

Broad Band Amplifier Design Utilizing Coaxial Transformers

By

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Introduction

The design of decade miniature wide broadband power amplifiers has been precipitated by the desire of the armed forces to maintain instant communications with all forces. This requires the design of all band transceivers to cover tactical ground and air frequencies in addition to civil telecommunication frequencies and those frequencies of our allies. All band transceivers or radios are commonplace in virtually every deployment of new platforms in addition to retrofitting existing communications systems.

This paper will discuss the design of miniature coaxial structures and examine the implementation of improved design techniques to enable the designer to obtain insight in matching the load line of power MOSFET transistors over decade bandwidths.

The design presentation is the development of large signal parameters for a typical power MOSFET device and the development of a suitable load line using coaxial transmission line transformers in conjunction with embedded lumped structures to enable an efficient load line match across a decade of bandwidth.

Simulation Methodology.

Linear simulation is derived when a circuit with active devices is operated at such a low power that the simulated measurements are no longer power dependent. This simulation can be achieved by two methods. First the circuit uses a non-linear model and non-linear simulator. The quiescent current is set at a nominal condition and power level used in the simulation is set to a low level as not to make the output data power dependent. Another linear simulation method is to use tabular data to describe an active device and simulate with a linear simulator. Usually the data file is in S parameter format although other formats have been used in the past at lower frequencies. If the non-linear model and the data file agree, both simulations will yield the same measurement data. In the case of using a non-linear model with a non linear simulator the simulation results are generally very close to actual amplifier performance.

Non linear simulators provide gain compression, power output, efficiency and harmonic power data. With somewhat less accuracy, intermodulation distortion can be simulated, but not with the same accuracy as the single tone measurements due to the fact that to obtain accurate results, the device model would have to track an actual device transfer curve closer than 5%. Five percent accuracy is generally acceptable for gain compression and efficiency measurements, but not for the slight non-linearity that causes low to intermediate levels of intermodulation distortion. Modeling technology is slowing improving and it is expected that intermodulation performance maybe accurately

modeled in the future. Non linear simulators generally are more costly, but are really the only choice if large signal performance simulation is desired, as in the case of this article.

Amplifier Design

First one must determine the optimum load line impedance required by the device. Computer load pull or optimization is required since any actual load pull techniques are only generally available for much higher frequencies. The physical structures for generating load impedances at frequencies below 500 MHz are so large as to be impractical to implement. Additionally, since the band width is multi-octave, broad band matching structures must be used to determine the load line rather than multiple narrow band measurements. A computer with suitable software and good device models is the most practical approach. In this article we will use popular softwares such as AWR-Microwave and Office and Agilent – ADS and using Polyfet RF Spice Models to demonstrate broad band matching techniques.

Impedance Behavior of Transistors

At low frequencies, the device's output impedance is relative high compared with the calculated load line required to produce the desired power. As the operating frequency is increased, the output capacitance (Coss), reverse capacitance (Crss) and an increased saturation voltage lowers the optimum load line to achieve satisfactory performance. Over a decade of bandwidth, the optimum impedance can drop by a factor of 2. That is

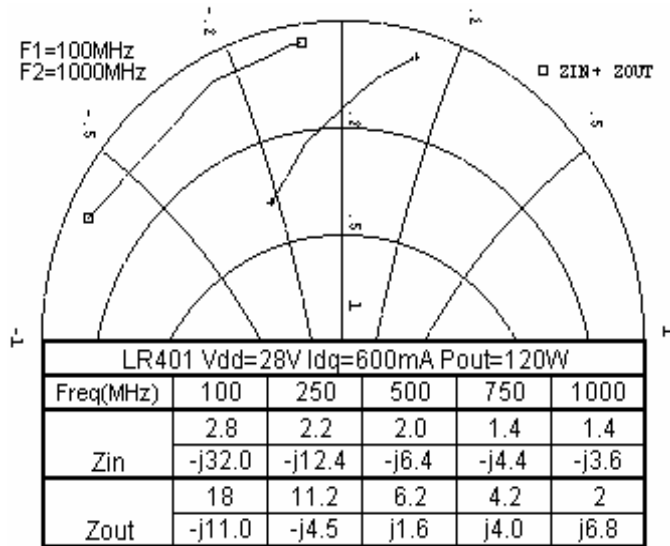


Figure 1 Zin Zout vs Frequency

components to achieve optimal power matching in a MOSFET power amplifier over more than a decade of bandwidth.

Computer simulated load pulling will be utilized to extract the first order magnitude of load line matching. This impedance information is only the starting point, since it will be extracted by a narrow band technique. Broad band extraction is an area that will be explored in the future as the results will take into account more realistic harmonic loading

to say that if the low frequency load line is 6 ohms, the upper operating frequency could require an impedance of 3 ohms with some amount of inductive or capacitive reactance. Figure 1 shows real value of Zout dropping from 11 ohms at low frequencies to 2 ohms at high frequency for the transistor LR401.

There has been considerable experimental and developmental work published on the attributes of coaxial transformer to achieve extremely wide bandwidths. This paper will explore how to implement the coaxial transformer with lumped

and allow more accurate broad band design implementation. In the case of Polyfet

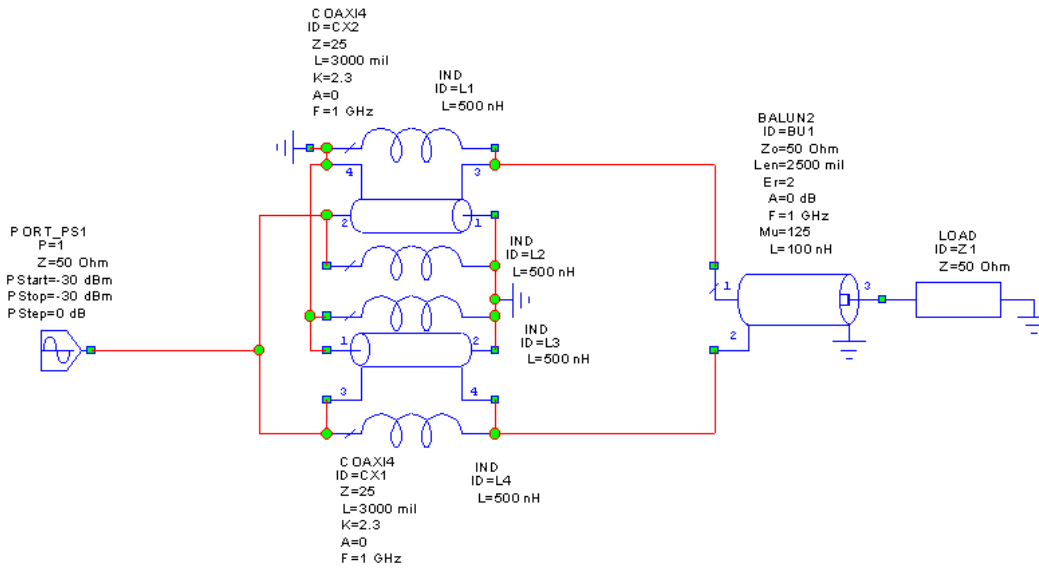


Figure 2 Conventional 4:1 with Balun

transistors, Zin Zout data can be found for each transistor in its respective data sheet.

Once the approximate load line has been determined, let us review the coaxial

Frequency (GHz)	ZIN[1] Coax (Real)	ZIN[1] Transformer (Imag)
0.03	11.10	4.92
0.08	12.94	1.91
0.13	13.07	0.94
0.18	12.99	0.45
0.23	12.87	0.17
0.28	12.73	0.02
0.33	12.60	-0.05
0.38	12.49	-0.06
0.43	12.41	-0.04
0.48	12.37	0.00
0.53	12.36	0.05
0.58	12.37	0.08
0.6	12.38	0.09

Figure 3 Uniform 4:1 transformation across frequency band

transformer matching techniques and explore the use of physical length, cable impedance, and lumped components in addition to ferrite loading to achieve optimum performance.

Of all the coaxial transformer designs, one of the most practical for wide band impedance matching is the 4:1 design with a balun transformer to achieve optimum balance. The standard accepted equation for transformation is that the Zo of the cable should be the square root of the product of the

input and output impedances. For example, if the input impedance is 12.5 ohms and the output impedance is 50 ohms, then the square root of

12.5 * 50 = 25. A 25-ohm impedance cable would give the optimum results across a wide operating bandwidth. Fig 3. shows a uniform impedance transformation ratio of four across the frequency band. It should be noted for the purpose of load line design, impedance is measured drain to drain. This allows single ended impedance measurements. Simply divide the impedance data by 2 to obtain individual device load impedance. At 30 Mhz the ratio falls off due to reactive shunt losses, which could be compensated with ferrite loading. The object is to design a load line that lowers the real resistance as the frequency increases. This requires some rethinking as to how one might exploit the benefits of transmission line matching in conjunction with techniques mentioned above to achieve a satisfactory load line over a decade of bandwidth.

A Novel Approach

The following is a presentation of how to embed a lumped matching network into a transmission matching network to achieve a suitable broad band power match. A

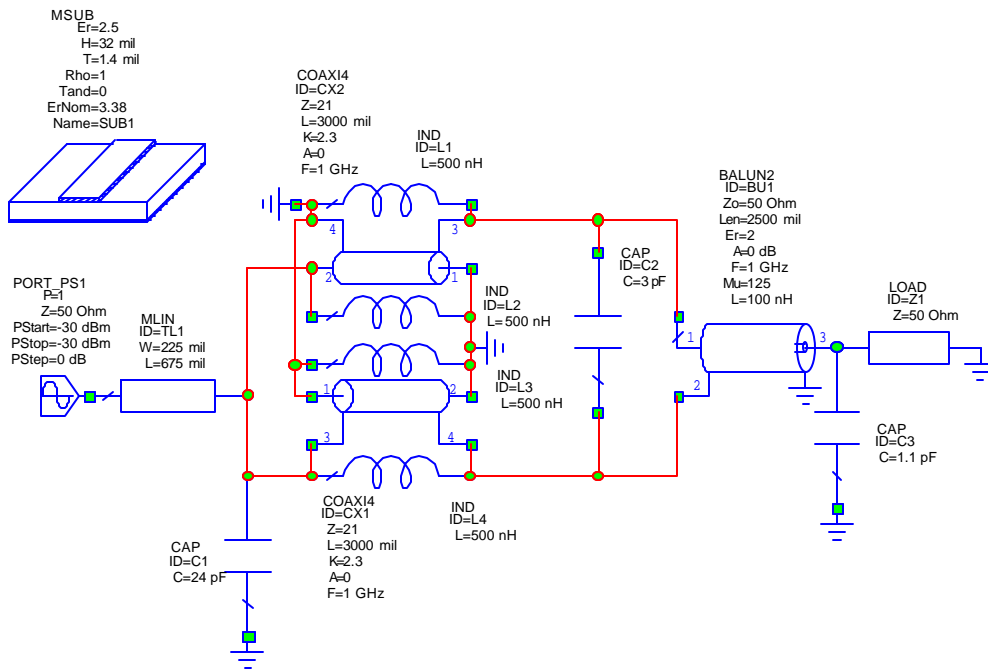


Figure 4 Variable 4:1 impedance

conventional design allow the coaxial transformer to transform the impedance to match the low end of the band and add additional low pass matching sections to lower the impedance at the upper band edge. Although this technique performs satisfactorily, using a micro-strip implementation will occupy considerable space. A novel approach, as shown in Fig 4, to this problem is to use the effective inductance of the coaxial transmission lines as the inductive component in a PI matching network. Only small chip capacitors will be needed to complete the transformation at the upper band edge. By a selection of the transmission line impedance and electrical length, a load line maybe created that will essentially provide the basic transformation ratios at the lower band

edge. As the operating frequency is increased the combination of the transmission line effective inductance along with the shunt capacitance will lower the load line to effectively match the device at the upper band edge. Fig. 5 shows the impedance dropping with increasing frequency. This can be accomplished is the same physical

Frequency (GHz)	ZIN[1] Coax Transformer (Real)	ZIN[1] Coax Transformer (Imag)
0.03	11.91	4.13
0.08	12.17	-1.02
0.13	10.06	-2.17
0.18	8.35	-1.77
0.23	7.29	-0.79
0.28	6.75	0.34
0.33	6.64	1.42
0.38	6.83	2.33
0.43	7.21	2.95
0.48	7.62	3.22
0.53	7.86	3.20
0.58	7.80	3.05
0.6	7.69	2.99

Figure 5 Impedance decreases with Freq

constraints as just a broad band transformer alone. Using this technique enables one to construct decade bandwidth power amplifiers with physical dimensions no larger than the transformers and the device. The savings in size can be critical in some applications.

lets calculate the low frequency load line. $(28-5)^2/2*80=3.31$ ohms or 6.62 for a push pull device. A 6.25-ohm load line that is achieved with a 4:1 coaxial transformer and a 1:1 balun easily accomplishes this task. Next using simulator generated large signal impedance data; review the optimum match at the upper band edge.

Designing the load line

For example to design an 80watt broad band amplifier that covers 30 512 MHz band, one would first calculate the load line for the lower band edge. Using a simple approximation of Steve Cripps law₁,

$$R_{load} = \frac{(V_{dd} - V_{dsat})^2}{2 * P_{out}}$$

The technique in broad band matching is normally to match the highest frequency and use the fact the power impedance contours where satisfactory operation can be obtained become larger as the operating frequency is reduced.

The next step is to use a linear simulator to embed the matching structure into the transformer structure. In order to successfully embed the upper edge matching network into the transformer the electrical length of the transformer should be shorter than 1/8 wavelength at the highest operating frequency. This will keep the transmission line acting as an inductance. Both the length and impedance maybe varied to optimize the performance over the band.

For example, to design an embedded matching network for the Polyfet LR401 push-pull MOSFET device, one would start with the power level desired and determine the low frequency load line. Since the low frequency load line is output power related and not necessarily a function of the output impedance of the device, we will use a 4:1 coaxial transformer followed by a 1:1 balun transform to establish a solid 6.25 ohm load line from the lower band edge up to several octaves higher or around 120 MHz. Above 120 MHz, the large signal impedance will determine the impedance transformation required to maintain adequate performance. The technique in broad band matching is normally to match the highest frequency and use the fact the power impedance contours where satisfactory operation can be obtained become larger as the operating frequency is reduced.

Large Signal Simulation

Once the load line has been designed, it is time for large signal simulation. The input matching section is designed in a similar manner as the output section with the exception that since the return loss can be measured during simulation, it is much easier to either manually tune or automatically optimize the input circuit.

Assuming the tentative circuit design has been completed, the next step is non-linear simulation. It is strongly recommended to start the simulation at a low input power level and check for small signal gain, flatness, and input return loss. The input return loss maybe tuned under small signal conditions since it will not change significantly as the power level is increased. Do not attempt to tune on the output matching section under small signal operation, since the load line tuning is extremely power sensitive. Once satisfactory gain and return loss has been obtained under small signal condition, slowly raise the input power until the amplifier starts to compress, typically the compression will first occur at mid to the higher frequencies. The goal of high power optimization is to obtain a flat compression point across the highest octave of amplifier operation. Manual tuning or an optimization feature may accomplish this goal. Manual tuning is usually the best avenue of approach since most optimization routines are somewhat linear simulation based, variables have to be constrained greatly (component values) in order to get meaningful results. With today's Pentium computers and improved EDA software, non linear simulation speeds approach that of linear simulation just a few years earlier. Real time non-linear tuning is a reality. As the optimum load line is approached, slight optimization of the input circuit will be required to obtain an optimum input return loss. Since the output load line tuning has minimal effect on the input tuning only a slight adjustment should be required.

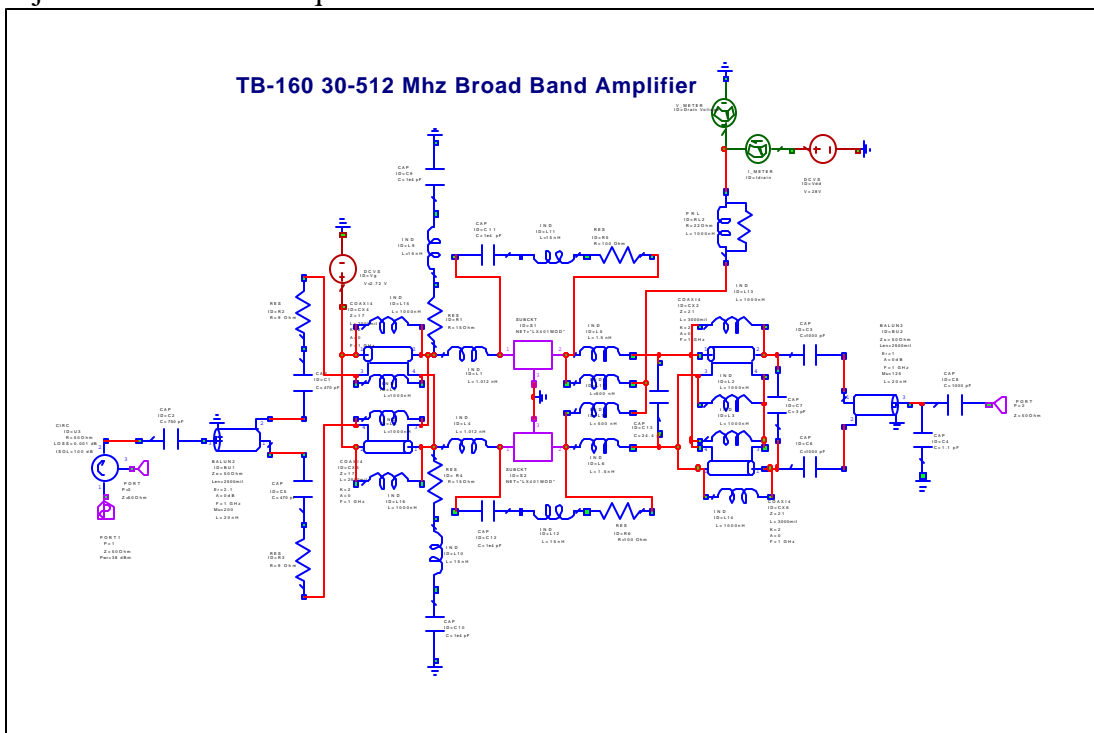


Figure 6 Input Schematic for Non Linear Simulation

The circuit used in simulation shown in Fig 6. consists of similar input and output matching networks described earlier in this article. The series R-C on the output of the input balun acts as series gate resistance to lower the gain of the transistor. Series RLC network between gate to source is added to stabilize the transistor from low frequency oscillations and series RLC drain to gate feedback is added to further enhance stability and achieve a flat band gain. The schematic shows additional inductances to represent strip line pads for components mounting. The drains of the transistors are fed to DC supplies through chokes that are represented by air coils. At the DC supply feed, there is a choke with a parallel resistor to further increase the stability of the amplifier. Figure 7 shows the computer generated artwork courtesy of AWR,.Inc.² and figure 8 is a picture of the actual amplifier built from the simulation and artwork.

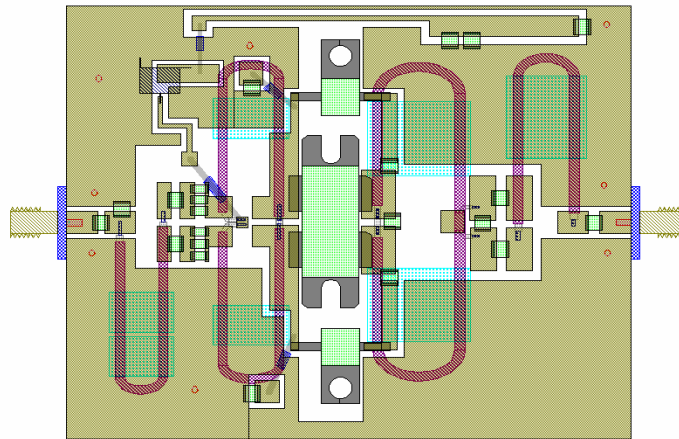


Figure 7 Input Schematic with layout Feature

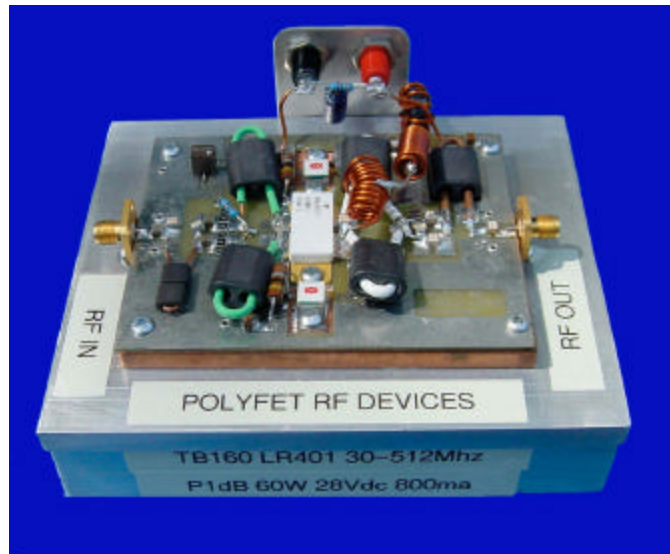


Figure 8 Actual Amplifier. Note small Size

Simulation Results

Very good correlation between simulated and actual measurements can be seen between Figs 9 and 10 and between Figs 11 and 12, verifying validity of models of both active and passive components.

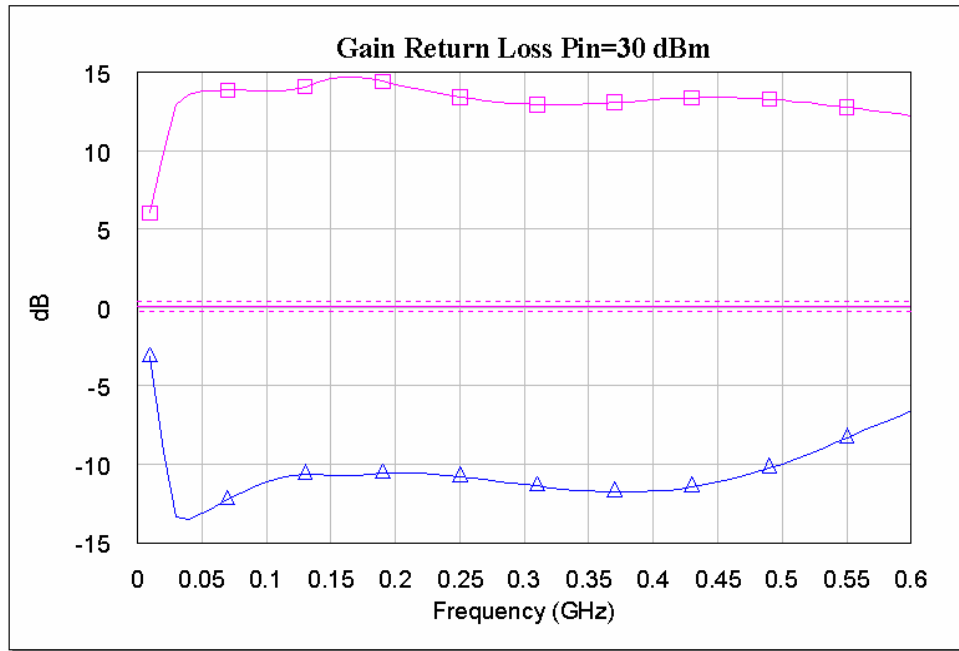


Figure 10 Simulated Values

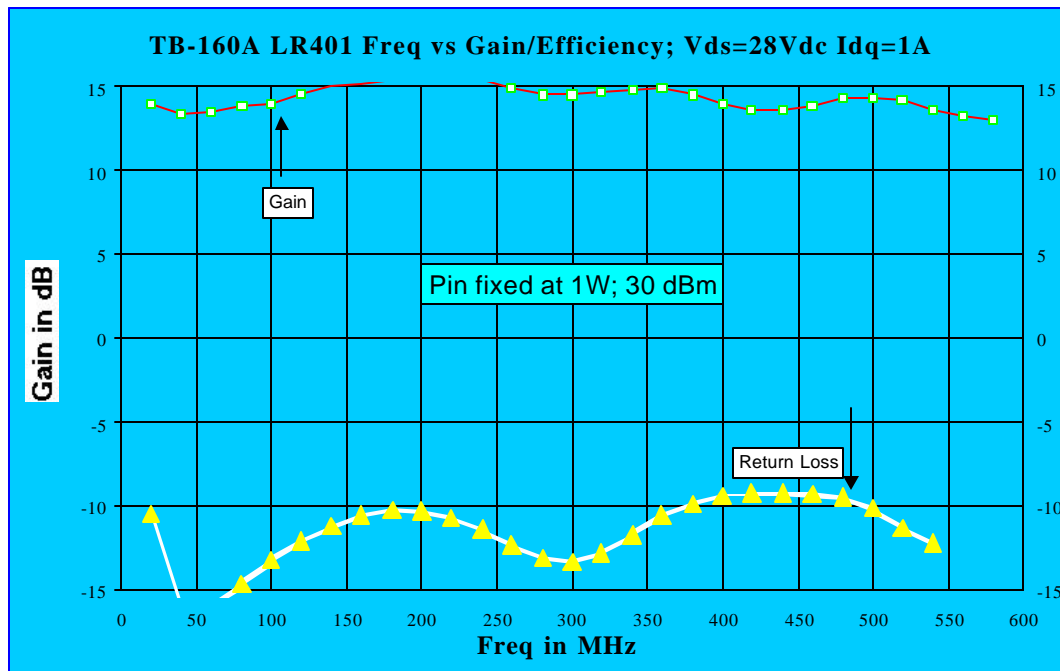


Figure 9 Actual Measurements

Figures 9 and 10 shows the performance results across the full 30-512 Mhz band width. Very good return loss was achieved. The gate series resistance in addition to lowering device gain also improves return loss. By its nature, the Ldmos transistor yielded very high gain of 14dB across the entire bandwidth at high power out. Figs 11 and 12 shows the results of Pin Pout. This measures the accuracy of simulation at both low and high power.

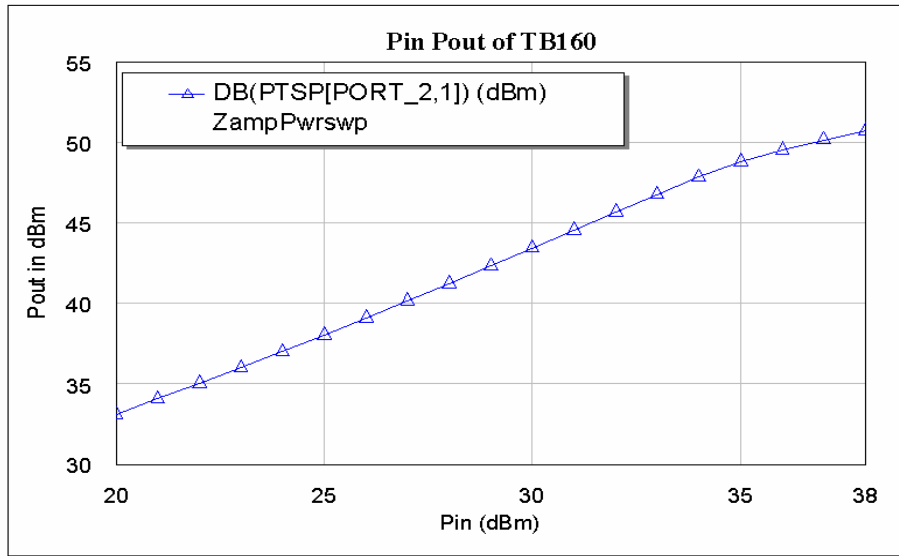


Figure 12 Simulated Pin vs Pout

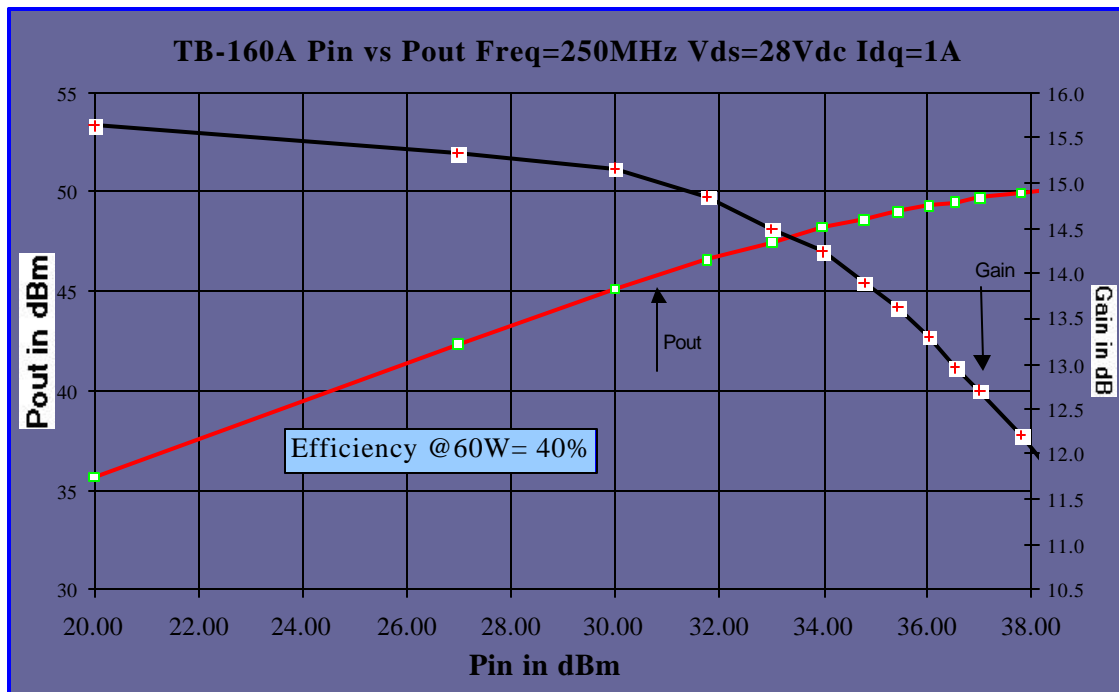


Figure 11 Actual Measurements Pin vs Pout

The simulation results shown here are from AWR-Microwave office. Similar results were achieved with Agilent's ADS software. Simulation files for both simulators can be downloaded from Polyfet's website www.polyfet.com. At this website, data sheet, S parameter and spice model for the LR401, as well as other transistors are also available. This topic was presented at the MTT 2002 microapps seminar and the slide presentation is also available at the website for download.

Conclusion

In conclusion, by implementing lumped impedance matching embedded into coaxial transmission line impedance transformation, an amplifier has been designed that possesses wide bandwidth, gain flatness, reasonable input VSWR, linearity and efficiency in a physically small footprint. It has also been demonstrated the feasibility to accurately simulate a high power broadband amplifier using off the shelf commercial non linear simulators.

References

1. RF Power Amplifiers for Wireless Communications by Steve Cripps (April 1999)

Acknowledgment

Thanks to Ryan Welch of AWR, Inc. - Microwave Office for creating amplifier layout drawing.