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Broadband VHF/UHF Amplifier Design Using Coaxial Transformers

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This article describes the methods used to design broadband coaxial transformer matching networks for an LDMOS power amplifier that delivers consistent performance over more than a decade bandwidth

The desire of the armed forces to maintain instant communications with all forces requires the design of miniature broadband power amplifiers with greater than decade bandwidth (30 to 512 MHz). This bandwidth is required for all-band transceivers that cover tactical ground and air frequencies in addition to civil telecommunication frequencies and the frequencies of our allies. All-band radios are commonplace in virtually every deployment of new platforms, as well as in the retrofitting of 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 into matching the load line of power MOSFET transistors over decade bandwidths.

This article presents 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, enabling an efficient load line match across a decade of bandwidth.

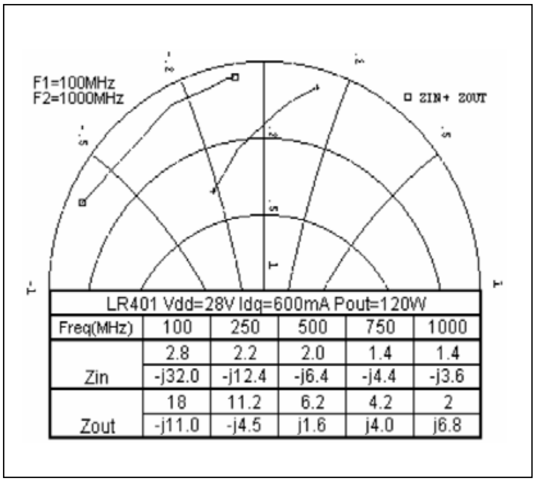
Simulation Methodology.

Linear simulation assumes that 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 nonlinear model and nonlinear simulator. The quiescent current is set at a nominal condition and the power level used in the simulation is set to a low level so 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 (e.g. impedance magnitude and angle). If the nonlinear 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 nonlinear simulator, the simulation results are generally very close to actual amplifier performance.

Nonlinear 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. To obtain accurate results, the device model would have to track an actual device transfer curve closer than 5 percent. Five percent accuracy is generally acceptable for gain compression and efficiency measurements, but not for the slight nonlinearity that causes low to intermediate levels of intermodulation distortion. Modeling technology is slowing improving and it is expected that intermodulation performance may be accurately modeled in the future. Nonlinear 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.



Freq(MHz)	100	250	500	750	1000
Zin	2.8	2.2	2.0	1.4	1.4
	-j32.0	-j12.4	-j6.4	-j4.4	-j3.6
Zout	18	11.2	6.2	4.2	2
	-j11.0	-j4.5	j1.6	j4.0	j6.8

Figure 1 · Z_{in} and Z_{out} vs. frequency.

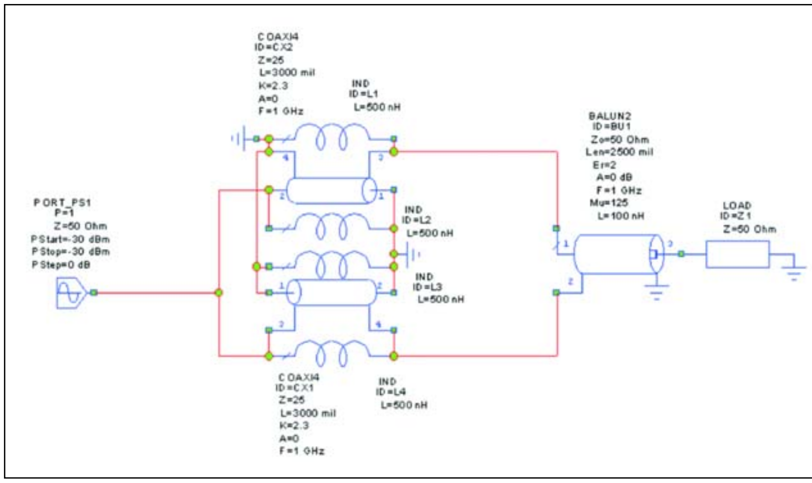


Figure 2 · Conventional 4:1 transformer with balun.

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 too large to be practical to implement. Additionally, since the band width is multi-octave, broadband 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 software packages such as Applied Wave Research's (AWR) Microwave Office and Agilent Technologies' ADS, used together with Polyfet RF Spice Models to demonstrate broadband matching techniques.

Impedance Behavior of Transistors

At low frequencies, the device's output impedance is relatively high compared with the calculated load line required to produce the desired power. As the operating frequency is increased, the output capacitance (C_{oss}), reverse capacitance (C_{rss}) 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 two. That is 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 Z_{out} 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 transformers to achieve extremely wide bandwidths. This paper will explore how to combine the coaxial transformer with lumped 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. Broadband extraction is an area that will be explored in the future as the results will take into account more realistic harmonic loading and allow more accurate broadband design implementation. In the case of Polyfet transistors, Z_{in}/Z_{out} 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 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 wideband impedance matching is the 4:1 design with a balun transformer to achieve optimum balance. The standard accepted equation for transformation is that the Z_0 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.

Figure 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 two to obtain individual device load impedance. At 30 MHz the ratio falls off due to reactive shunt losses, which could be compensated with

Frequency (GHz)	Coax transformer $Z_{in}[1]$ (Real)	$Z_{in}[1]$ (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 the frequency band.

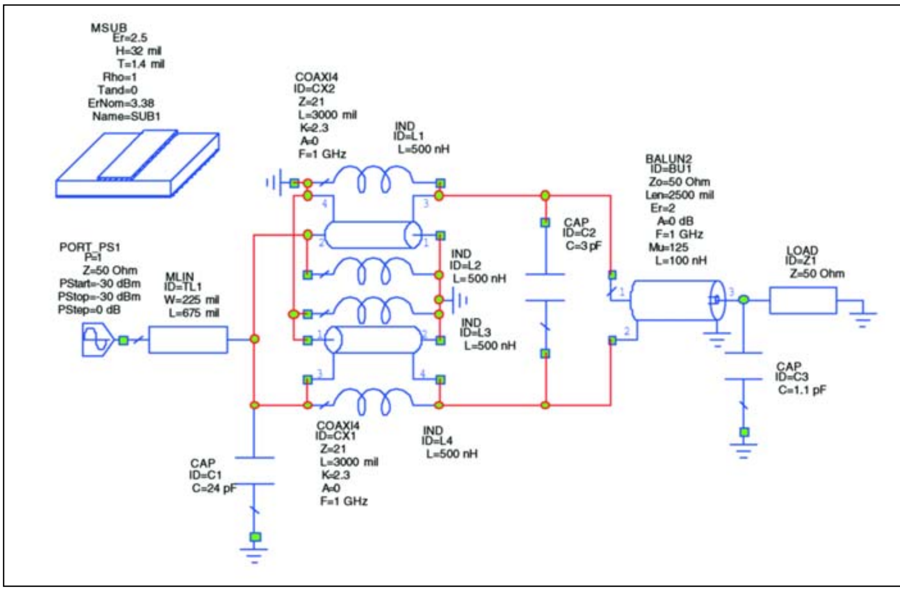


Figure 4 · Variable 4:1 impedance transformer and matching network.

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 conventional design allows the coaxial transformer to transform the impedance to obtain a match the low end of the band, then add additional lowpass matching sections to lower the impedance at the upper band edge. Although this technique performs satisfactorily, a microstrip implementation would occupy considerable space.

A novel approach to this problem, shown in Figure 4, 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 may be 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 and the shunt capacitance will lower the load line to effectively match the device at the upper band edge. Figure 5 shows the impedance dropping with increasing frequency. This can be accomplished with the same physical constraints as just a broadband transformer alone. 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.

Designing the Load Line

To design our example 80 watt broadband 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 law [1],

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

let's calculate the low frequency load line. $(28–5)^2/(2\times80) = 3.31$ ohms or 6.62 ohms for two push-pull devices. 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

Frequency (GHz)	Coax transformer $Z_{in}[1]$ (Real)	$Z_{in}[1]$ (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 frequency.

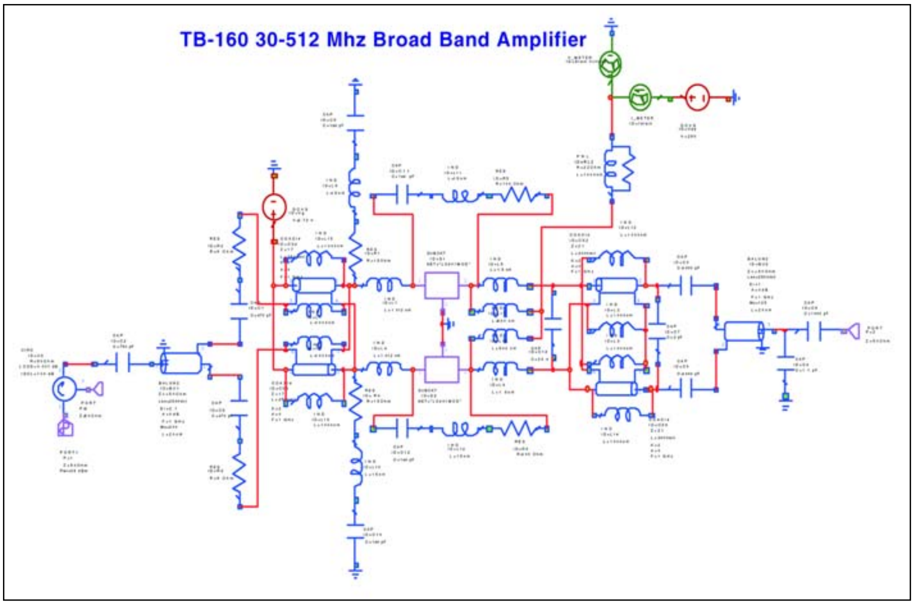


Figure 6 · Input schematic for nonlinear simulation.

large signal impedance data, review the optimum match at the upper band edge. 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 that 1/8 wavelength at the highest operating frequency. This will keep the transmission line acting as an inductance. Both the length and impedance may be 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 broadband 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 nonlinear simulation. It is strongly recommended to start the simulation at a low input power level and check for small signal gain, gain flatness, and input return loss. The input return loss may be 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

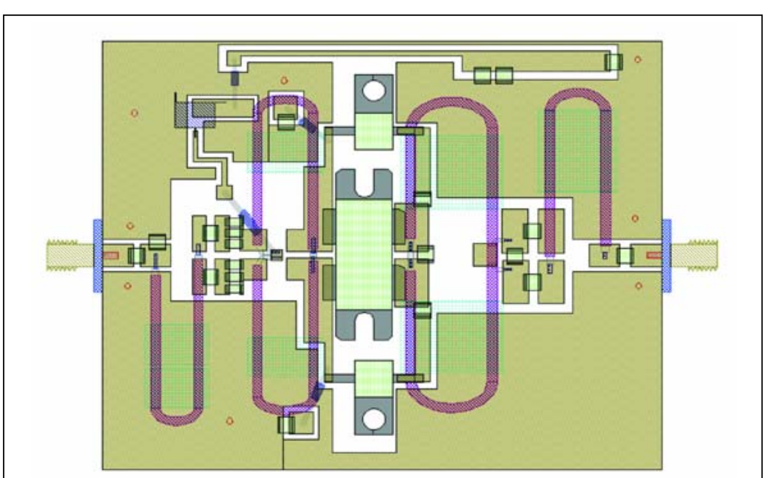


Figure 7 · Input circuit layout diagram.

Figure 8 · Actual amplifier; note the small size.

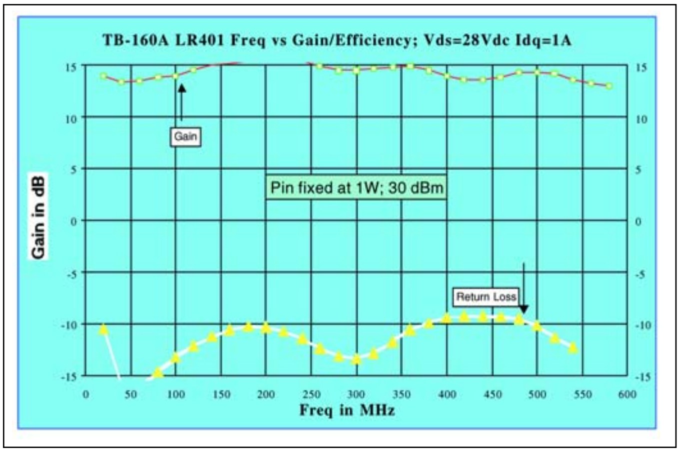


Figure 9 · Measured gain and return loss.

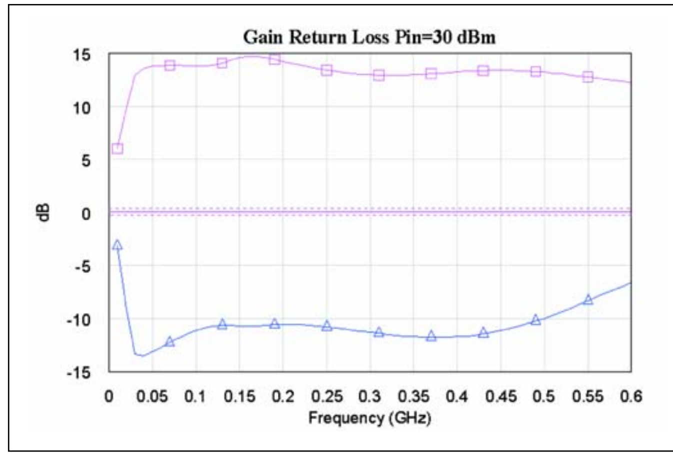


Figure 10 · Simulated values of gain and return loss.

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 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, and variables (component values) have to be constrained greatly in order to get meaningful results. With today's Pentium computers and improved EDA software, nonlinear simulation speeds approach that of linear simulation just a few years earlier.

Real time nonlinear tuning is a capability of present simulators. 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.

The circuit used in simulation shown in Figure 6 consists of similar input and output matching networks, as 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. A series RLC network between gate and 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 gain over the band. The schematic shows additional inductances to represent the printed circuit board pads for component 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 [2] and Figure 8 is a photo of the actual amplifier built from the simulation and artwork.

Simulation Results

Very good correlation between simulated and actual measurements

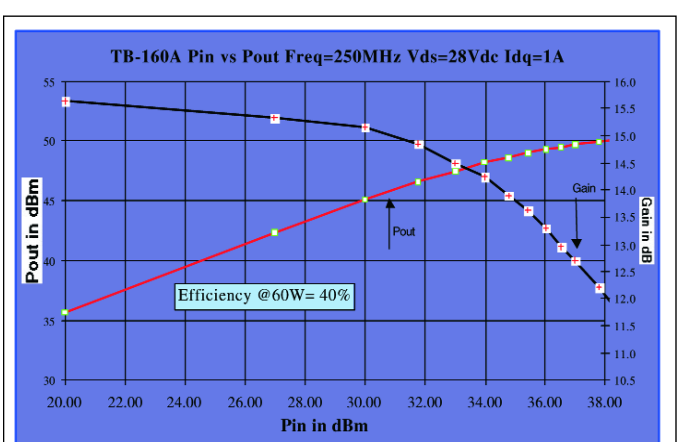


Figure 11 · Measured Pin vs. Pout.

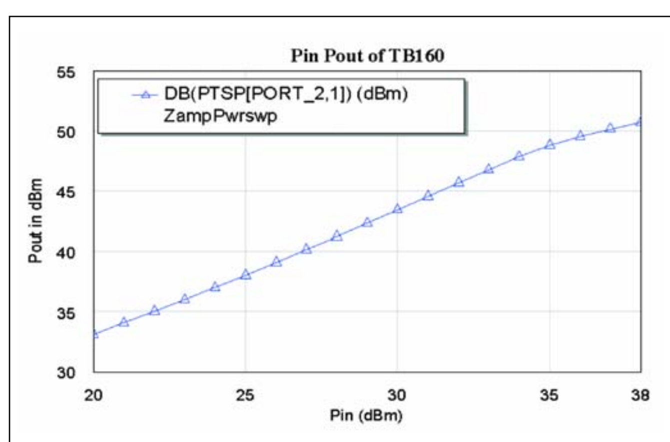


Figure 12 · Simulated Pin vs. Pout.

can be seen between Figures 9 and 10 and between Figures 11 and 12, verifying validity of models of both active and passive components.

Figures 9 and 10 show the measured and simulated gain and return loss performance across the full 30 to 512 MHz bandwidth. Very good return loss was achieved. The gate series resistance improves return loss in addition to lowering device gain. By its nature, the LDMOS transistor yielded very high gain of 14 dB across the entire bandwidth at high power out. Figures 11 and 12 show the results for P_{in} and P_{out}, This measures the accuracy of simulation at both low and high power.

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 MicroApps seminar at the 2002 MTT-S International Microwave Symposium. The slide presentation is also available at the Polyfet website for download (www.polyfet.com).

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. Steve Cripps, *RF Power Amplifiers for Wireless Communications*, Artech House, 1999.

Acknowledgment

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