SINGLE-TONE OPTIMISATION OF AN ADAPTIVE-BIAS DOHERTY STRUCTURE

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Abstract: The Doherty PA configuration has become well established as a means of enhancing PA efficiency. The improvement, however, is usually accompanied by deterioration in overall linearity. This paper addresses two important features of the Doherty PA configuration, which offer a means of improving the linearity/efficiency trade-off obtained using a classical adaptive bias implementation. One issue is the need to generate a suitable bias control voltage for the auxiliary PA device. Such control enables the use of two devices with equal periphery for main and auxiliary functions. The second issue is the use of phase compensation to ensure the combined signals sum in the correct manner prescribed by classical analysis. Both of these refinements are demonstrated using an experimental circuit operating at 1.8GHz. Extensive experimental data is presented on the beneficial effects of phase control, which show that a better compromise between optimum efficiency and linearity can be obtained using different phase offsets at different drive levels. This raises the interesting possibility of adjusting relative phase, bias and relative input magnitude dynamically in order to obtain improved linearity from the Doherty configuration, especially for signals having high peak to average ratios.

I. INTRODUCTION

Achieving highly efficient linear power amplification in modern communication systems poses a significant design problem. The low efficiencies associated with linear amplification are due to a number of reasons including the low-efficiency modes of operation such as class-A and class-AB that are used, and secondly the fact that amplifiers are usually 'backed-off' into more linear and less efficient regions of operation.

In the past, these problems have largely been avoided through the use of constant envelope modulation. This is no longer the case however, and the use of modern modulation schemes result in RF envelopes with significant peak-to-average power ratios. As well as having the effect of significantly reducing the average efficiency of the PA, the need to accurately amplify complex envelopes in terms of amplitude and phase imposes new and significant linearity requirements.

Meeting the requirements imposed by such modulation schemes can lead to poor PA efficiencies with significant implications on, for example, handset battery life and the running costs for mobile base-stations [1].

The Doherty amplifier structure is known for its ability to offer significantly improved efficiency over a typical dynamic range of 6dB [1,2,3].

One requirement of the Doherty amplifier is that the separate signals produced by main and auxiliary devices contain a phase delay such that the individual powers sum in-phase at the load [1]. In theory, this is easily achieved by the use of a simple delay line [5]. In practice however, this is not so easily achieved as the optimum phase has been found to change significantly in the upper 6dB of amplifier operation.

Through single-tone analysis, it is shown that adjusting firstly input phase and later relative input magnitude and auxiliary bias, can result in optimised efficiency and gain-flatness.

II. THE CLASSICAL DOHERTY STRUCTURE

Doherty operation employs the principle of active load-pull, using the current generated by an auxiliary device to dynamically reduce the load presented to the output of a main device via an impedance inverting λ/4 transformer.

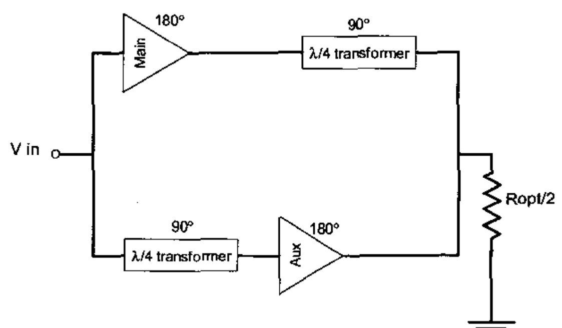

Fig. 1. The classical Doherty structure

The characteristic impedance of the transformer and the resistance of the load are carefully chosen to cause the main device to saturate prematurely at a point corresponding to half of the maximum input voltage. This point is termed the transition point and in the case of the classical Doherty corresponds to an output power of 6dB less than the maximum output power.

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As drive is further increased and passes the transition point, the reducing load presented to the main device maintains a highly efficient constant voltage state. The second $\lambda/4$ transformer is required merely to compensate for the 90° phase delay introduced.

III. THE EVALUATION PROTOTYPE

The required conduction behaviour is usually achieved by biasing the auxiliary device statically, in a reduced conduction mode relative to the main device. This approach causes complications however in that different sized devices will be necessary. In order to use two identical devices and therefore maintain structure simplicity, adaptive bias is used to control the conduction of the auxiliary device.

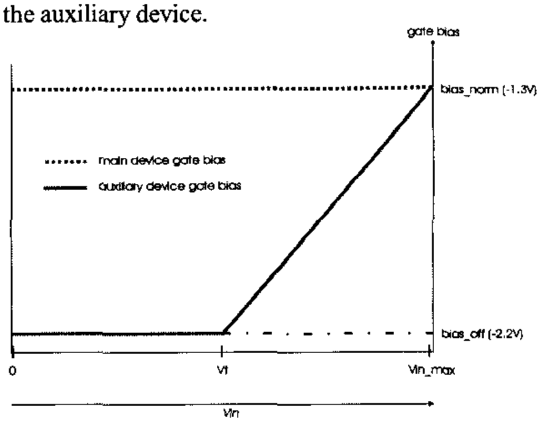

Fig. 2. Auxiliary bias vs. Vin for adaptive bias control

For input drive voltage (*Vin*) below the transition point (*Vt*), the auxiliary device is biased off at a voltage (*bias_off*), such that at the transition point, the applied drive causes the device to start conducting. This is shown in Fig. 2 and described by equation 1.

$$aux\_bias = bias\_off, 0 < Vin < Vt \quad (1)$$

For input drive voltage above the transition point voltage, the auxiliary gate bias voltage (*aux_bias*) is shifted linearly with increasing input voltage, such that at the maximum drive condition (*Vin_max*), both devices are biased at the same point (*bias_norm*) and delivering the same drain current, as shown in. Fig 2, and described by equation 2.

$$aux\_bias = bias\_off + \left(Fact \cdot (bias\_norm - bias\_off)\right) \quad (2)$$
$$\text{where} \quad Fact = \left(2 \cdot (Vin/Vin\_max)\right) - 1$$

The use of similar devices allows a symmetrical structure to be adopted [2], as shown in Fig 3. This consists of three 25 Ohm, $\lambda/4$ lines connected end-to-end with the two identical devices mounted with their drains attached directly to the line intersections. The centre line acts as the main combining impedance inverter and the other two lines act as an even-order harmonic trap and 25 to 50 Ohm transformer respectively. The input structures to each device are identical, unmatched and completely independent in terms of signal and bias.

IV. SINGLE-TONE MEASUREMENTS AND OPTIMISATION

Usually, Doherty structures employ a single input RF signal that is split according to a fixed power ratio and delivered at a fixed relative phase and magnitude to the main and auxiliary devices.

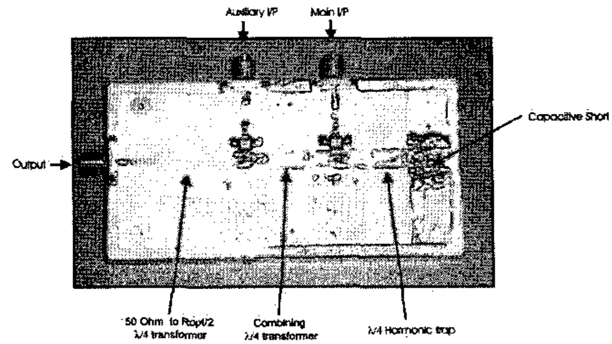

Fig. 3. The simple Doherty prototype

By using separate, phase coherent signal sources to drive the independent main and auxiliary inputs, it is possible to vary both the relative input phase and magnitude to observe the effects on key parameters such as efficiency and gain. Initial phase perturbation measurements show a significant variation in the required input phase for maximum efficiency throughout the upper 6dB region of operation.

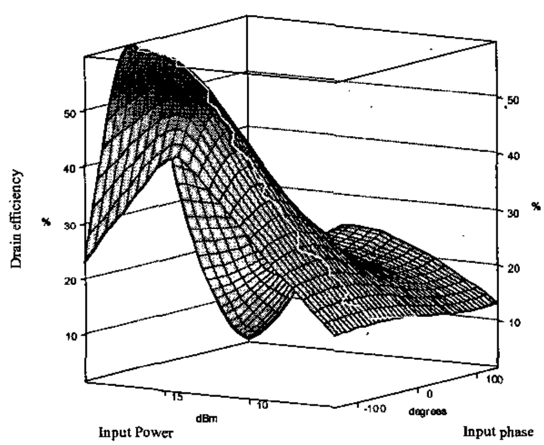

Fig. 4. Drain efficiency vs. relative input phase

This relationship is illustrated in the three-dimensional surface of Fig 4, which shows drain efficiency plotted against input power and relative input phase. A contour is added to help identify the maximum efficiency at each point of the power sweep. The relative phase required for maximum efficiency is a function of input drive however, and changes by approximately 50° between the transition point and maximum power point. This is better illustrated by the rotated view of Fig 4 shown in Fig 5.

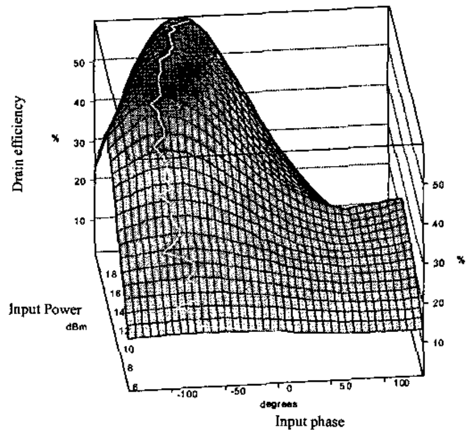

Fig. 5. Alternative view of drain efficiency

Being able to adjust the relative input phase for maximum efficiency raises some interesting questions, specifically, are there similar phase contours that give rise to other desirable conditions such as flat gain or constant phase delay?

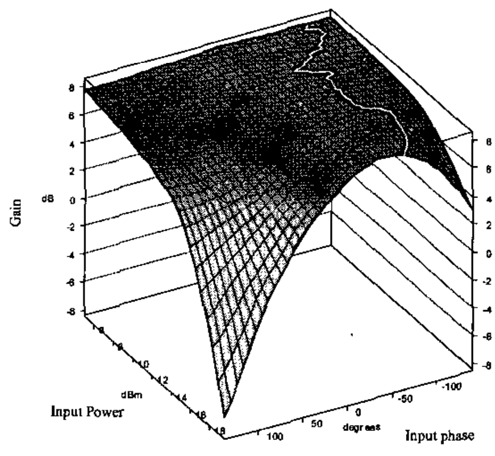

Fig. 6. gain vs. relative input phase

Fig 6 shows the three-dimensional surface for gain plotted against input power and relative input phase. A contour of constant gain is added to identify the required phase to achieve a flat gain of in this case, 7.9 dB.

Exactly the same process can be followed to identify a constant phase delay contour as shown in Fig 7.

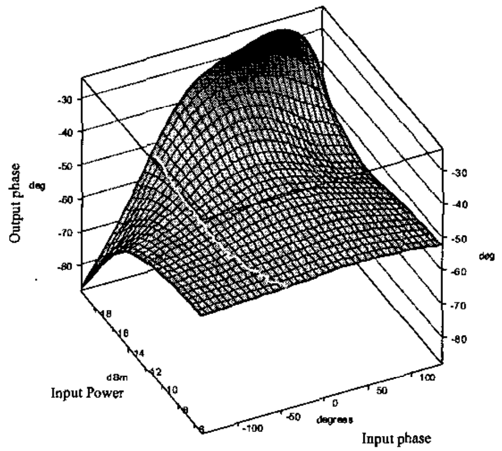

Fig. 7. Phase delay vs. relative input phase

The concept of optimisation through adjustments in input phase is interesting when considering tailoring Doherty structures for improved linearity or phase, or more likely some compromise in between. Closer examination of the profiles suggests that when optimizing for one parameter, there are likely to be significant negative impacts on other parameters. It is therefore important to consider the impact that optimising gain, efficiency and output phase has on other parameters.

In the following analysis, only the extreme cases are considered. For example, optimising for efficiency involves seeking the phase that results in absolute maximum efficiency. This is somewhat artificial as realising such a specific goal can excessively degrade other parameters, when in fact, a healthy and quite acceptable compromise may exist.

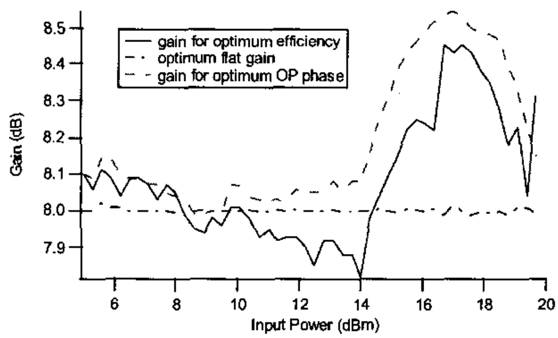

Fig. 8. Single-tone gain comparison

Fig 8 and Fig 9 show gain and drain efficiency for the three cases where the relative input phase has been adjusted for maximum efficiency, flat gain and constant phase delay.

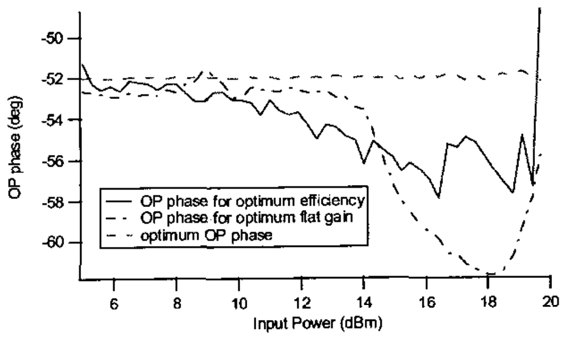

Fig. 9. Single-tone phase delay comparison

The results give some indication of the efficiency and linearity trade-offs involved in optimising a Doherty structure. They also show some promise, as the efficiency remains relatively unaffected when optimising for gain and phase flatness. This is shown in Fig 10.

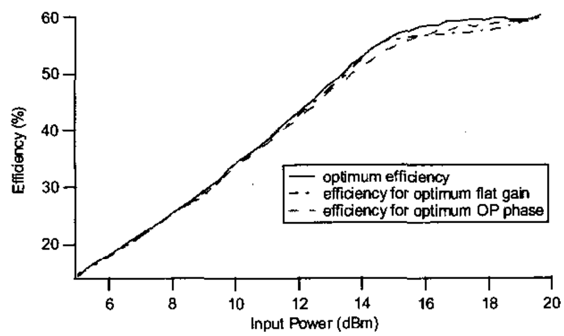

Fig. 10. Single-tone efficiency comparison

These observations have led to further experimentation and the perturbation of other parameters. Measurements have shown that varying the auxiliary bias voltage or the relative magnitude of the auxiliary input power will lead to similar relationships and optimisation possibilities.

V. Conclusions

Measurements have shown that by varying the relative input phase during power sweeps, an approximate 50° change in optimum input phase is observed throughout the high power region of operation. This is significant, as when considering simple Doherty realisations where phase offset between main and auxiliary inputs is fixed, the choice of phase offset significantly influences the end result. By changing the input phase dynamically with input drive however, it was noted that results could be optimised, not only for maximum efficiency, but also for flat gain and constant phase delay.

This observation led to further experimentation and measurements that show by varying either the auxiliary bias voltage or the relative magnitude of the auxiliary input power, as well as the relative input phase leads to definite possibilities for optimising efficiency, gain flatness and phase flatness.

It soon becomes clear however that improving one parameter generally leads to degradation of other parameters. Realistically, if such optimisation techniques are to be used, a more flexible way of extracting compromise auxiliary phase, auxiliary bias or auxiliary input power profiles will be needed where a range of acceptable gain, phase and efficiency can be specified and a 'best fit' solution sought. In addition, it is also considered probable that achieving the best possible results will involve changing more than one of the three control parameters at any one time.

Acknowledgements

The authors would like to thank Nokia Telecommunications Ltd for funding this activity and CELERITEK Ltd, UK for providing the devices.

References

[1]. P. B. Kennington, "High-Linearity RF Amplifier Design", Artech House, 2000.

[2]. S. C. Cripps, "Advanced Techniques in RF Power Amplifier Design", Artech House Publishers, 2002.

[3]. M. Iwamoto, A Williams, P. Chen, A. G. Metzger, L. E. Larson, P. M. Asbeck, "An Extended Doherty Amplifier With High Efficiency Over a Wide Dynamic Range", *IEE Transactions on Microwave Techniques, Vol.49, No. 12, December 2001*

[4]. W.H. Doherty, "A new high efficiency power amplifier for modulated waves", *Proc. IRE, Vol. 24, pp. 1163-1182, September 1936.*

[5]. F. H. Raab, "Efficiency of a Doherty RF Power-Amplifier System", *IEEE Transactions on Broadcasting, Vol. BC-33, No. 3, September 1987*

[6]. S. C. Cripps, "RF Power Amplifier Design for Wireless Communications", Artech House, 1999.

[7]. R. A. McMorrow, D. M. Upton, P. R. Maloney, "The Microwave Doherty Amplifier", *IEEE MTT-S Int. Microwave Symp. Dig., 1994, pp. 1653-1656*