A Load Pull/Hot S22 Analyzer for Transmit Array Amplifiers

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Introduction: Transmit arrays offer new versatility in high field imaging, integration of transmit mode interventional devices, and improved RF safety and SAR control. However, a major engineering challenge is control of coil-to-coil coupling at different power levels. One class of solutions uses on-coil current sensors to fix coil currents using analog quadrature closed loop feedback (Cartesian Feedback)[1], or by open loop preconditioning (signal vectors)[2]. Fully digital Cartesian feedback is also an option. The second class of solutions employs amplifier output impedance control to emulate preamp decoupling[3,4]. Here, one attempts to extend small signal current source behavior of transistors to higher power levels, despite well known nonlinear pitfalls. In both approaches, a need exists to quantify amplifier output impedance properties under transmit power conditions. We present an automated load pull and hot S22 system that can characterize transmit array impedance behavior under transmit power conditions.

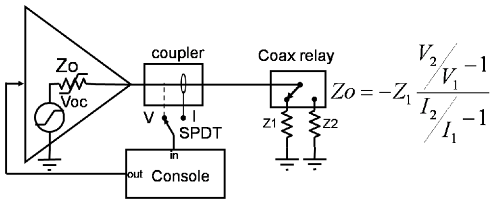

Figure 1: Load pull measurement system.

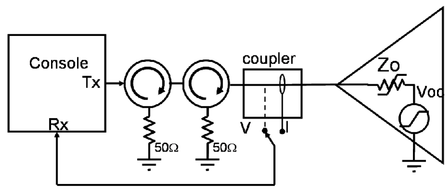

Figure 2: Hot S22 Method

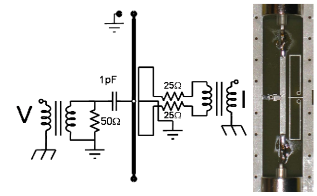

Figure 3: Directional Coupler

Theory and Methods: We base our load pull (Fig. 1) measurements on the concept of a nonlinear Thevenin circuit in which we can assign an equivalent open circuit output voltage and output series impedance at each power level. By switching between two (or more) different known output loads, and measuring output voltage and current, we can infer the internal amplifier impedance responsible for the output level change. We employ a variation of the Bruene directional coupler to simultaneously measure load voltage and current. In contrast, "Hot S22" (Fig. 2) employs the same directional coupler to measure the small signal output impedance looking into the amplifier output while power transmitting at a nearby frequency. We constructed printed circuit directional couplers that tap into the micro-strip voltage, and sense current by inductive pickup loop (Fig. 3). Given its symmetry, only four S parameters are relevant: power reflection S11, power transmission S21, voltage transfer S31, and current transfer S41. A 50Ω calibration directly yields the ratio S31/S41. S11 and S21 are extracted by open and short circuit test loads. These calibrations were validated by direct network analyzer measurements. The coupler V and I outputs were multiplexed by a Mini-Circuits ZX80-DR230-S+ SPDT switch to a MEDUSA console operating as a signal analyzer[5]. The test loads were switched between Z1=50Ω and Z2=25Ω using a high power coax SPDT relay switch (Tohtsu CX-230). An RF pulse sequence (Fig. 4) interleaved V/I/V measures for test loads Z1-Z2-Z1. For Hot S22, two circulators were inserted between the MEDUSA output operating at 64 MHz and a power amplifier operating at 67MHz. This steered power output to a 50 ohm dump while allowing full transmission of the MEDUSA signals to the directional coupler- in effect, treating the amplifier output as if it were a passive load. Isolation exceeded 40dB. Above the circulator pass-band, the circulator presents a high impedance at least through 200 MHz.

Results: Figure 5 shows the load pull measure of output impedance for a MRF141G based 300W amplifier with and without an additional circulator termination. As expected, the circulator forces the apparent output impedance to about 50 ohms. In its absence, output impedance changes substantially over the power range. In these plots, the test loads were separated from the amplifier by a half wavelength. Consequently, all harmonics "saw" the same impedance. However, divergent results appeared as power increased when additional λ/8, λ/4 etc. lengths were added. This did not occur for the circulator termination. As a validation check, the coupler measurement of the reference and test load impedances always remained constant over full power indicating good measurement fidelity. A hot S22 measurement of a circulator terminated amplifier yielded roughly a 50 ohm output under no power or high power conditions.

Discussion & Conclusions: The divergence in apparent load-pull impedance, for different cable lengths may seem disturbing yet may be correct. RF transistors typically have nonlinear output capacitance. Harmonic content can cross mix with device nonlinearity to create an additional fundamental component, yet the harmonic levels depend heavily on the load impedance at harmonic frequencies. Harmonic balance simulations are typically employed to analyze these phenomena[6]. Hence predictable results demand that harmonic components be well terminated, preferably in a short circuit to inhibit voltage modulation of device capacitance. Our circulators actually presented high impedances at harmonics. Two key issues are apparent: 1) that power amp decoupling could be dependent on load changes of adjacent channels, and 2) that decoupling impedance will not be constant over all power levels. Minimization of these effects will also require transmit coil elements that properly terminate harmonic content. This analyser system provides a means to test for devices that best meet these complex requirements.

References:[1] D Hoult et al, JMR 171:64,2004,, [2] G Scott et al, 16th ISMRM, 146,2008[3] Nam et al, 13th ISMRM 917:2005, [4]X Chu et al, 15th ISMRM, 172,2007,[5] P Stang et al, 15th ISMRM, 169, 2007. [6] Nonlinear Microwave & RF Circuits, Stephen A Maas. 2nd Ed. 2003.

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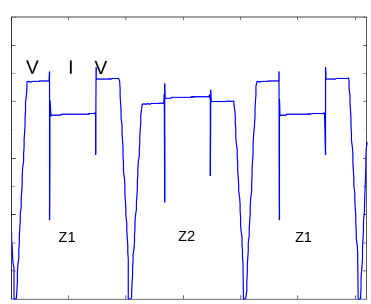

Figure 4: RF Load Pull Pulse Sequence.

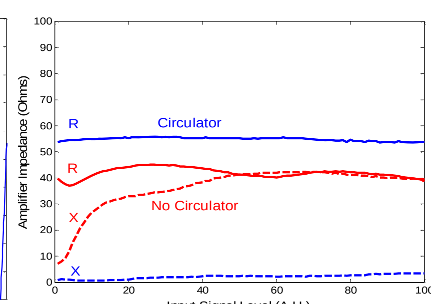

Figure 5: Amplifier output impedance.