

# High Efficiency Communications Amplifier

*A microwave Doherty amplifier is described by the authors which uses an old low frequency amplifier configuration to obtain high efficiency over a 6 dB range, important for linear communication systems having many independent channels.*

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New commercial and military telecommunications systems have shown a trend toward using digital modulation techniques over the past few years. These digital systems require the capacity to handle a high density of carrier frequencies to be cost effective. The additional trend toward space based systems imposes high efficiency and weight constraints. Power amplifiers represent an important design challenge if they are to conform to these specifications.

Unfortunately, high efficiency in power amplifiers has been difficult to attain while supporting a large number of carrier frequencies wherein good linearity is also required. In fact, this is a direct trade-off in conventional amplifier design. It is important to note that the amount that the input drive must be reduced from the saturation level is directly proportional to the number of carrier frequencies.

Previous techniques have been developed to overcome this problem. However, they require complicated circuit designs that are large and difficult to implement and none of these techniques is suitable for implementation in a space based or high volume communication or radar system due to the attendant size, weight, reliability,

For points of operation between these two extremes, the Doherty amplifier works in the following manner: The peak amplifier is designed to begin operation when the carrier amplifier just begins to saturate. Maximum linear efficiency is obtained at this point. As the input drive level is further increased, the peak amplifier is activated and delivers output power to the load. Because the RF voltage at the load,  $R/2$ , is saturated, the additional current supplied by the peak amplifier has the effect of increasing the load impedance at the output end of the quarter-wave transformer. The effective change *at the carrier amplifier end* of the transformer is a *reduction in the apparent load impedance*, enabling the carrier to deliver more power while its RF voltage remains saturated. This continues until the second extreme is reached. At this point four times the output power of the carrier amplifier alone is delivered to the load, and the maximum efficiency again is obtained. The efficiency between the extremes falls off only slightly from the maximum, since the duty factor for the peak amplifier is relatively low.

In this way the Doherty amplifier effectively allows 6 dB of linear power amplification beyond the point at which a standard Class B amplifier begins to saturate, and throughout the 6 dB extension the overall amplifying efficiency remains close to the maximum attainable linear efficiency.

### Practical Design Considerations

Selection of the transistor device peripheries resulted in a Class B load-line having an acceptable match to 50 ohms, facilitating characterization of the amplifier. The optimal load-line impedance decreases in inverse proportion to device size, as is true for any power amplifier. The 600 $\mu\text{m}$  devices selected can be operated without an input matching network into a purely resistive load-line of 50 $\Omega$  and achieve adequate power performance. Representative results of a device operated in Class B are 12 dB of gain, 60% power-added efficiency, and normalized power output of 600 mW/mm at the 1 dB compression point.

An advantage of constructing the amplifier in this manner is the robustness of the combining technique, brought about by the lack of input matching circuitry. The PHEMT devices consist of six 100 micron width gate fingers with gate lengths of 0.25 microns. An airbridged source-over-gate geometry was used to fabricate these devices. Each 100 microns of cell had 50 microns channel-to-channel spacing with a source-to-drain width of 5 microns. Offset single recess gates with mesa doped

at  $5 \times 10^{17}$  atoms/cm<sup>3</sup> are used, while the source and drain bars are 20 and 30 microns in width, respectively.

A standard broadband stripline coupler was used as the quadrature input hybrid network. The isolated port was terminated with an external 50 ohm resistor. The outputs of the coupler were connected to bias tees to inject the DC gate bias voltages onto the signal lines. Two semi-rigid 0.141" diameter coaxial transmission lines of approximately equal length were used here, while another matched length set was used between the bias tees and the test fixture. The test fixture was furnished with SMA microwave coaxial connectors which terminated onto a 25 mil thick 99.6% pure alumina substrate upon which were printed thin-film microstrip lines of 24 mils in width. These lines served to transport the microwave signal from the SMA connectors up to the center-bar where the active devices were mounted. Connections to and from the active devices were made by thermosonic bonding with 1 mil diameter gold wire.

DC bias to the output terminal of the devices was provided by another bias tee similar to that used in the input circuit. The microwave Doherty network and the final output matching network were realized on one piece of 99.6% pure alumina substrate material 25 mils thick. An additional length of 50 ohm line was printed on the substrate for fixturing convenience. The quarter wave output combiner is realized as a single 50 ohm microstrip transmission line. An arbitrary length of 25 ohm microstrip transmission line is then merged into a specified 35 ohm line which provides the necessary impedance transformation to the system impedance of 50 ohm. Except for the 25 ohm line, all of these lengths are a quarterwave at the design frequency of 1370 MHz. A computer plot of the artwork used to fabricate the alumina is shown as Figure 2.

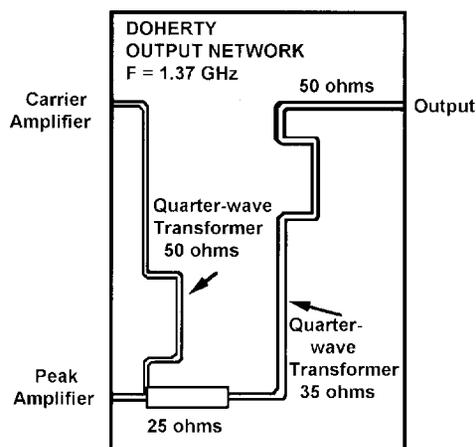


Figure 2. Microwave Doherty prototype output circuit. This circuit was fabricated on a 25 mil alumina substrate.

During operation of the amplifier the carrier device is biased for Class B while the peak device is biased below pinch-off. Suitable bias voltages can be determined beforehand by inspecting the I-V characteristics of the devices on a curve tracer.

### Measured CW and NPR Performance

The test setup employed to obtain the CW data consisted of a conventional CW source with some power amplification as shown in Figure 3. Special attention was given to ensure that all of the interfaces between interconnects remained at 50 ohms through the use of pads and isolators. Output from the device under test (DUT) was also monitored on a spectrum analyzer to permit observation of any instabilities which might occur. Power output from the DUT is measured using averaging power meters with appropriate corrections for coupling factors.

stress the amplifier.

The NPR test was first used by AT&T to measure distortion in voice telephony systems. This test methodology is better than traditional distortion tests as band limited white noise more closely approximates a fully loaded multichannel communications signal. The NPR signal can be modeled as a carrier with complex wideband AM and PM modulation. Since complex wide band AM and PM modulated signals have a larger peak to average time variation, the amplifier performance with the NPR signal will be different than with single or two tone stimuli. The amplifier distortion can be determined by filling all but one of the system channels with noise and observing the level of noise in this unoccupied channel after the amplifier. Third and fifth order intermodulation products generated by the amplifier can be observed most easily in this unoccupied channel. The NPR is calculated as the power ratio of these distortion products to that of an equal, adjacent, channel which is filled with noise. Figure 4 is an idealized representation of an NPR test signal as viewed on a spectrum analyzer.

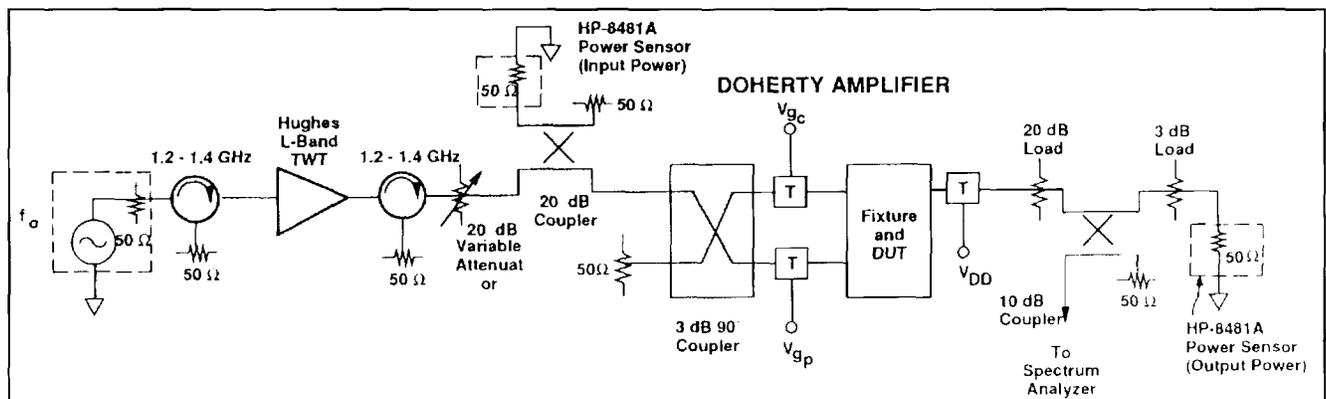


Figure 3. Test equipment configuration.

### Linearity Evaluation Techniques

Amplifier linearity and efficiency are both important in the characterization of power amplifiers used in communications applications. These amplifiers need to operate under adverse conditions while obtaining maximum output power with low distortion. Noise power ratio (NPR) measurements are a good way to evaluate amplifier performance when the real life signal includes multiple channels of information. NPR is a distortion measurement used to help determine the amplifier's maximum spurious free dynamic range. Another distortion measurement commonly used to determine amplifier linearity is the two/three tone test. However, in commercial applications, two/three tone testing does not provide the randomly changing amplitude versus time waveform or the peak to average ratio needed to fully

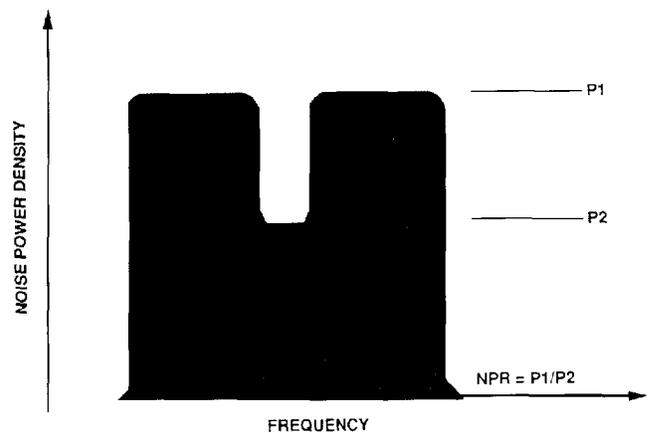


Figure 4. Measured I/O power (dBm).

The most common method for performing this measurement is identical to that originally used by AT&T. White noise is injected into a band-pass filter limiting

the noise to the DUT bandwidth, followed by a notch filter creating the unoccupied channel. This signal feeds directly into the DUT. NPR is determined by using more filters and a power meter to measure the signal. By increasing the input noise level while monitoring the NPR, the onset of system saturation can be determined.

There are some common variations to this technique which add more flexibility to the measurement. The noise signal is generated at baseband or some intermediate frequency then mixed with a variable local oscillator producing a range of frequencies. Now the band limited noise signal can be shifted in frequency to suit the needs of a particular amplifier under test. Additional notch filters at different frequencies can be switched in to determine the NPR at different points in the system band. Another variation that adds flexibility is the use of a spectrum analyzer. A spectrum analyzer can be utilized without the cost of using additional mixers to downconvert the notch frequency to a power meter. Also, automatic gain control (AGC) can be used to hold the total power in the noise bandwidth constant with and without the notch filter inserted. This way, both distorted power and transmitted power can be measured at the same frequency, saving the cost of some filters.

A measurement setup used to make an NPR measurement using this technique is shown in Figure 5. A variable attenuator can be inserted before the DUT to sweep the input power while the NPR is measured using a spectrum analyzer.

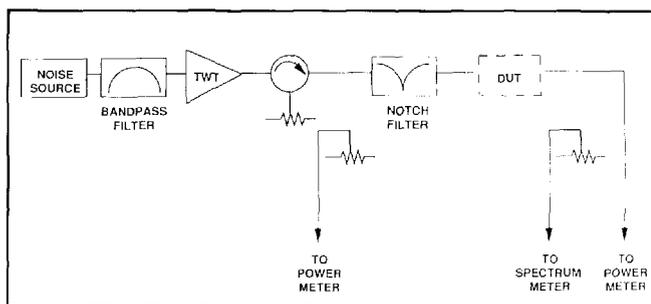


Figure 5. Measured efficiency of Doherty compared to ideal Class B amplifier.

The measured input power and output power in dBm for the Microwave Doherty Amplifier is shown in Figure 6. The highest output power shown on the graph is 28.5 dBm and represents the 1 dB gain compression point. This corresponds to a power density of 590 mW/mm, consistent with the performance of Class B amplifiers with these devices. Figure 7 shows the power added efficiency versus output power. At one dB compression the efficiency was 61%. This level of efficiency is main-

tained through a 5.5 dB reduction in output power. The efficiency for powers below this point fall off in a manner similar to that for a Class B amplifier. Although theory suggests a 6 dB range of peak efficiency, this result can be considered good, given that efficiency doesn't actually remain constant with increased load impedance for microwave transistors.

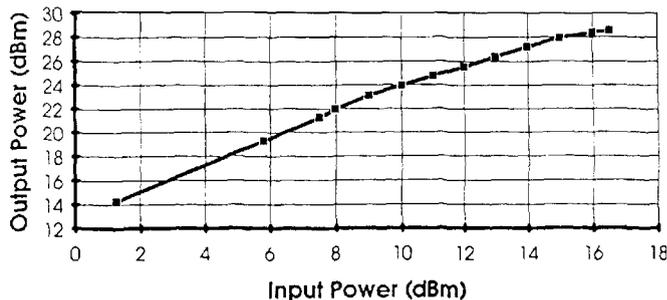


Figure 6. Measured input and output power for the Doherty Amplifier.

The efficiency of a Class B amplifier is proportional to the square root of its output power. The idealized efficiency performance of a Class B amplifier with a maximum efficiency comparable to the microwave Doherty amplifier has also been included in Figure 7. At 5.5 dB back-off from peak output power, the efficiency improvement offered by the Doherty amplifier is about 27 percentage points. While Class C or F amplification techniques could be employed to produce an amplifier with a peak efficiency greater than 62%, it would still fall off with reduced drive in the same manner as a Class B amplifier.

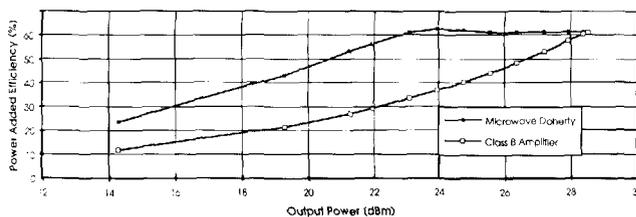


Figure 7. Ideal efficiency performance of a Class B amplifier compared to that measured for the Doherty amplifier.

Since most of the tuned circuitry typical to amplifiers was omitted in this experiment, the bandwidth was limited only by the quarter wave combiners. Comparable power performance over a 30% bandwidth was observed, however, the gain over this range was not flat. A larger and more complex realization of this technique would require input matching circuitry as well as a lumped element output combiner, particularly if implemented in MMIC form. These features will serve to further limit the bandwidth and careful attention to the design will be necessary.

Amplification and distribution of complex multi-carrier communication signals require new thinking about the behavior of power amplifiers. No longer can the peak efficiency and power output of the amplifier be accorded the most weight in the selection process. Rather, the behavior of the amplifier as a function of back-off primarily determines the overall system efficiency when handling multi-carrier signals. Future digital systems such as PCS/PCN and CT1, 2 will also reduce power output upon command thus compounding the efficiency problems for a fixed bias design. It is also desired that any solution be readily realizable in MMIC form and the Doherty amplifier can be so designed. The microwave Doherty Amplifier fulfills most of the needs for an amplifier suited to the next generation of signals. The added complexity of the circuit represents a relatively minor impact in cost and risk compared to the benefits afforded by its performance.

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*He has authored several papers on solid-state circuit design and is a co-inventor of a high efficiency amplifier. He is currently leading a module development effort for a satellite-based communications system. Peter Maloney is a section manager in the Microwave & Antenna Department of Raytheon's Equipment Division.*

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*David Upton received a BSEE Degree from Merrimack College in 1983 while first working for Analogic, Inc. on prototype NMR (MRI) transmitters and receivers. He was employed at the M/A-Com GaAs foundry in Lowell, MA and at M/A-Com's Microwave Circuits Co., Burlington, MA from 1984 until 1989. Since then he has been a member of Raytheon Company's Equipment Development Laboratories working on GaAs MMIC design and T/R module design.*

*He holds two patents in the area of low-noise design with others pending on the high efficiency amplifier techniques co-developed at Raytheon. David Upton has published several papers in conjunction with R. McMorrow and P. Maloney on these topics. He is an active amateur radio operator with the call sign WB1CMG.*