Pulsed Power Regulated Tx Array Amplifier Architecture

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Introduction Transmit array systems are now the focus of intense development because of their potential for SAR management, interventional safety systems, and B1 shimming. Equipment room logistics, and inherent inefficiencies of remotely deployed MRI power amplifiers create challenges, especially for high channel counts. In the VHF and UHF broadcast bands, RF pallet amplifiers, at about 1$/Watt, offer a reasonable price-point, and are sufficiently compact to be sited at the magnet. Proton MRI is very narrow-band and can benefit from feedback linearization of *somewhat* linear low cost amplifier pallets. Moreover, these amplifiers could be operated in a regulated pulsed mode requiring only modest power supplies. The challenge is to design a feedback amplifier system that can incorporate device protection similar to circulators, be guaranteed stable under changing loads, with the potential of local pulsed regulation proximal to an MRI magnet. We propose a comprehensive, pulse regulated, RF feedback architecture to meet these needs and present component validations up to 300MHz operation.

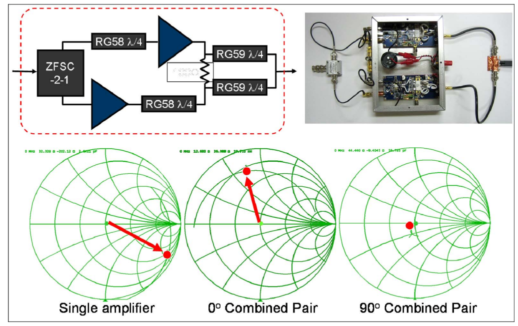

Figure 1: A 300MHz balanced implementation using output Wilkinson combiner and input 0 degree splitter creates 50Ω output port impedances.

Architecture Overview: The pulsed-power architecture incorporates several important elements: a pulsed power regulated supply, a balanced amplifier stage, mono-match directional coupler power sensing, and a frequency offset Cartesian feedback variant of RF feedback. In this approach, a power supply capable of handling only the average power needs is employed. A capacitor bank, high voltage power regulator, and RF feedback then take the burden of maintaining precision control of the RF waveforms.

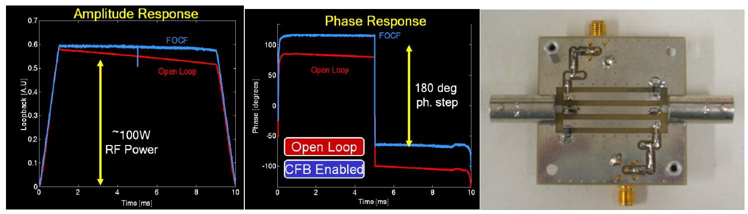

Figure 2: Cartesian feedback RF droop test of a 10ms trapezoidal rotary echo pulse. The power supply and capacitor voltage drop by 7 to 8 volts causing a subsequent RF amplitude droop and temporal phase drift for the open loop test (red). In comparison the CF linearized output (blue) is stabilized despite the power supply rail modulation. (Right) Mono-match bi-directional coupler for MR compatible power sensing.

Balanced Amplifier: Kurokawa's balanced amplifier architecture[1] combines two matched RF amplifiers with quadrature hybrids at input and output (Fig. 1). This synthesizes an approximate 50Ω input and output impedance even if each amplifier port impedance is highly reactive over power levels. As shown, a single amplifier, or 0 degree combined pair DO NOT present 50Ω impedances. The balanced amplifier demonstration was constructed from a matched pair of 100W, 100-500MHz pallet amplifiers (PP100-500-100 PMTRF Inc). Instead of hybrids, the input quadrature splitter was constructed with a Mini-circuits ZFSC-2-1 0^o splitter and an extra λ/4 coax length on one input branch. A similar λ/4 length was added to the opposing output branch and combined by a Wilkinson combiner constructed from λ/4 pair of RG59 75Ω coax and a 100Ω resistor.

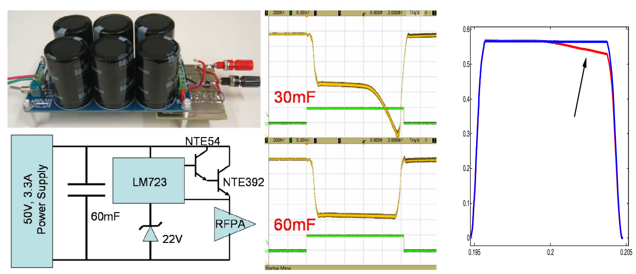

Figure 3: The pulse regulator system employs a 60mF capacitor bank and post-regulator with a Darlington transistor stage to stabilize the RF amplifier rails. The center scope shot shows the droop with inadequate (30mF) capacitors, and the right is the corresponding RF droop (red).

Cartesian Loop: The amplifier is linearized by a frequency offset Cartesian feedback loop (FOCF) [2], but the feedback error subtraction can now occur at RF rather than after quadrature down-conversion without impacting loop performance [3]. This simplifies circuit complexity and dynamic range needs of the down-mixers. The forward voltage V_{FWD} of a 50Ω mono-match coupler (Fig. 2). can provide the feedback signal. By definition, V^2_{FWD}/Z_o is the available power from the amplifier and has no load dependence. This RF feedback also provides precision stabilization of the output impedance to ~50Ω, overcoming imperfections and mismatch of the balanced amplifier. Figure 2 shows FOCF open (red) and closed (blue) loop responses of a 298 MHz trapezoid pulse with 180^o phase reversal halfway when an under-rated power supply is employed. The RF droop is obvious in the open-loop case.

Pulsed Power Regulator: Because the peak to average power needs of MRI are so extreme, we also developed a pulse-regulated system using 75-150W power supplies, and a 60mF capacitor bank. The power regulator uses a Darlington transistor stage capable of supplying over 500 Watts of pulsed energy. Unlike the RF feedback, the intent is to allow the power supply to remain remote from the magnet, while the capacitor bank can deliver local regulated power. In Fig. 3, our tests show RF droop (red) when an inadequate (30mF) capacitor bank is employed. The waveform shape (also 298 MHz) remains undistorted with a 60 mF capacitor bank.

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Discussion & Conclusion : Ultimately, as research sites attempt to add more parallel transmit channels, placement of the RF amplifiers at the magnet becomes more desirable. The power supplies likely must remain remote from the magnet. However, by 128MHz, and certainly 300 MHz, RF power amplifiers seldom contain ferrite components. It is then a matter of providing the necessary precision supply and RF control to meet the demanding amplitude and phase stability requirements of MRI. When integrated, the pulsed power regulation, RF feedback, and balanced amplifier topology are well suited to provide precision control, and precise impedance control in a coupled transmit array environment.

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References:

[1] K. Kurokawa, Bell Syst. Tech. J. p1675, Oct 1965 [2] M. Zanchi, IEEE TMI,30:512, 2011. [3] M. Faulkner, IEEE Tran. Veh. Tec. 47:209, 1998. Grant support: NIH R01EB008108, R21EB007715, R01EB005407. Acknowledgements: GE Healthcare, GE Faculty Fellowship.