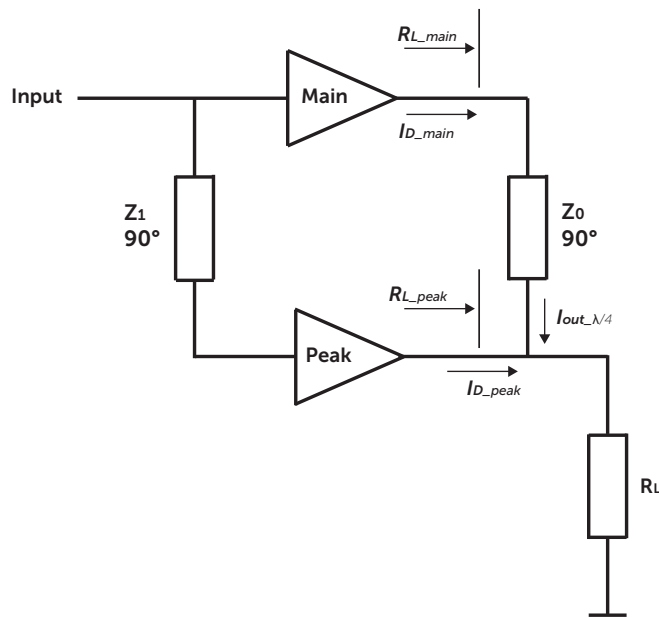


# Active Load-Pull System in Doherty Power Amplifier

## Application Note #63

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This paper explains how the Mesuro Active Load-Pull measurement system can be used to aid the design and optimization of Doherty power amplifiers, and shows how the Measurement system can offer new, useful information that can improve Doherty designs.

## Abstract

In general terms, power amplifiers used in communications systems must be large enough to amplify envelope peaks. This leads to amplifiers that are designed to offer the best efficiency at peak power, while actually spending most of the time operating inefficiently, amplifying smaller signals. With the advancement in next generation communication systems, which employ signals with ever increasing peak to average ratio, the pressures on the PA design continue to grow.

Techniques such as Doherty amplifier structures [1] are therefore used to extend high efficiency device operation to lower power levels, allowing for significantly improved average power amplifier (PA) efficiency. This white paper explains how the Mesuro Active Load-Pull measurement system can be used to aid the design and optimization of Doherty power amplifiers, and shows how the Measurement system can offer new, useful information that can improve Doherty designs.

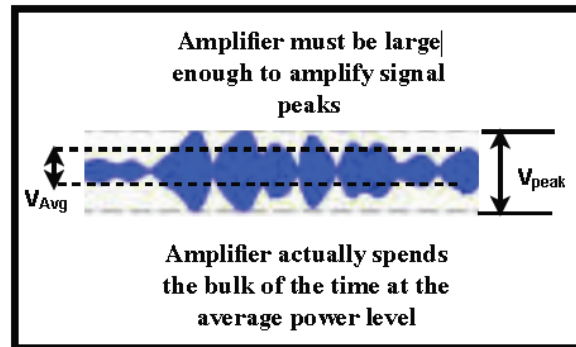


Figure 1

**Index Terms:** Doherty amplifier, Active Load Pull

# Introduction

In a Doherty amplifier, shown in schematic form in Figure 2, we are interested in the interaction between two, closely-coupled devices. Unlike balanced amplifier configurations, the devices are allowed to interact via an impedance transformer. In essence, the structure employs active load-pull between the "Main" and "Auxiliary" device which cause the impedance presented to both devices to vary, quite dramatically, as a function of the envelope magnitude. The aim is

to maintain the high voltage swing around the main device, which allows the high efficiency operation at peak power to be maintained as we back the amplifier off. This can be achieved by operating the "main" device into higher impedance  $2R$  (twice the optimum at peak power), when the signal level is at its average power level, then reduce the impedance seen by this device to the optimum impedance  $R$  as the power increases towards the peak power of the signal.

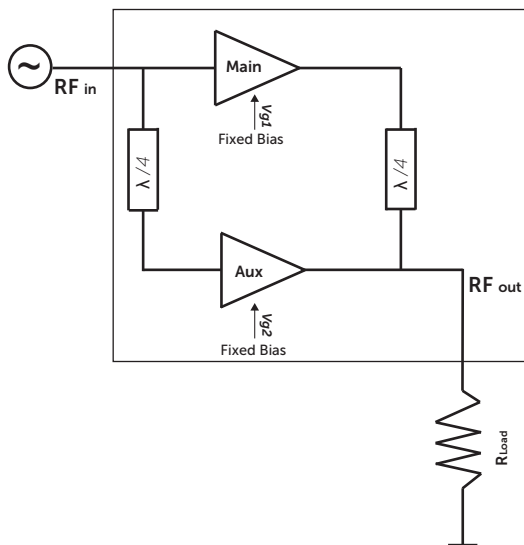
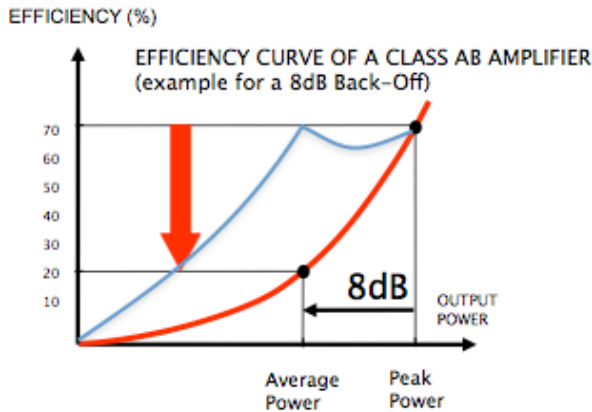


Figure 2

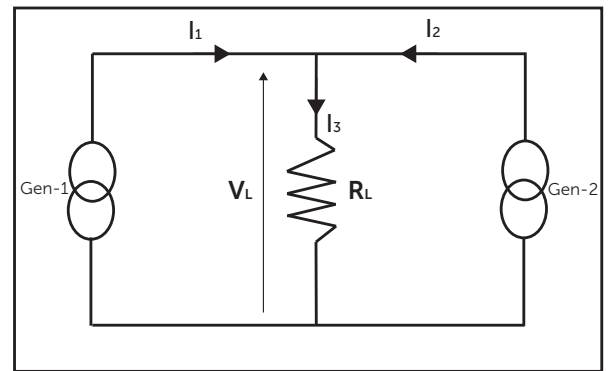


Figure 3

The principle of the Doherty power amplifier operation can be described using ideal current generators as represented in figure 3. Phase coherent currents  $I_1$  and  $I_2$  flow within the load, developing the load voltage  $V_L$ . By "pulling" the load, the approach allows the possibility of maintaining a constant voltage across the load and in this case, at the output of Gen-1.

In a device with Doherty amplifier the main device is typically biased in class B, with the auxiliary device biased deeper in class C. This way at low power levels, up to the average signal power, only the main device conducts, in this case the main device 'sees' only the physical load resistance which has a value of  $2R$ . When the power becomes large enough for the auxiliary device to begin to conduct, the current supplied by this device appears as voltage injection at the "main" device. As this voltage increases it gradually reduces the impedance 'seen' by the main device, reaching the optimum impedance ( $R$ ) at the peak power. At the same time, the impedance seen by the "auxiliary" device decreases from a very high impedance (close to open circuit), as it begins to conduct, down to a value of  $R$ , such that at peak power both devices are operating into their optimum impedance, both delivering half of the total power. Careful selection of the bias and impedance transforming circuit then allows for dramatically improved average efficiency of the amplifier.

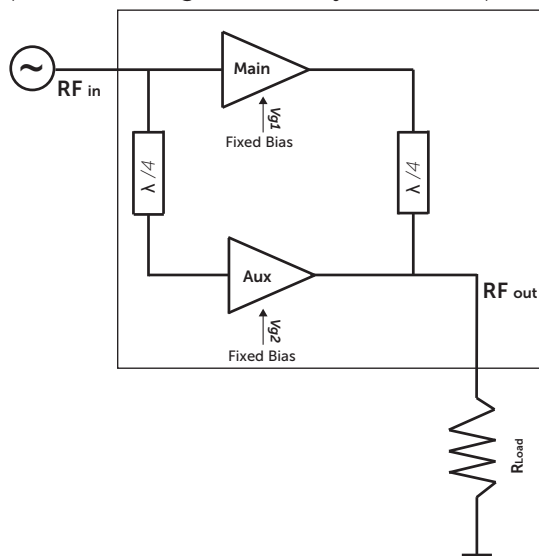


Figure 4

Figure 4 shows the classical Doherty structure which is a closed structure, RFIN to RFOUT. The RF power division and bias is set internally within the structure and typically remains fixed. As such, the Doherty design is treated as a black box when measured, characterized and optimized, often leading to a design purely conducted in a

CAD environment, using models (which always employ some form of approximation) for both active and passive circuit elements.

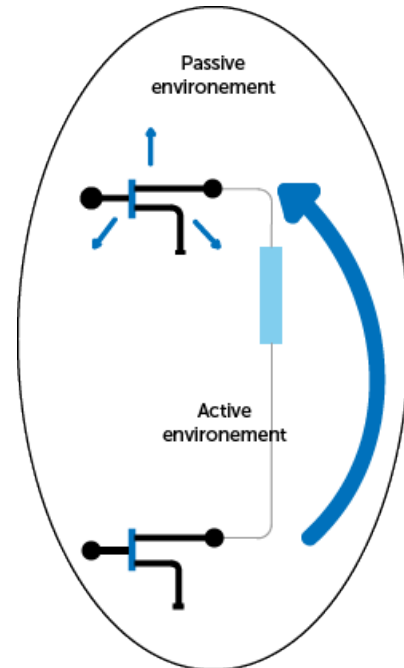


Figure 5

As probing the voltage and current directly within the structure is not possible, the structure provides a complex, dynamic impedance environment that can be difficult to understand, often leading to a requirement for multiple design iterations to meet a desired specification.

To avoid the limitations inherent to a black-box design approach, the PA designer needs to have increased information about and understanding of the behavior of the devices in the amplifier. The Mesuro measurement system allows the user to vary all of the important parameters that optimize the performance of the Doherty amplifier, the next section explains how by understanding the ideal and realistic dynamic impedance environments that exist around both main and auxiliary devices within the Doherty, it is possible to perturbate, explore and to ultimately identify the characteristics of the output matching network that are required to deliver optimum performance.

# Testing Doherty Structures using the Mesuro Active Load Pull System

The impedance environment within a Doherty structure is complex, and dynamic, if we understand it however, we can use active load-pull to synthesize it, both in terms of impedance caused by device interaction, and the natural impedance caused by the passive structure. We therefore use waveform engineering in Doherty design to synthesize the complete environment around each device within the Doherty structure. Note here that the use of waveform engineering techniques relies on the ability to de-embed back to the current generator plane - To fully exploit this approach the Mesuro measurement software has in-built functionality that not only allows the user to view measurement data at this current generator plane but also to load-pull the device from this reference plane. This Waveform engineering approach includes synthesis of the input drive, output load impedance and the bias conditions used while carefully observing the resulting voltages and currents generated.

The Mesuro measurement system can be configured in a variety of ways to fully characterize the Doherty structure, we will examine each of these and discuss how waveform engineering can be used to aid the designer of this type of structure:

Measurements begin with the Main device. As explained in the previous section, the object of this investigation is to dynamically vary the load as a function of input drive. The aim in real terms is to maintain a constant voltage swing (maximizing efficiency), while allowing linear current growth (maintain device linearity). The first step is to define the appropriate bias condition for the device. The Mesuro measurement system, using the setup shown in figure 6 allows for both DC and RF measurements.

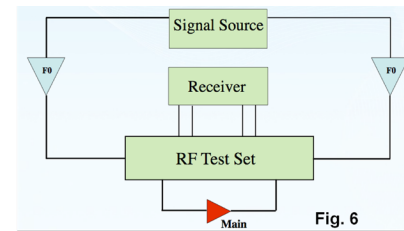


Figure 6

The desired class B bias point can therefore be estimated through DC measurements, then confirmed through the generated RF waveforms (a device operating in class B will have well defined output waveforms, a sinusoidal voltage, and out-of-phase half-rectified current waveform with a 50% conduction angle). The de-embedded current waveforms of a 0.25W MESFET device as this optimization is completed are shown in figure 7, with the chosen bias point highlighted with a dashed blue line.

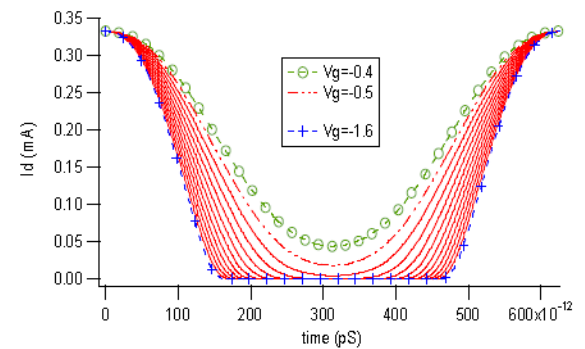


Figure 7

Now starting at the peak envelope power, we can perform load-pull measurements to calculate the optimum impedance  $R$ . Once complete we can store the voltage and current waveforms, then reduce the input drive - at each new power level, down to the value of the average signal power level. We can then use waveform engineering to maintain, as closely as possible, a constant voltage waveform. The result of such an optimization using the same 0.25W MESFET device is shown in Figure 8.

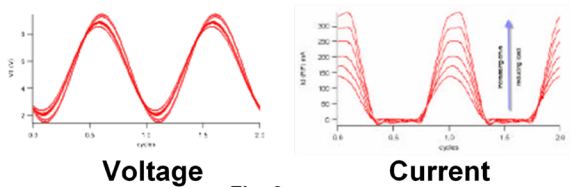


Figure 8

Once complete, it is possible to emulate the performance of the Doherty amplifier. For example using this approach it is possible to plot the emulated efficiency plateaux. In addition, by plotting the waveforms as dynamic load-lines on the I-V plane along with the DC measurement data, it is possible to observe key performance-related behavior, including the proximity of the load-line to the knee-region boundary, as well as any evidence of RF-DC dispersion.

This is illustrated in Figure 9, where for the MESFET device analyzed it is clear that the dynamic load-lines are where they are expected to be in relation to the IV plane, and there is good agreement between the boundary conditions revealed by the dynamic RF load-lines and those defined by the measured DC characteristics.

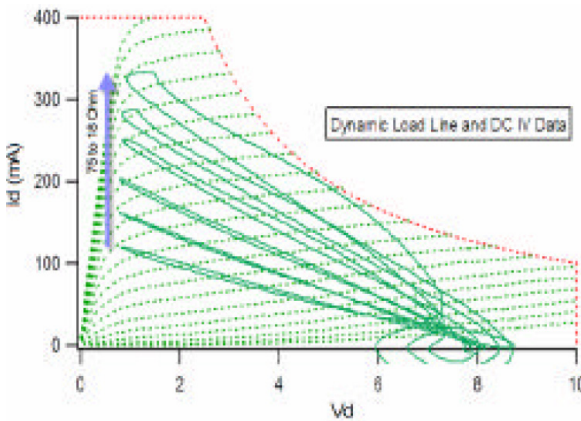


Figure 9

Once complete, it is possible to emulate the performance of the Doherty amplifier. For example using this approach it is possible to plot the emulated efficiency plateaux. In addition to this fundamental analysis the Mesuro system offers additional benefits to the designer in the form of impedance control at the harmonics.

This provides an even more powerful tool where harmonic impedances can also be used to engineer the waveforms for optimum performance - Through this approach it is possible to combine the very high efficiency performance obtained by harmonically optimized amplifiers such as class F and class J realizations, with the efficiency plateaux that can be obtained from a Doherty design.

Next we can analyze at the "auxiliary" device in isolation, the first step is again to try and optimize the bias conditions. In this case we are trying to bias the "auxiliary" device in such a way that it begins to conduct as the input power to the Doherty structure reaches the average power of the modulated signal. Again using the setup shown in figure 6, we can conduct DC and RF measurements to do this.

Using the information from the "main" device it is then possible to emulate the impedance environment around this device. This time, as well as being interested in the power and efficiency of the device under varying power conditions, we are also interested in the generated voltage. It is important to note that it is often the "auxiliary" device that causes reliability problems in Doherty amplifiers. This is because this device has a very dramatic impedance variation as the power increases, at switch-on the "auxiliary" device sees a very high impedance approaching an open circuit, which reduces down to R the optimum impedance as we reach peak power - using the active load-pull system it is possible to emulate this, as, unlike passive systems, the Mesuro system can overcome loss and reach all parts of the Smith chart.

When the device is operating into the high impedance state the generated voltage will of course be large, analysis of the measured voltage waveforms can show if we are getting close to the voltage breakdown of the "auxiliary" device, which could lead to damage, stress and ultimately failure of this device, the design can be modified if necessary after this investigation to avoid

this, improving the reliability. (This is often simply a case of altering the gate voltage, so that this device turns on slightly later - thus reducing the impedance seen on turn-on).

Finally, with the output matching network in place we can modify the measurement system setup as shown in figure 10, to have dual, independent drive. In this case, the measurement system captures only the output performance for this 50 Ohm measurement. This measurement approach can be used to consider what happens if we have imperfect phase balance between the main and auxiliary devices. This can be used in two ways, firstly to consider what would happen if the design did not offer an ideal phase relationship for the "main" and "auxiliary" devices (This could be useful for example if we were trying to design a wider-band Doherty amplifier, where it would only be possible to design the correct relationship at a single frequency, with trade-offs used to design the relationship over the rest of the band).

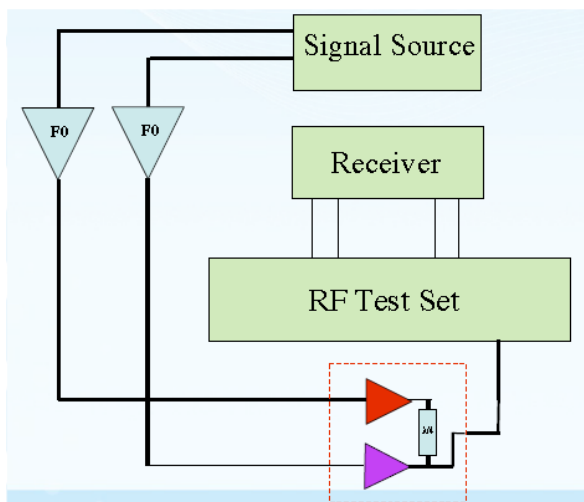


Figure 10

Alternatively in a more standard design these measurements could be used to allow the designer to correct for AM/PM behavior before the design is manufactured. Figure 11 shows a 3D plot showing the relationship between efficiency as a function of  $P_{in}$  as the phase between the input signal to the two devices is varied, for the same MESFET Doherty amplifier.

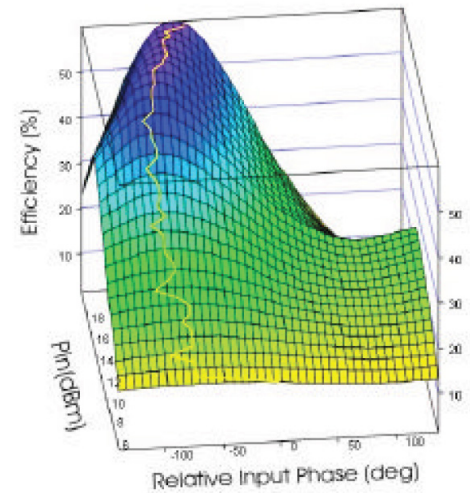


Figure 11

Once the investigations are complete, the design can be realized by attempting to realize a matching network to recreate the optimum conditions discovered using the Mesuro measurement system. Inevitably there will be some design trade-offs which mean that compromises will be necessary. Therefore, once the passive circuit environment has been designed, it is often useful to repeat some of the measurements using the measurement system to give a more realistic idea of the performance that can be expected from the manufactured design. In doing this, if the desired specifications are not met, further optimization of the design can be conducted, each time using the measurement system to verify the performance. In this way, by the time the design is committed to manufacture there is greater confidence that the design will meet the specifications.



# Doherty Structures using New Device Processes and Materials

Designing with immature device processes and materials leads to added difficulties in PA design. One major advantage of the Mesuro measurement system, as discussed earlier, is the ability to observe the dynamic load-line behavior, through the measurement of voltage and current waveforms. Using the waveforms to compare the dynamic RF performance (at the de-embedded current plane) with the DC performance can give the designer a clear understanding of device-related issues, and even offer insight into by-passing the problem through appropriate redesign, such as operating the device under different bias/load conditions [2,3].

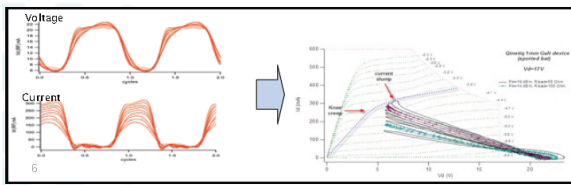


Figure 12

The above analysis, illustrates how the device's knee voltage has 'crept' from around 3V to 6V and the available RF current has collapsed from approximately 500 mA to 300 mA. Compounding these problems, the resulting sub-optimal impedance presented to the device results in disappointing output power and efficiency. To re-optimize the Doherty structure such that the effects of knee voltage 'walk-out' are reduced, further large-signal measurements were conducted and a drain voltage of  $V_d=12V$ . This allowed for a reduced 'slumped' current of 350mA and the reduced knee voltage of 3V. Using this approach, the value of R was conveniently maintained at  $50\Omega$ , allowing the same structure to be used. The new dynamic load-line is shown in figure 13, and clearly shows that the collapse

in knee-voltage is not as significant and has receded to somewhere in the region of 3V, for a similar maximum current of 300 mA.

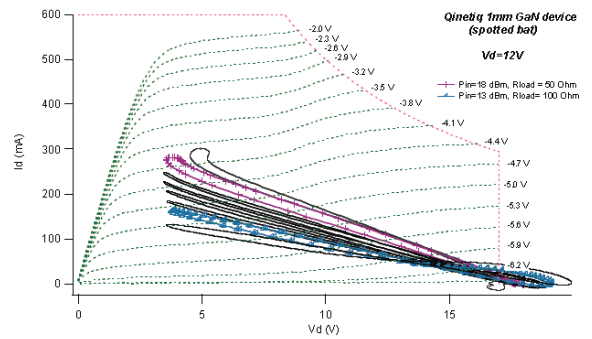


Figure 13

When device performance is re-considered, in comparison to the  $V_d=17V$  case, figure 14 reveals a plateau of improved efficiency between 40% and 50% over 8 dB of dynamic range, representing an approximate 10% improvement. This is alongside a maximum output power of 27.5 dBm, only marginally lower than the  $V_d=17V$  case.

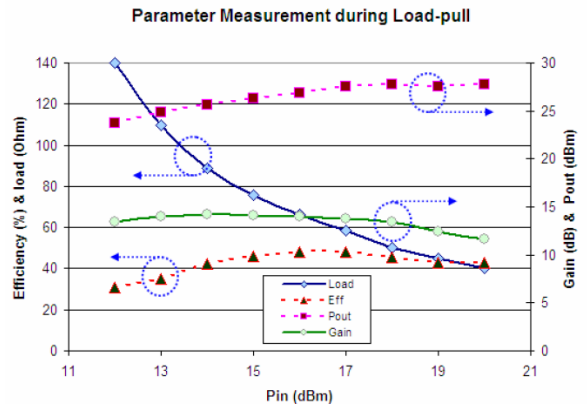


Figure 14



## Conclusion

This application note has described how the Mesuro active load-pull system can be used to design and, perhaps more importantly, optimize Doherty designs. The system can be used in its standard configuration to independently measure and optimize the 'Main' and 'Auxiliary' devices. Once complete the output stage design can be completed, and the system re-configured to look at the input of the structure - this is particularly useful for wide-band Doherty design, where the effects of un-even phase of the drive signal can be observed. In addition using this information, it may be possible to take account of AM-PM behavior and compensate with the input architecture. A case was also examined where an immature device technology (in this case an early immature GaN transistor) was used for the Doherty design, here the current and voltage waveforms, plotted as a dynamic load-line, were used to diagnose a device related problem, and allowed re-optimization of the design before manufacture.

Importantly the measurement system also allows for optimization of harmonic impedance allowing the designer to further improve overall efficiency performance by combining the Doherty Amplifier approach with a harmonically tuned class of operation.

It is clear that by capturing the right set of measurements, and then re-optimizing the design before manufacture, the design cycle can be significantly reduced, reducing time to market for new products. In addition by considering time-domain waveforms within the design process and through appropriate design techniques the reliability of the Doherty amplifier can also be improved.

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