

# An Extended Doherty Amplifier with High Efficiency Over a Wide Power Range

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**ABSTRACT** — An extension of the Doherty amplifier architecture which maintains high efficiency over a wide range of output power ( $>6$ dB) is presented. This extended Doherty amplifier is demonstrated experimentally with InGaP/GaAs HBTs at a frequency of 950MHz.  $P_{1dB}$  is measured at 27.5dBm with PAE of 46%. PAE of at least 39% is maintained for over an output power range of 12dB backed-off from  $P_{1dB}$ . This is an improvement over the classical Doherty amplifier, where high efficiency is typically obtained up to 5-6dB backed-off from  $P_{1dB}$ . Generalized design equations for the Doherty amplifier are derived to show a careful choice of the output matching circuit and device scaling parameters can improve efficiencies at lower output power.

## I. INTRODUCTION

Digital modulation formats used in present day commercial wireless communication systems require transmitters to incorporate sophisticated power control. In the case of CDMA, it is very important for handsets to transmit power at variable levels so that signals received by the base station are similar in strength to maximize system capacity [1]. Owing to such an aggressive system requirement, it is very common for power amplifiers in mobile transmitters to operate at output power levels of more than 10dB backed-off from peak power. Unfortunately, a significant consequence of this requirement is that the power amplifier must operate within regions where it is not the most efficient. Since the power amplifier uses a large portion of the battery power in handsets, it is desirable for amplifiers in these applications to have higher efficiencies at lower power to extend battery life. A promising architecture to achieve this result is the Doherty amplifier (Fig. 1), in which power from a main amplifier and an auxiliary amplifier are combined with appropriate phasing [2-9].

Fig. 2 shows a comparison of efficiency characteristics of various power amplifiers. In the classical Doherty amplifier operation, high efficiencies are obtained over a nominal 6dB of output power range. Raab analytically showed the possibility of extending the peak efficiency region over a wider range of output power [3]. In this

paper, we experimentally demonstrate an extended Doherty amplifier with high efficiency over a wider range of output power compared to a classical Doherty design. General design equations are also derived, and practical implementation issues are discussed in detail.

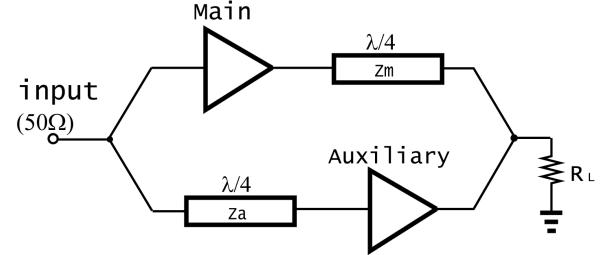


Fig 1. Diagram of the Doherty amplifier.

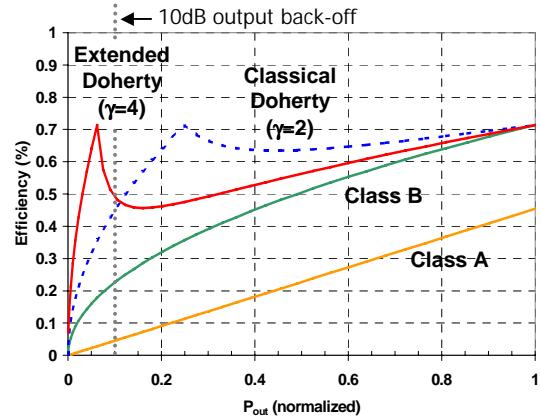


Fig 2. Comparison of calculated efficiency characteristics.

## II. PRINCIPLE OF OPERATION AND ANALYSIS

The Doherty amplifier consists of main and auxiliary amplifiers with their outputs connected by a quarter-wave transmission line ( $Z_m$ ). There is a quarter-wave transmission line ( $Z_a$ ) at the input of the auxiliary amplifier to compensate for the equivalent delay at the output. The main amplifier is biased Class B and the auxiliary amplifier is biased Class C so that it turns on when the main

amplifier reaches saturation. The auxiliary amplifier's current contribution reduces the effective impedance seen at the main amplifier's output. This "load-pulling" effect allows the main amplifier to deliver more current to the load while it remains saturated. Since an amplifier in saturation typically operates very efficiently, the total efficiency of the system remains high in this high power range until the auxiliary amplifier saturates.

Fig. 3 shows a schematic of the idealized Doherty output network that consists of two current sources (representing the two amplifiers), a quarter-wave transmission line with characteristic impedance  $Z_m$ , and the output load  $R_L$ .

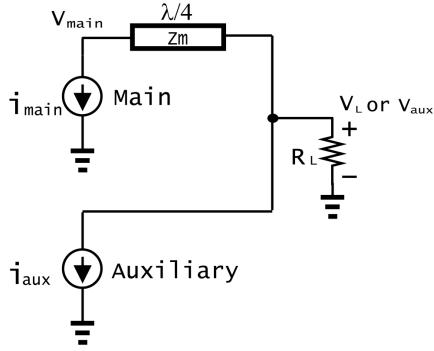


Fig. 3. Idealized output circuit used for analysis

Circuit analysis shows that the voltages at the output of the main amplifier and the load are given by:

$$V_{main} = \frac{Z_m^2}{R_L} i_{main} + jZ_m i_{aux} \quad (1)$$

$$V_L = -jZ_m i_{main} \quad (2)$$

If  $i_{critical}$  is defined as the value of  $i_{main}$  when the main amplifier reaches saturation, then  $i_{aux}$  can be defined in relation to  $i_{main}$  as

$$i_{aux} = \begin{cases} 0 & i_{main} < i_{critical} \\ j\gamma(i_{main} - i_{critical}) & i_{main} \geq i_{critical} \end{cases} \quad (3)$$

where  $\gamma$  is a parameter that determines the value of  $i_{critical}$  in relation to  $i_{max\_main}$ , the maximum value of  $i_{main}$ ,

$$i_{critical} = \frac{1}{\gamma} i_{max\_main} \quad (4)$$

The value of  $Z_m$  is obtained by inserting  $i_{aux}$  (3) into the expression for  $V_{main}$  (1), and solving for  $Z_m$  that makes  $V_{main}$  a constant, or saturated, value:

$$Z_m = \gamma R_L \quad (5)$$

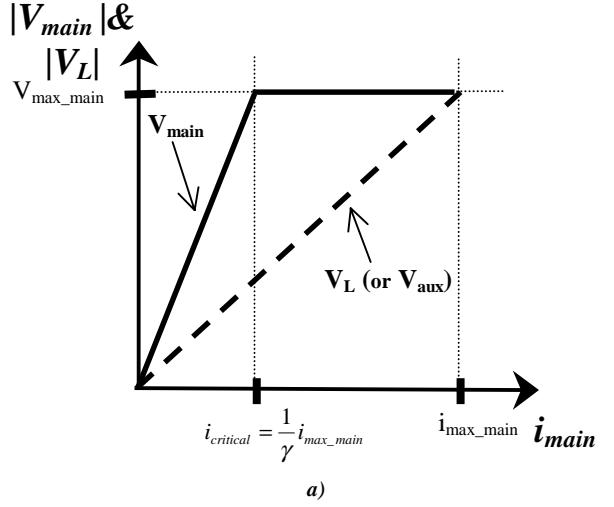
where  $V_{main}$  is

$$V_{main} = \begin{cases} \frac{Z_m^2}{R_L} i_{main} & i_{main} < i_{critical} \\ \frac{Z_m^2}{R_L} i_{critical} & i_{main} \geq i_{critical} \end{cases} \quad (6)$$

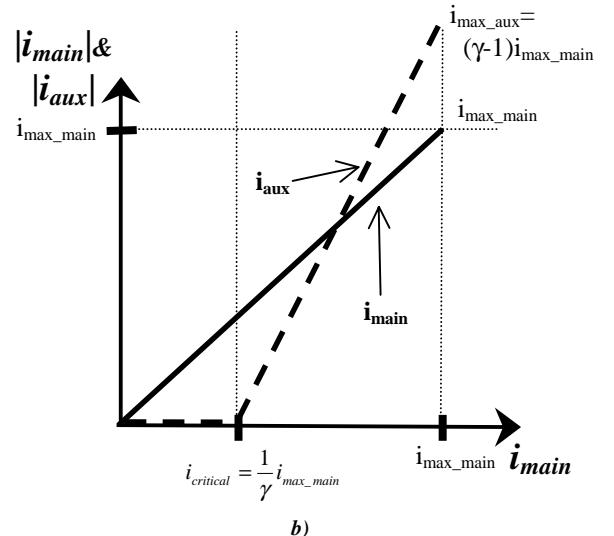
Using expressions for  $\gamma$ ,  $V_{main}$ , and  $V_L$ , the effective load seen by the two amplifiers can be analytically obtained for low drive power ( $i_{main} < i_{critical}$ ) and peak power conditions ( $i_{main} = i_{max\_main}$ ).

$$R_{main} = \gamma^2 R_L \quad i_{main} < i_{critical} \quad (7)$$

$$\left. \begin{array}{l} R_{main} = \gamma R_L \\ R_{aux} = \frac{\gamma}{\gamma-1} R_L \end{array} \right\} \quad i_{main} = i_{max\_main} \quad (8)$$



a)



b)

Fig. 4. Graphical representation (not drawn to scale) of the Doherty output as a function of  $i_{main}$ : a) voltages; b) currents.

Figures 4a and 4b graphically summarize equations (1)–(6). Figure 4a shows  $V_{\text{main}}$  and  $V_L$  (or  $V_{\text{aux}}$ ) as a function of  $i_{\text{main}}$ .  $V_{\text{main}}$  increases proportionally to  $i_{\text{main}}$  with a slope of  $\gamma^2 R_L$  and reaches a constant saturated value,  $V_{\text{max}}$ , at  $i_{\text{critical}}$ . Figure 4b shows  $i_{\text{main}}$  and  $i_{\text{aux}}$  plotted against  $i_{\text{main}}$ . This graph is useful in determining the maximum currents of the two amplifiers. Since  $\gamma$  is the slope of  $i_{\text{aux}}$  with respect to  $i_{\text{main}}$ , the value of maximum current  $i_{\text{max\_aux}}$  in relationship to  $i_{\text{max\_main}}$  can be determined, and proper areas of the two devices can be selected.

With  $\gamma=2$ , the classical operation of the Doherty amplifier is obtained where  $i_{\text{critical}}$  is half that of  $i_{\text{max\_main}}$ . This results in a peak efficiency starting from 6dB backed-off from peak power. The main amplifier can be made to saturate at a lower fraction of  $i_{\text{max\_main}}$  by choosing a higher value of  $\gamma$ . With an appropriate choice of  $Z_m$  given by (5) and scaling of the device size of the auxiliary amplifier governed by (3) to accommodate larger currents, an extended Doherty amplifier with  $\gamma>2$  can be designed which has higher efficiencies at back-off from peak power.

### III. DESIGN AND IMPLEMENTATION

A 950MHz ½Watt extended Doherty amplifier with  $\gamma=4$  was designed with InGaP/GaAs HBTs using microstrip on a printed circuit board from M.G. Chemicals with 60mil thick FR-4 dielectric ( $\epsilon_r\sim 4.3$ ,  $\tan \delta=0.025$ ). The HBTs were wire-bonded on to Tech-Ceram microwave packages. Since the auxiliary amplifier turns on at  $1/4$  the value of  $i_{\text{max\_main}}$ , we should theoretically observe high efficiencies starting from 12dB backed-off from peak power. A simplified circuit schematic is shown in Fig. 5.

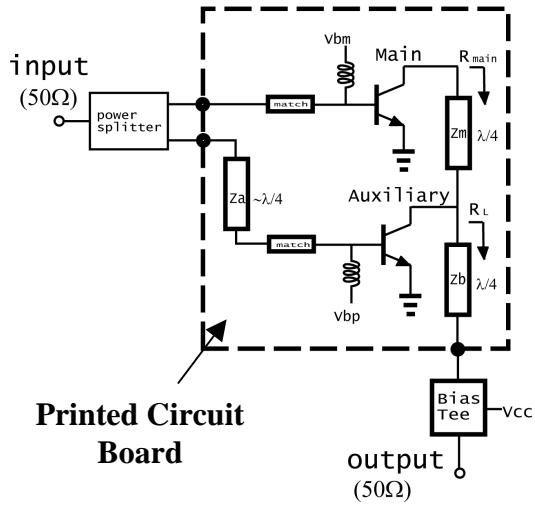


Fig. 5. Circuit implementation of the extended Doherty amplifier.

According to (7) and (8),  $\gamma=4$  results in the effective load seen by the main amplifier at low drive power to be  $16R_L$  and at peak power to be  $4R_L$ . The impedance

transformation from the output ( $50\Omega$ ) to  $R_L=4.5\Omega$  is done using a quarter-wave microstrip line and the quarter-wave transformation from  $R_L$  to the output of the main amplifier ( $R_{\text{main}}=72\Omega$ ) is also done using microstrip ( $Z_m=18\Omega$ ). By using microstrip for the output impedance transformations, biasing the collectors of the two transistors (with  $V_{\text{CE}}=4\text{V}$ ) is facilitated with external bias tees. According to Fig 4b, the ideal scaling ratio between the auxiliary and main amplifiers to maintain the same current density at maximum power should be 3 to 1. However, due to availability issues of the power HBT devices, a scaling ratio of 4 to 1 was chosen with total emitter areas of  $3360\mu\text{m}^2$  and  $840\mu\text{m}^2$  for the auxiliary and main amplifiers, respectively. The input matching networks for both the main and auxiliary amplifier employ simple LC low pass networks. It was found from simulations using Agilent-Eesof ADS that adjusting the delay in the auxiliary amplifier input path ( $Z_a$ ) was critical for proper Doherty operation. This delay was adjusted so that the output of the auxiliary amplifier lagged the output of the main amplifier by 90 degrees. Finally, the choice of the input power splitter was found to be very important. Several power dividing topologies were explored, including a resistive splitter and a Wilkinson power divider. It was determined that a 1:2 ratio power divider described in detail in [10] gave the best results. By having twice the power delivered to the auxiliary amplifier than the main amplifier, gain flatness was achieved in the output power range when the auxiliary amplifier was on.

### IV. EXPERIMENTAL RESULTS

Power measurements were made on this amplifier at 950MHz. Fig. 6 shows a one-tone power sweep with measured output power, PAE, and gain as a function of input power.

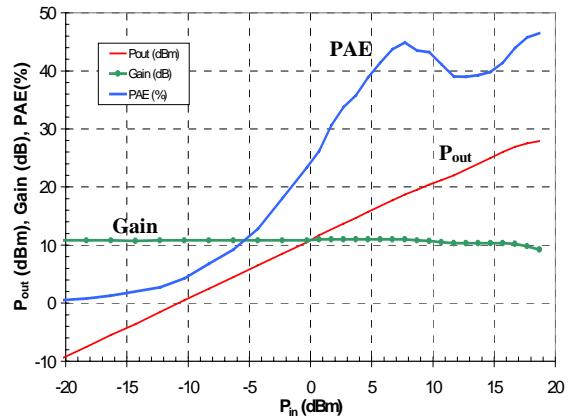


Fig. 6. Output power, gain, PAE versus input power.

The characteristic behavior of the Doherty amplifier is discernable where PAE reaches an initial peak and remains high until peak power is reached. This initial peak PAE at 45% (which is approximately when the main amplifier

saturates and the auxiliary amplifier turns on) occurs at an output power of 18.5dBm.  $P_{1dB}$  is at 27.5dBm with a PAE of 46%. The output power range between these two critical points is 9dB. This result is an improvement over the classical Doherty amplifier, where this high efficiency region is typically 5-6dB backed-off from  $P_{1dB}$ . Additionally, PAE of at least 39% is maintained over an output power range of 12dB from  $P_{1dB}$ .

A single transistor “control” amplifier with similar gain,  $P_{1dB}$ , output bias voltage, and quiescent current (using the same HBT as the auxiliary amplifier) was designed and measured for comparison purposes. PAE and DC currents for both the extended Doherty and “control” amplifiers are plotted against output back-off from  $P_{1dB}$  in Fig. 7. Also shown is a probability density function (or power usage profile) of a representative mobile transmitter. The key feature of the extended Doherty amplifier is demonstrated when its efficiency characteristics and the probability of transmission are considered together. For example, PAE of 43.5% is measured at 10dB back-off, and PAE of 15% is measured at 20dB back-off from  $P_{1dB}$ .

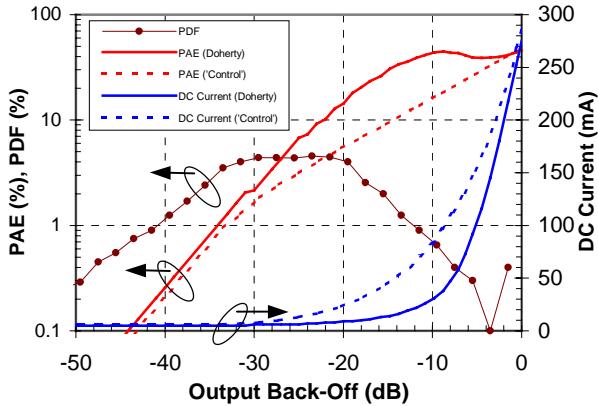


Fig. 7. PAE, PDF, and DC current versus output back-off

Using the definition of average system efficiency from Hanington *et al.* [11],

$$\eta_{ave} = \frac{\langle P_{out} \rangle}{\langle P_{in} \rangle} \quad (9)$$

average efficiencies for the extended Doherty and “control” amplifiers are calculated to be,

$$\begin{aligned} \eta_{ave} &= 24.3\% & \text{(Extended Doherty)} \\ \eta_{ave} &= 14.7\% & \text{("Control")} \end{aligned}$$

There are several issues that need to be addressed for the extended Doherty amplifier to be suitable for mobile transmitter applications. In the current implementation, quarter wave lines used at the input and output are long, where quarter wavelength at 950MHz is approximately 1.6 inches on FR-4. However, this can be alleviated by representing it with an equivalent lumped  $\pi$ -network, which will reduce the size of the circuit. Another

important issue is linearity. In this implementation, the amplifiers were biased for optimal efficiency and sufficient gain, without regard for linearity. It is anticipated that good linearity can be achieved by adjusting the bias, although this will reduce peak efficiency.

## V. CONCLUSION

An  $\frac{1}{2}$ W extended Doherty amplifier with high efficiency over a wide range of output power was demonstrated with InGaP/GaAs HBTs. PAE of at least 39% is maintain over a range of 12dB backed-off from  $P_{1dB}$ . With the need of higher efficiencies at low power in wireless communications, this type of amplifier may potentially play an important role in such applications.

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