "open-circuited" and the VSWR rises to a peak of approximately 1.8:1 and, at high input powers, the VSWR also rises, up to a maximum of nearly 2:1. The high VSWR at high input powers could create a limitation on the cancellation of the signals that appear at the antenna, creating unwanted distortion. However, the antenna hybrid itself provides an additional 3 dB of isolation, and a circulator could be employed to further improve the VSWR if necessary.

The bandwidth of this technique is sufficiently broad to accommodate a variety of modulation schemes without significant degradation in the power returned to the power supply. Fig. 6 plots the variation in efficiency using a 50% amplitude modulation of the input signal at a 10-kHz rate. In this case, there is little difference between this result and the continuous-wave (CW) result of Fig. 3. Even wider bandwidths are required for a CDMA case, where the typical modulation bandwidth is increased to 1.25 MHz. In this case, the measured results of Fig. 6 show a modest decrease of efficiency from a peak of over 60% to just over 50%.

It should be noted that this particular power re-use circuit is only one of several ways to approach this problem depending on the center frequency and the bandwidth of the signal. An alternative implementation of the power re-use circuit at lower frequencies could be a transformer and diode pair, followed
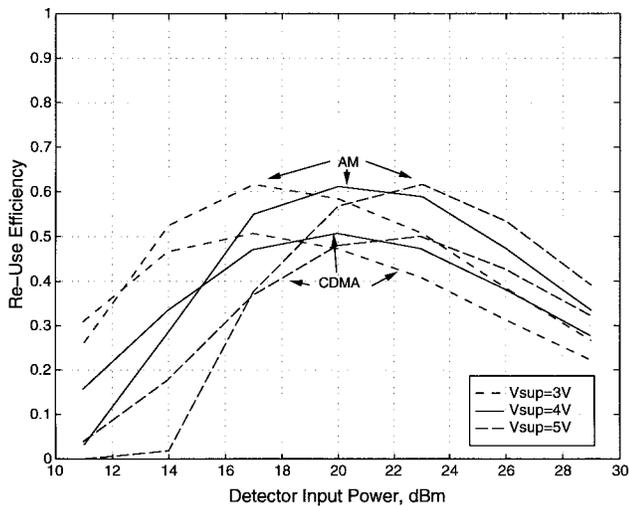
Fig. 6. Measured variation of circuit efficiency as a function of input power level for 50% AM at 10 kHz and CDMA at 1.25 MHz at a carrier frequency of 1.96 GHz, for $V_{\mathrm{sup}} = 3, 4,$ and 5 V.

by a dc–dc converter. One of the main goals in this design was to optimize the power re-use efficiency at the 1.96-GHz band, and to investigate the effect of variations in the power-supply voltage on efficiency. However, from a practical standpoint, a dc–dc converter would be desirable to provide the proper supply voltage to the power amplifiers in any given system. This approach has recently been developed for the case of dynamic power-supply variations in linear power amplifiers [9].

One issue that has not been addressed to this point is the inherent problem in the LINC architecture due to amplitude and phase imbalance between the two power amplifiers. Both of these imbalances will result in a lower amplitude modulation index signal on the output to the antenna and the detector. A small degradation in re-use efficiency will be noticed in the system due to this effect.

IV. CONCLUSION

A new technique has been presented for the power-added efficiency improvement of outphased microwave power amplifiers, which involves the "recycling" of a portion of the wasted power in the summing hybrid *back* to the power supply. The circuit achieved a peak power re-use efficiency of over 60%, and the efficiency was greater than 40% over more than a decade of input power at 1.96 GHz. This technique promises to improve the overall efficiency of outphased microwave power amplifiers, making them more attractive for future generations of highly linear amplifiers.

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Peter M. Asbeck (M'75–SM'97), for photograph and biography, see this issue, p. 1437.

Lawrence E. Larson (S'82–M'82–SM'90), for photograph and biography, see this issue, p. 1403.