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An Outphasing Transmitter Using Class-E PAs and Asymmetric Combining: Part 1

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This two-part series describes the development of a design technique, and prototype circuits, for linear power amplification using high-efficiency nonlinear (class-E) circuits

High efficiency linear amplification is of great interest in modern communication systems as it increases talk time, decreases power consumption, decreases heat dissipation, and improves reliability. The efficiency of linear power amplifiers (PAs) is highest at the peak output power (PEP) and decreases significantly for low amplitudes, as shown in Figure 1. Signals with time-varying amplitudes (amplitude modulation) therefore produce time-varying efficiencies, the probability density function (pdf) of the envelope is a means of how much time an envelope spends in certain amplitude level, as shown in Figure 2. Hence, obtaining a high average efficiency [1] therefore requires a combination of amplifier and architecture that improves efficiency at low as well as high amplitudes. It is achieved by combining high-efficiency power amplifier and a transmitter architecture such as envelope elimination, Doherty, or outphasing [1].

An outphasing transmitter (Figure 3) produces a variable-amplitude output by varying the phases of the driving signals to its RF-power amplifiers. The phase modulation causes the instantaneous vector sum of outputs of the two PAs to follow the desired signal amplitude. In a microwave implementation, power combiners based upon transmission lines are typical.

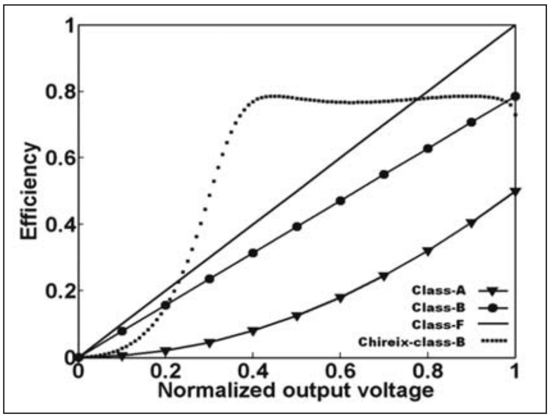

Figure 1 · Efficiency vs. normalized output voltage for linear PAs and Chireix-outphasing using ideal class-B PAs.

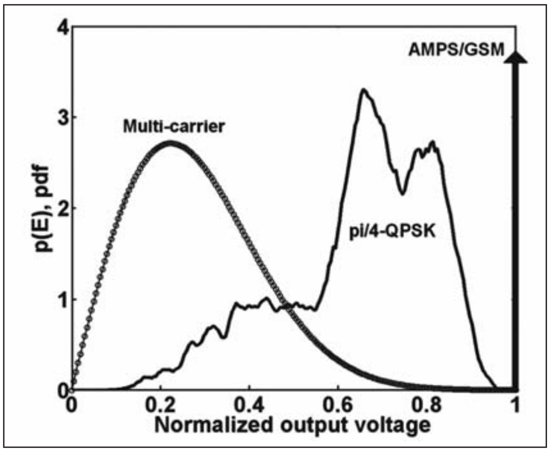

Figure 2 · Envelope probability density functions.

The outphasing transmitter, also known as linear amplification using non-linear components (LINC) was originally developed to provide linear amplification with active devices that have poor linearity [1, 2]. H. Chireix added complementary shunt reactances at the inputs of the combiner to improve the efficiency over a range of amplitudes (Fig. 3).

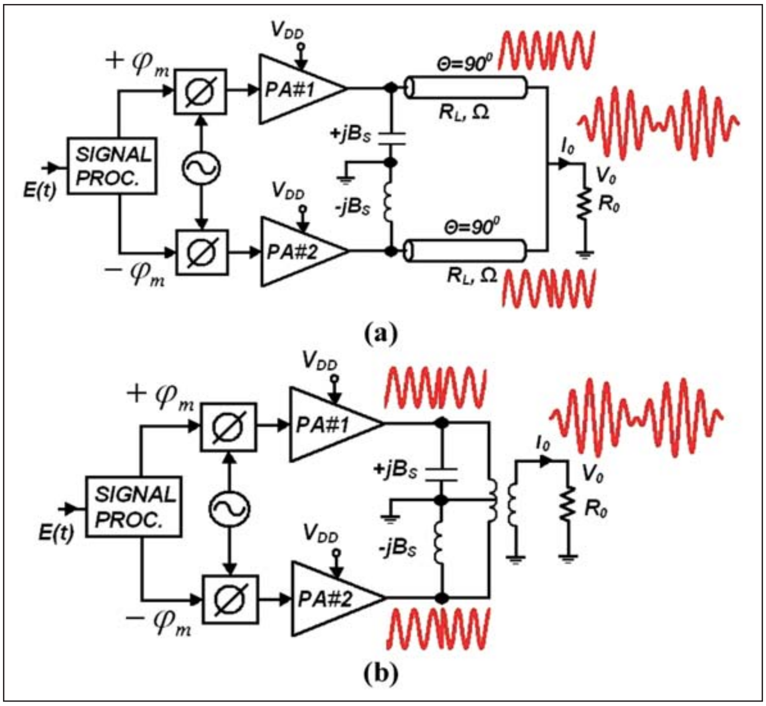

Figure 3 · Classical Chireix-outphasing transmitters with quarter-wave length transmission lines (a) and transformer (b) combiner.

Outphasing is attractive because signal phase can easily be modulated over a wide bandwidth. Research to date on using the Chireix technique at microwave frequencies has focused on using class-B, -D, and -F PAs, [3, 4]. The class-E amplifier offers excellent efficiency (ideally 100 percent) at RF and microwave frequencies [1, 5]. However, the impedances presented to a class-E PA by a conventional Chireix outphasing system cause it to be inefficient, and the system to have poor dynamic range. This article presents a new concept that solves these problems, using asymmetric coupling that allows a class-E PA to operate with high efficiency over a wide range of amplitude.

Conventional Outphasing

In an outphasing transmitter, the drive circuit generates two input signals with phases of $+\varphi_m$ and $-\varphi_m$ as shown in Figure 4, so that one PA is driven with a phase difference $\Delta\varphi_m$ (from 0° to 180°) from the other. Then, these two signals are amplified and added, hence, output signal is proportional to the sine of the difference in phase between the two inputs to the power combiner; that is:

$$V_{0PEP}\sin\varphi_m \tag{1}$$

and the phase modulation therefore must be:

$$\varphi_m(t)=\arcsin(E(t)) \tag{2}$$

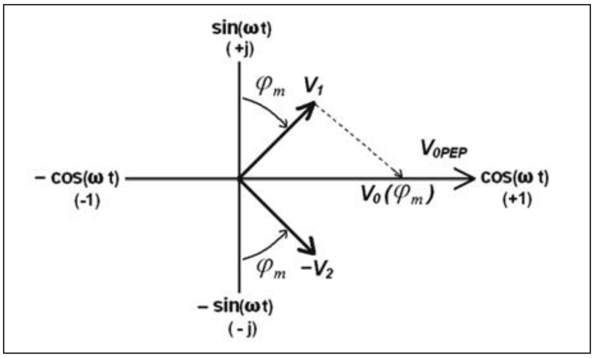

Figure 4 · Vector representation of the two drive signals.

where the time varying envelope amplitude can be expressed in term of the normalized output voltage:

$$E(t)=\frac{V_0}{V_{0PEP}} \tag{3}$$

The PAs must act as voltage sources; saturated PAs operating in classes A, B, C, D, and F ideally behave as voltage sources for proper operation.

The ideal load-pull contours are shown in Figure 5 for ideal saturated class-F PAs at nominal load. Output power is proportional to the parallel resistance component and efficiency varies with the power factor $(R/\{|R+jX|\})$ because of the extra current that passes through the shunt reactance [6]. The impedance locus produced by simple outphasing causes the PAs to be subjected to reactive loads that degrade their efficiencies. The impedances seen by PA1 and PA2 with quarter-wave length transmission lines combiner are respectively (circular markers in Fig. 5, PA1 top, PA2 bottom):

$$Z_{PA1}(t)=\frac{R_L^2(\sin\varphi_m+j\cos\varphi_m)}{2R_0\cdot E} \tag{4}$$

and,

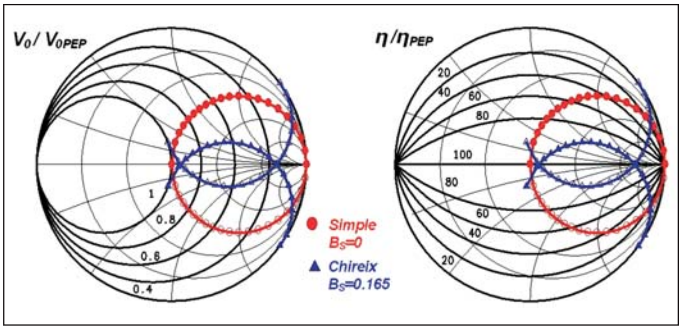

Figure 5 · Impedance loci for outphasing with ideal class-F PAs.

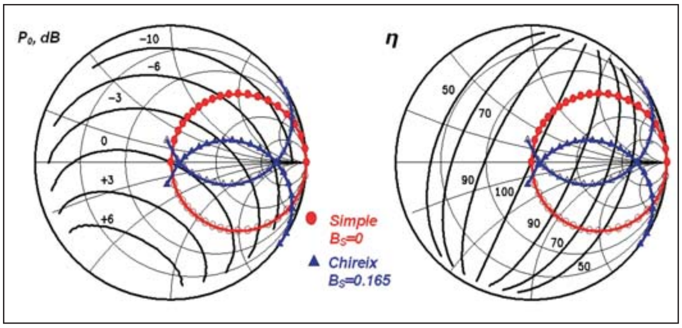

Figure 6 · Impedance loci for outphasing using voltage sources devices on the load-pull contours of the ideal class-E PA.

$$Z_{PA2}(t) = \frac{R_L^2(\sin\varphi_m - j\cos\varphi_m)}{2R_0 \cdot E} \tag{5}$$

The addition of the Chireix shunt impedances moves the impedance loci to regions of higher efficiency [2, 7]. As a result the admittances seen by PA1 and PA2 are:

$$Y_{PA1}(t) = \frac{1}{Z_{PA1}} + jB_S \tag{6}$$

and

$$Y_{PA2}(t) = \frac{1}{Z_{PA2}} - jB_S \tag{7}$$

Shunt susceptance BS in Figure 3 can be chosen to cancel the reactive components of the impedance at one specific signal amplitude. This allows the PA to achieve maximum efficiency at this amplitude, as well as a range of nearby amplitudes. For example, in the classic configuration of Fig. 3, efficiency is improved for the upper half (6 dB) of the amplitude range, resulting in significantly higher average efficiency for modulated signals [7].

Conventional Outphasing with Class-E PAs

The load-pull contours [8] of an ideal class-E PA are shown in Figure 6. It is immediately apparent that there are problems in using class-E PAs in the classical outphasing architecture. For phase difference $\Delta\varphi_m$ = 0° the impedance locus is at the center of the Smith chart. As $\Delta\varphi_m$ increases, the impedance of PA1 (top circular markers) moves along top contour while the impedance of PA2 (bottom circular markers) moves along bottom contour. Both impedances approach to the right side of the Smith chart when phase difference increases. The outputs of the two PAs vary, but are not changed by the same amount. In fact, they can maintain a nearly constant output voltage over a wide range of phase differences because the output of PA1 increases while that of PA2 decreases. Equally important is that efficiency of PA2 decreases rapidly as its load impedance moves toward the right side of the Smith chart.

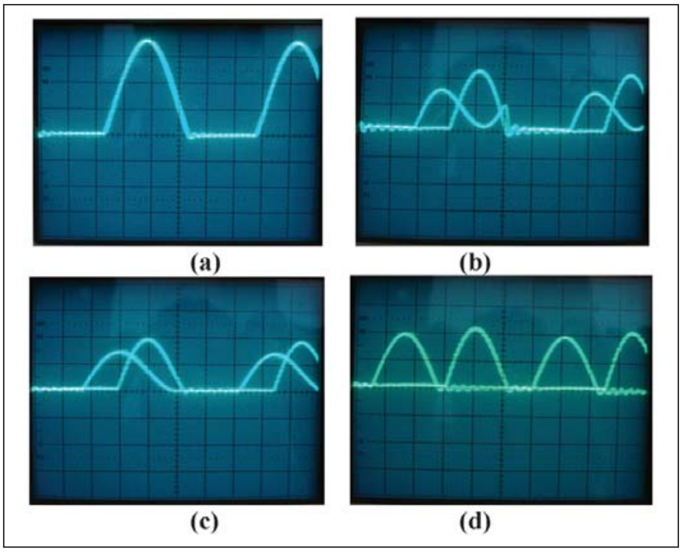
(a) (b) (c) (d)

Figure 7 · Drain waveforms (PA1 right, PA2 left) of the conventional-simple outphasing class-E PAs; (a) $\Delta\varphi_m$ = 0° (20 V/div), (b) $\Delta\varphi_m$ = 90°, (c) $\Delta\varphi_m$ = 135°, and (d) $\Delta\varphi_m$ = 170° (40 V/div).

The asymmetric loading of the two PAs is apparent in Figure 7. While both PAs have very similar drain waveforms at PEP ($\Delta\varphi_m$ = 0°; Fig. 7(a)), the reactive loads cause the waveforms to vary differently (amplitude and shape) for drive phase differences other than 0° (Fig. 7(b-d)), both output and efficiency then drop as the phase difference $\Delta\varphi_m$ is increased. While the PEP efficiency is compared with that of a single class-E PA that is better than a linear amplifier, the average-efficiency characteristics are about the same [9].

The addition of Chireix shunt impedances does not change the performance of the class-E PAs significantly, and the same problem with efficiency and output power remains (triangular markers in Fig. 6), the system presents very good efficiency over all drive phases. However, it delivers nearly constant output power regardless the drive phase difference (Fig. 8). As a result, it does not provide a useful dynamic range required for communication applications.

An important observation made during the experiments is that for certain Chireix reactances and certain phase differences, one PA is presented with negative load resistance. As a result, it rectifies the signal from the other PA, causing it to return power to the DC supply.

A previous publication addressed outphasing of class-E amplifiers [9], and it does not include Chireix impedances. Power output is nearly constant over the first 30° of phase variation. Both output and efficiency then drop as the phase difference is increased.

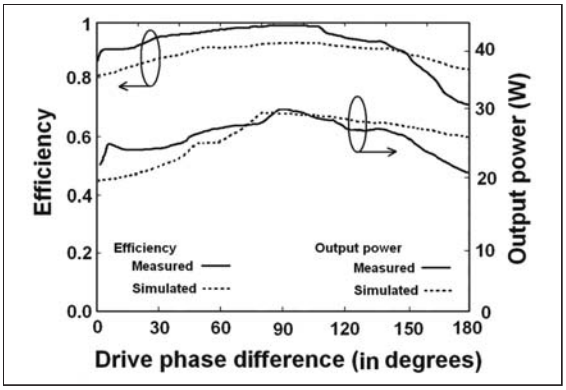

Figure 8 · Conventional Chireix-outphasing class-E efficiency and output power.

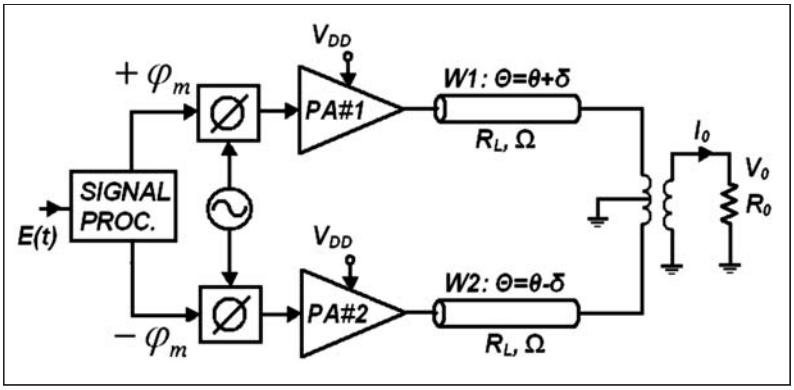

Figure 9 · Asymmetric outphasing with class-E PAs.

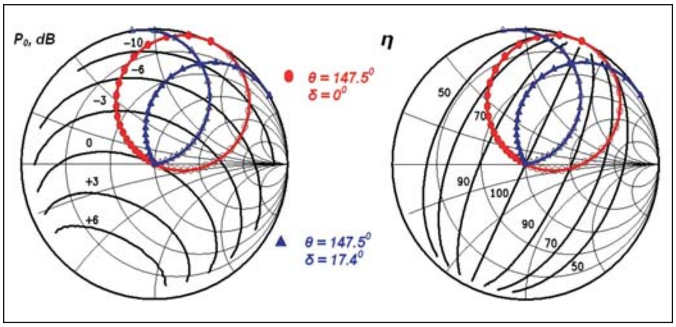

Figure 10 · Impedance loci for outphasing with ideal class-E.

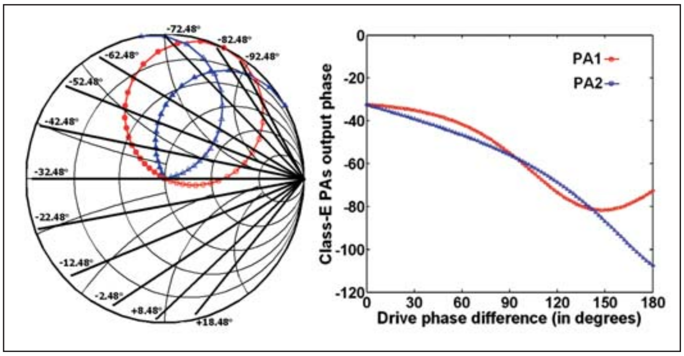

Figure 11 · Impedance loci for outphasing with ideal class-E on the output phase contours of the class-E PA, and each PA's output phase vs. drive phase $\Delta\varphi_m$, for θ = 147.5° and δ = 17.4°.

Asymmetric Outphasing for Class-E PAs

The new architecture for outphasing of class-E PAs is shown in Figure 9. Transmission lines W1 and W2 have electrical lengths of θ + δ and θ – δ, respectively. The essence of the new combining technique is as follows:

1. Transmission lines W1 and W2 rotate the impedance loci to center them on the line at 65°, which corresponds to the maximum efficiency of the class-E PAs (Fig. 10 η = 1 line). This requires θ ≈ 147.5° (Figs. 9 and 10).

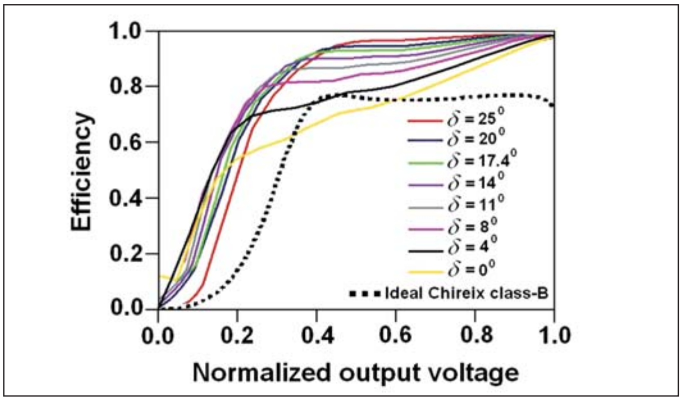

Figure 12 · Simulated class-E outphasing efficiency vs. normalized output voltage for various values of δ with θ = 147.5°.

2. As a result of centering the impedance loci, the amplitudes of the two PA outputs ideally vary identically with difference in phase between the drive signals.

3. The phases of the two PA outputs are nearly the same over most of the amplitude range of $\Delta\varphi_m$ (Fig. 11).

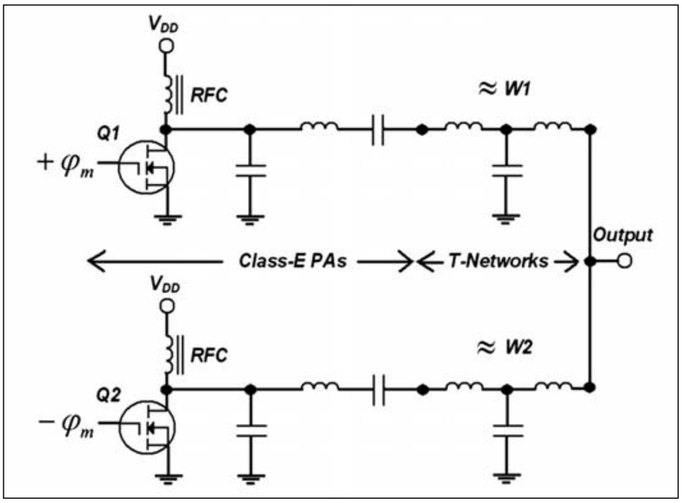

Figure 13 · Prototype 1.82 MHz outphasing transmitter.

4. Since the amplitudes of the two PAs are ideally equal and the phases are approximately equal, the impedances produced by combining are approximately as assumed.

5. In practice, the variation of amplitude with $\Delta\varphi_m$ is not a simple function, and the two amplitudes are not exactly equal. Predistortion can be used to set the phases to produce the desired amplitude.

6. The phase shifts within the two PAs also vary, and are not necessarily the same in both PAs. Predistortion compensates for the phase shift differences.

7. Differential line length δ can be used to move the impedance loci closer to the $\eta = 1$ line in Figure 10. The value of δ can be chosen to alter the instantaneous-efficiency characteristics (Fig. 12) to optimize the average efficiency for a given signal or set of signals.

8. In practice, it is also necessary to give attention to obtaining a reasonable dynamic range of output voltage.

HF Prototype

A prototype PA (Fig. 13) operating at 1.82 MHz was used to verify the new technique [10]. This frequency allows the use of low-cost MOSFETs and direct observation of the drain waveforms. These results are also confirmed by simulation using PSpice.

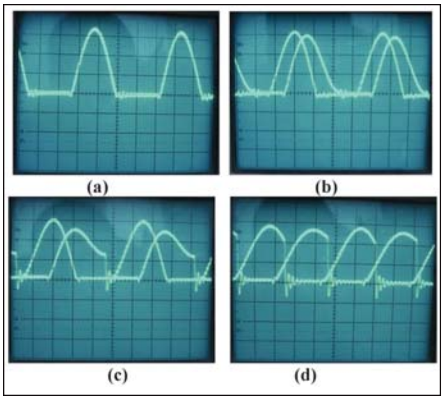

Figure 14 · Waveforms for asymmetric combining: (PA1 right, PA2 left) of the outphasing class-E PAs; (a) $\Delta\varphi_m = 0°$ (20 V/div), (b) $\Delta\varphi_m = 90°$, (c) $\Delta\varphi_m = 135°$, and (d) $\Delta\varphi_m = 180°$ (40 V/div).

Two identical class-E power amplifiers were implemented using lumped element L-C series output networks. The two amplifiers are assembled on a single board using IRF510 MOSFETs and RF4 substrate. The properly tuned PAs achieve a drain efficiency of 95% with an output power of 14-W each.

The prototype asymmetric combiner (Fig. 13) is implemented using lumped elements (LC) T networks instead of transmission lines W1 and W2. The values of the LC elements are determined by equating the ABCD matrix of a transmission line with that of the desired T network. The drain waveforms are shown in Figure 14. The waveforms of the two PAs remain considerably more similar than those of conventional out-

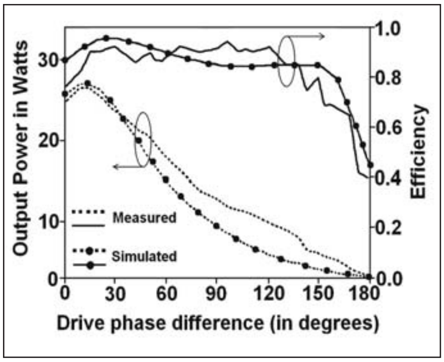

Figure 15 · Simulated and measured class-E outphasing output power and efficiency vs. drive phase $\Delta\varphi_m$, for $\theta = 147.5°$ and $\delta = 17.4°$.

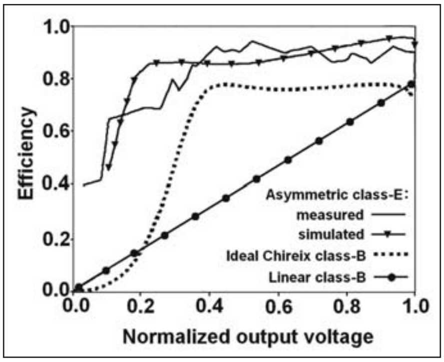

Figure 16 · Simulated and measured class-E outphasing efficiency vs. normalized output voltage, for $\theta = 147.5°$ and $\delta = 17.4°$.

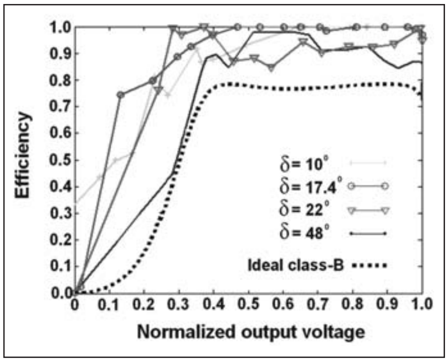

Figure 17 · Measured comparison of efficiency vs. output voltage for different δ in its respective T networks.

phasing in Figure 7.

The results of simulation are shown in Figures 15 and 16. The new technique not only has a good dynamic range of amplitude variation, but also maintains an efficiency of 85% or better for amplitudes from 0.8 W to full output (27.5 W). In contrast, the efficiency for outphasing with ideal class-B PAs is no better than 78%. Indeed the asymmetric class-E outphasing ideally presents better efficiency when $\delta = 0°$ (asymmetric but not optimized) over most output voltages compared to that of class-B (Fig. 16).

The measured characteristics of the prototype are also shown in Fig. 15 and 16. The output power varies from 25.7 W at PEP ($\Delta\varphi_m = 0$) to nearly zero (0.54 W) for a phase difference $\Delta\varphi_m$ of 180°. The efficiency is better than that of the ideal class B over the entire range of amplitudes. The value of the difference δ in line length (or its equivalent LC T-network) does not appear to be critical, and high efficiency is obtained for δ equals to 10°, 22° and 48°, as shown in Figure 17.

Part 2 of this article will present the design and performance results of a 900 MHz prototype amplifier.

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