Non-linear Modeling Speeds HBT Power Amplifier Design

by Nidhi Vashisht, Applications Engineer and John Bellantoni, Director of Applications Engineering, TriQuint Semiconductor

Introduction

Modern RF design techniques increasingly take advantage of improvements in modeling and device characterization to speed time-to-market and reduce costs. In particular, the area of power amplifier design has progressed rapidly from the days of simple impedance calculations and endless empirical adjustments. When linear simulators first made their appearance in the design community, power amplifiers were developed using load-pull data to synthesize matching networks entirely within the simulator environment.

The development of powerful non-linear simulators based on numerical methods such as harmonic balance has spurred the need for accurate, non-linear models that can be used to predict spectral content due to non-linearities inherent in microwave power devices. As the telecommunications industry has migrated toward complex digital modulation schemes, multi-carrier base stations and highly efficient handsets, the ability to accurately predict linearity and efficiency of the power amplifier is now one of the real keys to remaining competitive in the marketplace.

Equipped with an accurate non-linear model and some software, an RF designer can simulate all critical power amplifier performance parameters. Once a design has been established, the simulation can be optimized for an application's particular requirements, or re-tuned for operation in a different frequency band. Trade-offs between performance parameters can be examined in detail, and time-to-market can be improved by reducing the amount of energy and hours spent empirically optimizing and tweaking RF circuits.

Non-linear models in general are developed for specific devices. This article presents the models that have recently been released for the TriQuint AP60X series of High Voltage Heterojunction Bipolar Transistors (HV-HBT). Exhibiting superior efficiency and back-off linearity compared to silicon solutions, the TriQuint AP60X devices are ideal for meeting the demanding requirements of multi-carrier power amplifiers in base stations and the final stages of cellular repeater amplifiers.

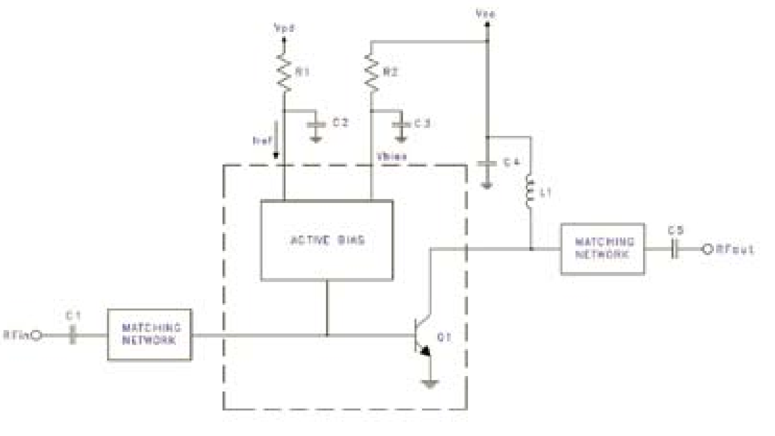

Figure 1: A generic circuit diagram for the active bias topology used in HBT amplifiers. The active bias is a buffered current mirror circuit that supplies bias to the base of the RF transistor. Matching and bias networks complete the amplifier.

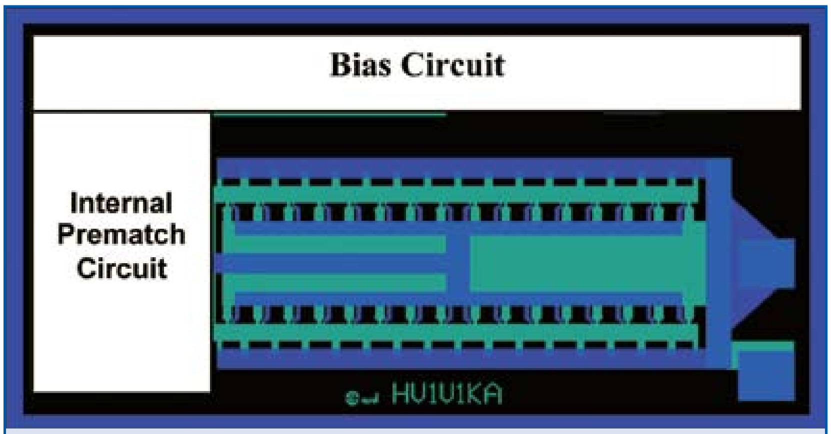

Figure 2: Layout of basic building block (1BB)

Table 1: AP60X HBT PA performance table

Model	Frequency (MHz)	Pavg (dBm)	P1dB (dBm)	Power Gain (dB)	ACLR1 (1) (dBc)	Efficiency %	Vcc=Vbias (V)	Vpd (V)	Icq (mA)
AP601	900	+24	32.5	15.8	-50	17	+28	+5	45
	1960	+24	32.7	15	-49	17			
	2140	+24	32.5	13.5	-51	17			
AP602	900	+27	35.7	15.5	-47	17			85
	1960	+27	35.7	14.2	-50	17			
	2140	+27	35.7	13	-50	15.7			
AP603	900	+30	38.2	17	-51	16.6			165
	1960	+30	38.2	12	-49	14			
	2140	+30	38.2	11.8	-49	14.6			

Note 1: WCDMA 3GPP test model 1+64DPCH, 65% clipping, 8.6 dB PAR @ 0.01% probability.

The AP60X HV-HBT Product Family

TriQuint's AP60X HV-HBT products are ideal for pre-driver and driver stages in mobile infrastructure equipment. This product family includes three devices released so far: the 2 watt AP601, the 4 watt AP602 and the 7 Watt AP603. These devices have integrated active bias networks, as shown in Figure 1. The quiescent current (Icq) is set by an external resistor, allowing the bias mode to be adjusted for the target application. Matching for a specific band is done externally. The use of external surface mount matching networks allows a single printed circuit board (PCB) to be bill of materials (BOM) populated for the desired band of operation, greatly reducing the cost of producing a separate PCB for each band in a multi-band product line. All three AP60X devices maintain high efficiency while providing excellent back-off linearity performance over the 400-2200 MHz frequency range, as shown in Table 1. The good linearity performance in the back-off region makes AP60X devices ideal for use in systems employing digital modulated signals with high peak-to-average ratios (PAR).

The AP60X HV-HBT series is designed applying a building block approach. Figure 2 shows the layout of a basic building block (1BB) of 28V GaAs HBT with its related bias circuit. The building block is composed of 32 fingers of power HBT, an input prematch circuit connected with the base and a small transistor used as an emitter follower in the bias circuit. Each emitter finger of 32 fingers of power HBT incorporates the required ballast resistor to minimize the possibility of thermal runaway. Arraying building blocks in

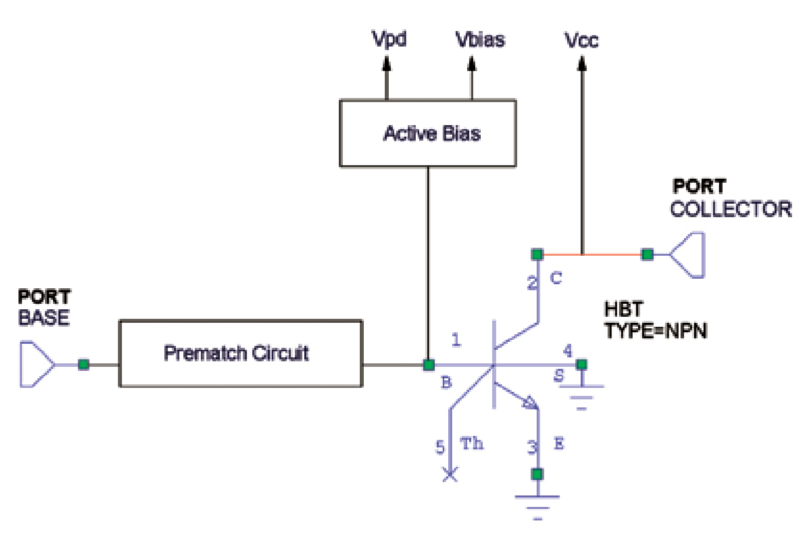

Figure 3: HBT Model for AP60X product family

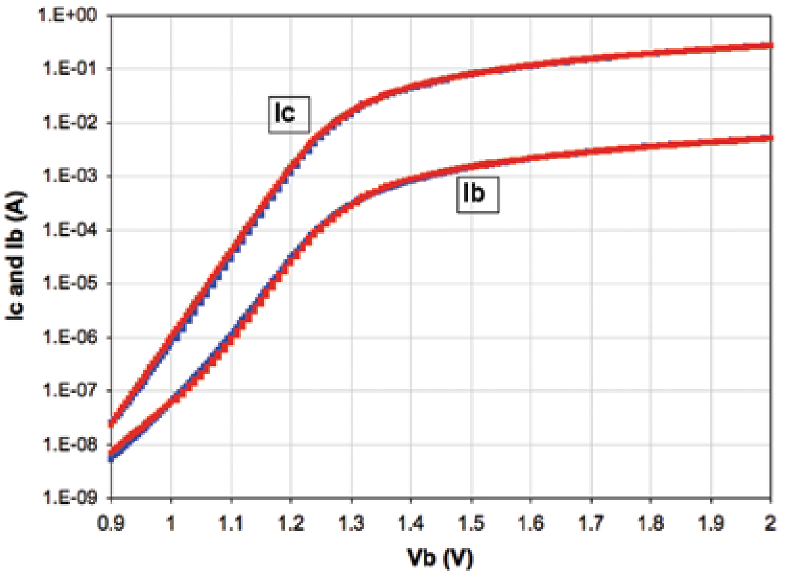

Figure 4: Simulation (blue) vs. measurement (red) Gummel plot of the 28 V HBT building block.

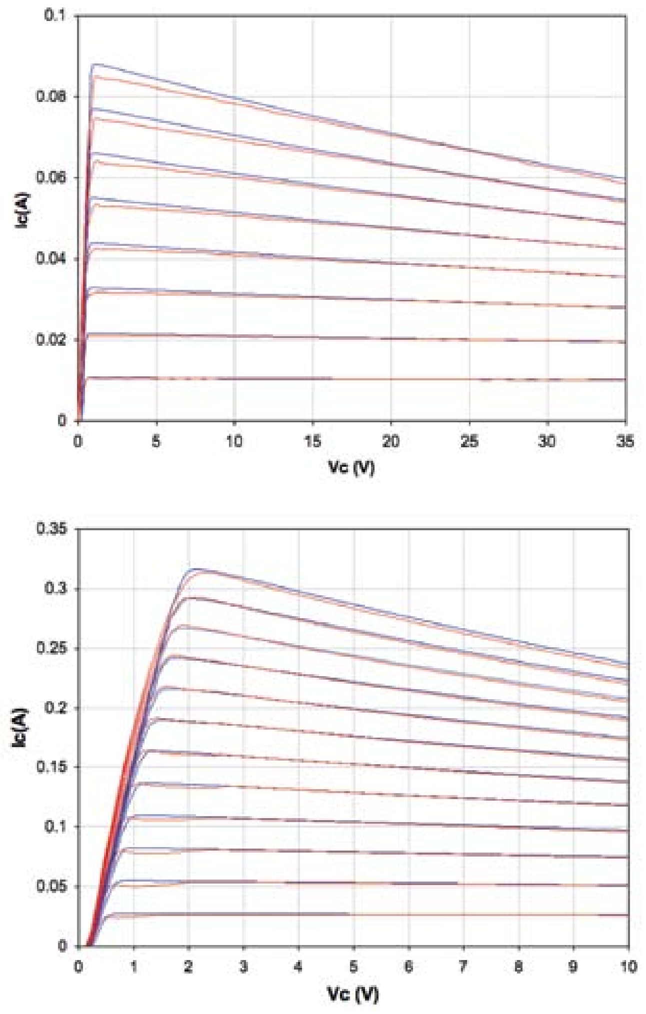

Figure 5: Simulation (blue) vs. measurement (red) I-V plot of the 28 V HBT building block: (top) High voltage/low current, high voltage set for Vcc=35 V and low current set for Icc = 85 mA; (bottom) Low voltage/high current, low voltage set for Vcc=10 V and high current set for 320 mA.

parallel on the same die results in higher power performance.

Model Development

Non-linear scalable models for the AP60X family were developed by the TriQuint modeling team in both Agilent Advanced Design System (ADS) and AWR Microwave Office (MWO). These encoded, non-linear models are now available to RF designers on a limited basis.

The Agilent HBT (AHBT) model in ADS, which is a generic III-V heterojunction bipolar non-linear model, was employed to develop the AP60X series [1]. Two device models are included in the AHBT model card: one for 32 fingers of power HBT and the other for the small transistor used as an emitter follower in the bias circuit.

TriQuint's modeling team used the UCSD HBT model in AWR to develop the scalable non-linear models, including an internal pre-match and transistor used as the emitter follower in the bias circuit. Both the UCSD HBT and AHBT model have been shown to provide similar results for I-V curves and RF performance predictions. Figure 3 illustrates the HBT model, including the internal prematch circuit and bias circuit.

The models were verified based on extracted device parameters and by comparing the results of simulation with measurements. Parasitic capacitance and inductance associated with the multi-finger HBT as well the package parasitics are taken into consideration. The 1BB model precisely fits the measured results for the Gummel plot and various I-V plots, as shown in Figure 4 and Figure 5. Successful verification of S-parameter up to 8 GHz under 17 bias conditions, junction capacitances (Cbe and Cbc) as a function of voltage, and measurement over temperature has been performed on the models. Careful determination of transit time parameters, Kirk effect parameters, and cutoff frequency (ft) model is vital for simulation of intermodulation distortion (IMD). The simulated ft matches the measured results reasonably well in a wide current and voltage range, which confirms accurate prediction of IMD.

The scalability of the model was verified with both small and large signal performance measurements on multiple building blocks used to construct the AP60X series of devices.

Designing an AP603 Power Amplifier

Verification of the non-linear model proceeded by developing and characterizing an AP603 amplifier at 2140 MHz. The device is mounted on PCB with input matching tuned for optimum input return loss and output matching tuned for high linearity at the 2140 MHz operating frequency. Non-linear AP603 performance is simulated with the same matching networks placed on the board. In the simulations, parasitic inductances (0.75 nH) were added in series with the shunt tuning capacitors to account for ground vias present on the board. Figure 6 and Figure 7 illustrate a good agreement obtained between the simulated and measured ACLR1 and IMD3 plots of a AP603 power amplifier designed for 2140 MHz.

Non-Linear Model Verification Using Load-Pull Data

Accuracy of the AP601 non-linear model is demonstrated by comparing actual harmonic load-pull measurements to sim-

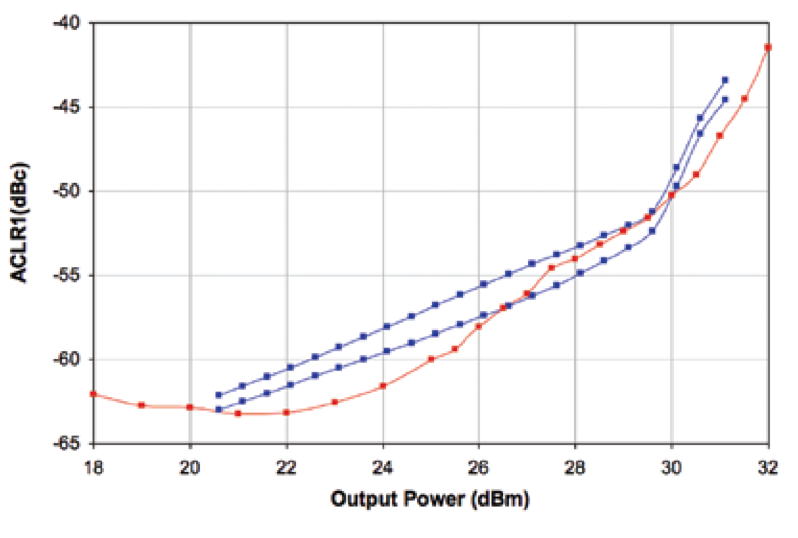

Figure 6: Simulation (blue) vs. measurement (red) for ACLR1 of the AHBT AP603 non-linear model tuned at 2140 MHz. ACLR1 measured at 5 MHz offset using W-CDMA TM 1+64DPCH, PAR 8.6 dB @ 0.01% probability, Icq=160 mA.

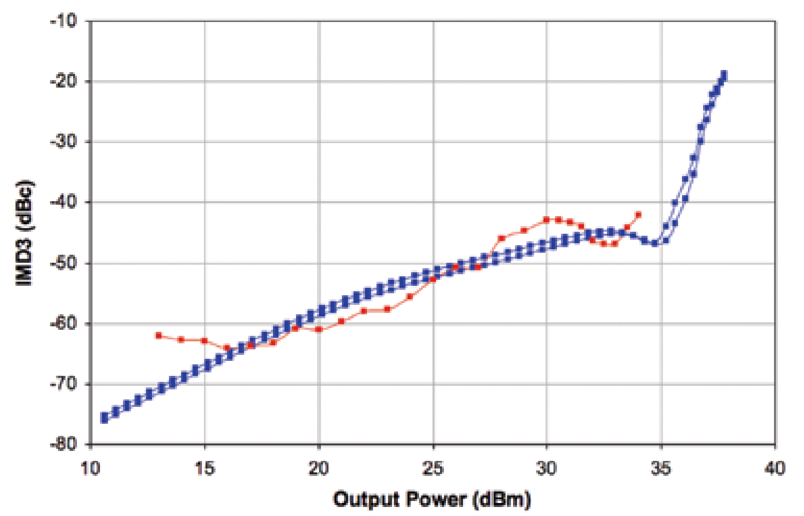

Figure 7: Simulation (blue) vs. measurement (red) for IMD3 of the UCSD AP603 non-linear model tuned at 2140 MHz. IMD3 performance measured using a CW signal at 2140 MHz and 1 MHz spacing.

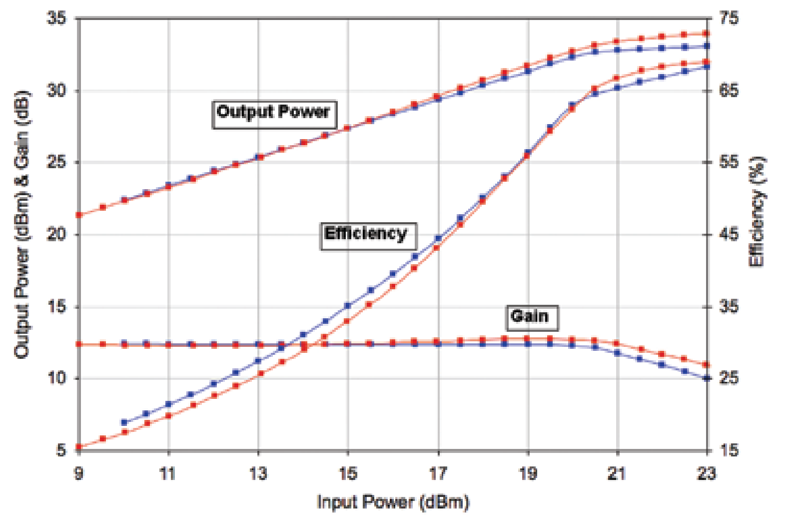

Figure 8: Simulation (blue) vs. measurement (red) of a AP601 device harmonic load-pull at 2.5 GHz with Icq = 40 mA, Vcc = 28 V.

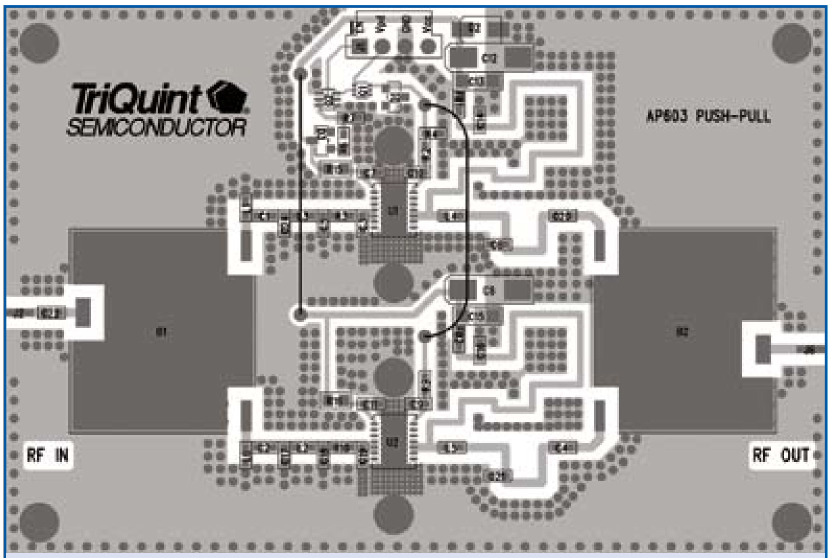

Figure 9: Board layout of an AP603 push-pull amplifier. Design tuned for 400-800 MHz. B1 and B2 are Anaren 3A325 baluns.

ulations performed using the non-linear model. A harmonic load-pull varies the impedance at the output of a device, with separate control of the impedance at harmonic frequencies. Device characterization of an AP601 was performed using a harmonic load-pull at 2.5GHz and quiescent currents of 14 mA and 40 mA. Figure 8 displays gain, efficiency and output power plots for an AP601 device using a harmonic load-pull setup on a simulator vs. bench testing.

AP603 400-800 MHz Push-Pull Amplifier Design

The non-linear AP603 model was used to develop a wide frequency range 400-800 MHz match in a push-pull configuration. A 50 Ω push-pull amplifier employs two similarly-matched 25 Ω amplifiers working in 180º phase opposition between baluns, presenting 25 Ω impedance to each amplifier. The design is based on the 50 Ω single-ended AP603 400-800 MHz reference design that can be found on the AP603 device page of the TriQuint website. Utilizing standard transform techniques the load impedance seen by AP603 in the single-ended 50 Ω 400-800 MHz reference design was retuned to provide equivalent load impedance with $Z_0 = 25$ Ω. Subsequently, the non-linear computer model was used to design and fabricate the push-pull amplifier, as presented in Figure 9. Good agreement between simulated and measured performance for the small signal S-parameters and output IMD3 is shown in Figure 10.

Conclusion

Based on Agilent AHBT and AWR UCSD software, TriQuint Semiconductor has developed accurate and reliable non-linear HBT models for the AP60X series of GaAs high voltage power amplifiers. The models can precisely simulate the full-scale device characteristics of multiple finger power HBTs such as DC, thermal, junction capacitances, S-parameters, output power, gain, operation current, efficiency, IM3 and ACLR. Excellent agreement has been achieved between simulated and measured performance. The unit building block model for the HBT power device scales well for the AP601, AP602 and AP603 devices up to a P1dB of 38.2 dBm. Based on the success of the AP60X models, future design tool resources will include non-linear models for the TriQuint family of 5V GaAs HBT amplifiers.

Acknowledgement

The authors would like to thank Xiangkun Zhang for developing the scalable non-linear models and Paul Laferriere for the AP603 push-pull amplifier design simulations.

More Information

Non-linear scalable models for the AP60X family developed by TriQuint in both Agilent Advanced Design System

(ADS) and AWR Microwave Office (MWO) are available to RF designers on a limited basis. Tell TriQuint about your latest project by visiting: www.triquint.com/hvhbt-models. Find additional RF design information at www.triquint.com/tech-connect.

References

[1] X. Zhang et al., "A scalable high power nonlinear HBT model for a 28V HVHBT," IEEE MTT-S Dig. IMS2008 THP1F-01, 2008, pp. 1413-1416.

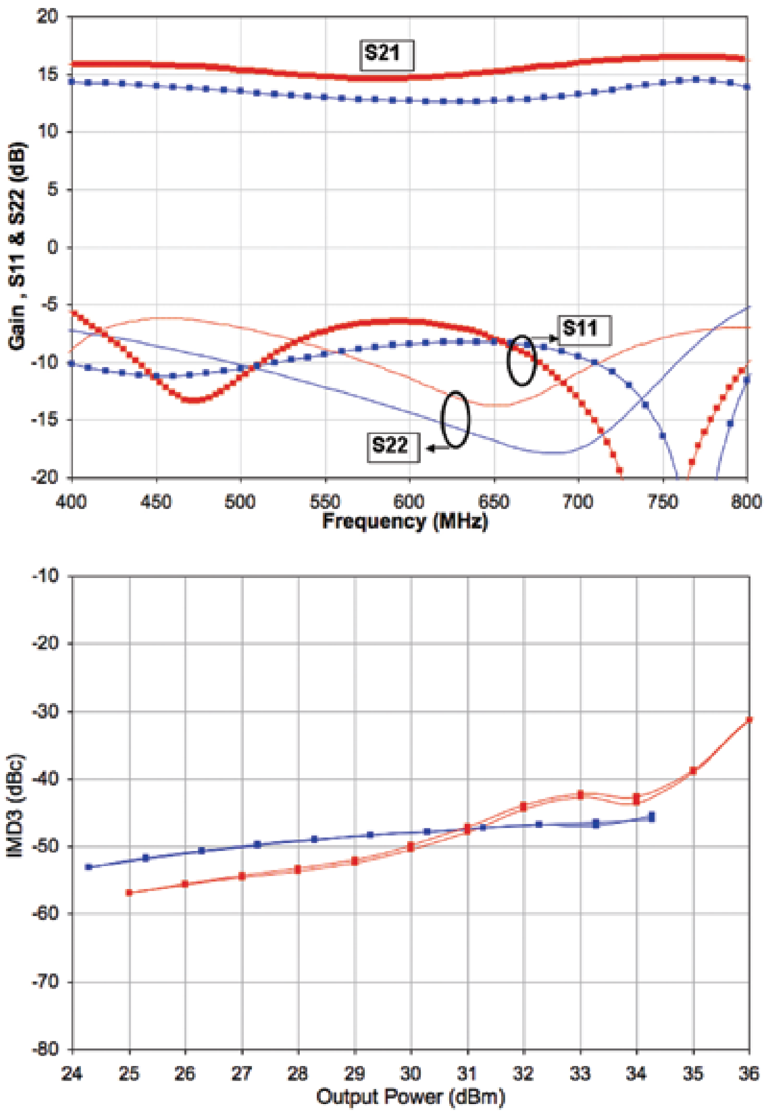

Figure 10: AP603 push-pull amplifier design tuned for 400-800 MHz. Simulation (blue) vs. measurement (red) plots: (top) small signal S-parameter; (bottom) IMD3 at 800 MHz and 1 MHz spacing.